

Physics 5D - Midterm Review Lecture

5 pm Friday November 1

Reminder:

Midterm Exam here next Monday Nov 4
One 8.5x11" page with notes OK

Practice Midterm and Solutions are at
physics.ucsc.edu/~joel/Phys5D

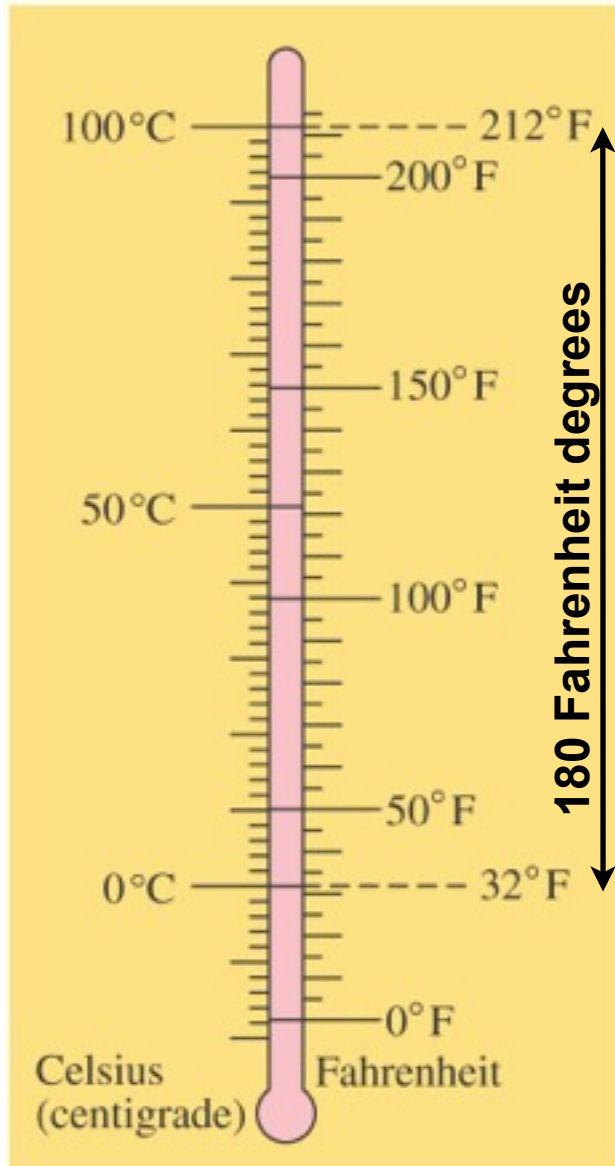
Physics 5D - Heat, Thermodynamics, and Kinetic Theory

Homework and Lecture slides are posted at <http://physics.ucsc.edu/~joel/Phys5D>, the Phys5D website. Late homework will not be accepted since solutions are posted on the class website (password: Entropy) just after the homework is due. Recorded Lectures 3-4-5 are online at <https://webcast.ucsc.edu/>.

Course Schedule

Date	Topic	Readings
1. Sept 30	Temperature, Thermal Expansion, Ideal Gas Law	17.1-17.10
2. Oct 7	Kinetic Theory of Gases, Changes of Phase	18.1-18.5
3. Oct 14	Mean Free Path, Internal Energy of Gases	18.6-19.3
4. Oct 21	Heat and the 1 st Law of Thermodynamics	19.4-19.9
5. Oct 28	Heat Transfer; Heat Engines, Carnot Cycle	19.10-20.2
6. Nov 4	Midterm Exam (in class, one page of notes allowed)	
7. Nov 18	The 2 nd Law of Thermodynamics, Heat Pumps	20.3-20.5
8. Nov 25	Entropy, Disorder, Statistical Interpretation of 2 nd Law	20.6-20.10
9. Dec 2	Thermodynamics of Earth and Cosmos; Overview of the Course	
10. Dec 11	Final Exam (5-8 pm, in class, two pages of notes allowed)	

17-2 Temperature and Thermometers



Temperature is generally measured using either the Fahrenheit or the Celsius / Kelvin scales.

The freezing point of water is 0°C , or 32°F ; the boiling point of water is 100°C , or 212°F

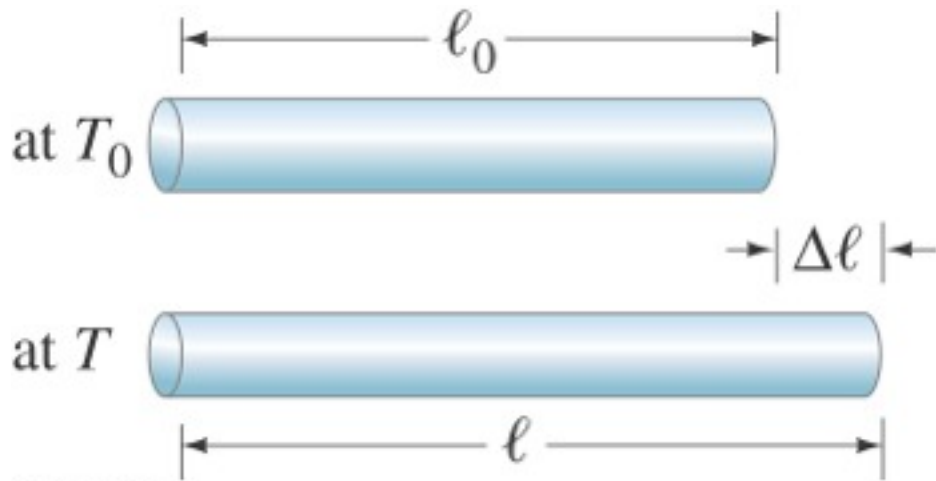
$$T_F \text{ }^{\circ}\text{F} = 32 \text{ }^{\circ}\text{F} + 1.8 T_C$$

$$T_K = T_C + 273.15 \text{ K}$$

Absolute zero = 0 K

$$= -273.15 \text{ }^{\circ}\text{C}$$

17-4 Thermal Expansion



Linear expansion occurs when an object is heated.

$$l = l_0(1 + \alpha \Delta T)$$

Here, α is the coefficient of linear expansion.

Example: $\alpha_{Al} = 25 \times 10^{-6}$, so if $\Delta T = 100\text{C}$, an aluminum bar grows in length by a factor 1.0025

17-4 Thermal Expansion

Volume expansion is similar, except that it is relevant for liquids and gases as well as solids:

$$\Delta V = \beta V_0 \Delta T.$$

Here, β is the coefficient of volume expansion.

For uniform solids, $\beta \approx 3\alpha$ because each of the 3 dimensions expands by the same factor α :

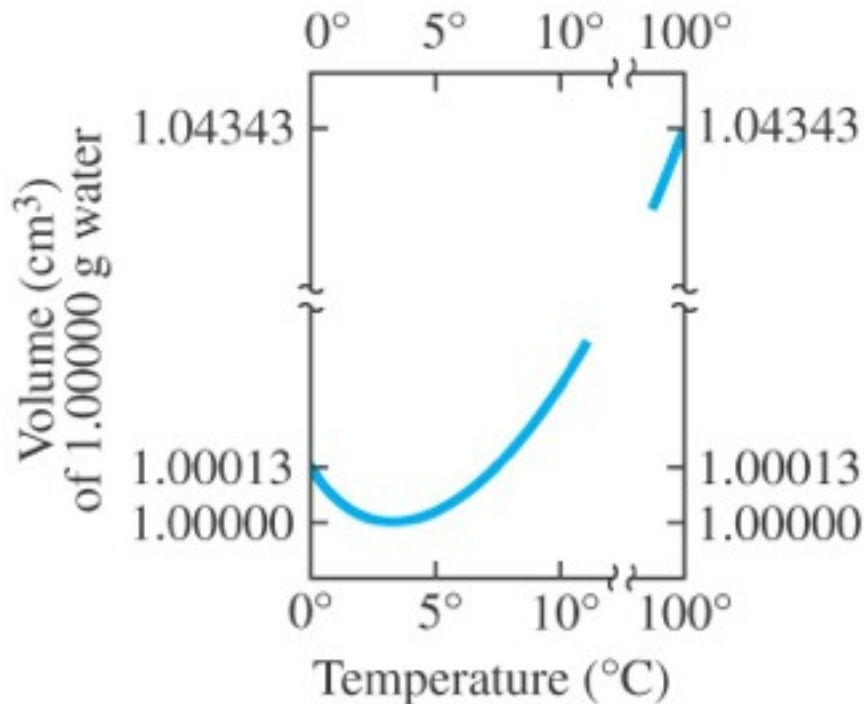
$$\Delta V = \ell_0^3 [(1 + \alpha \Delta T)^3 - 1] = \ell_0^3 3\alpha \Delta T$$

neglecting terms of order $(\alpha \Delta T)^2$.

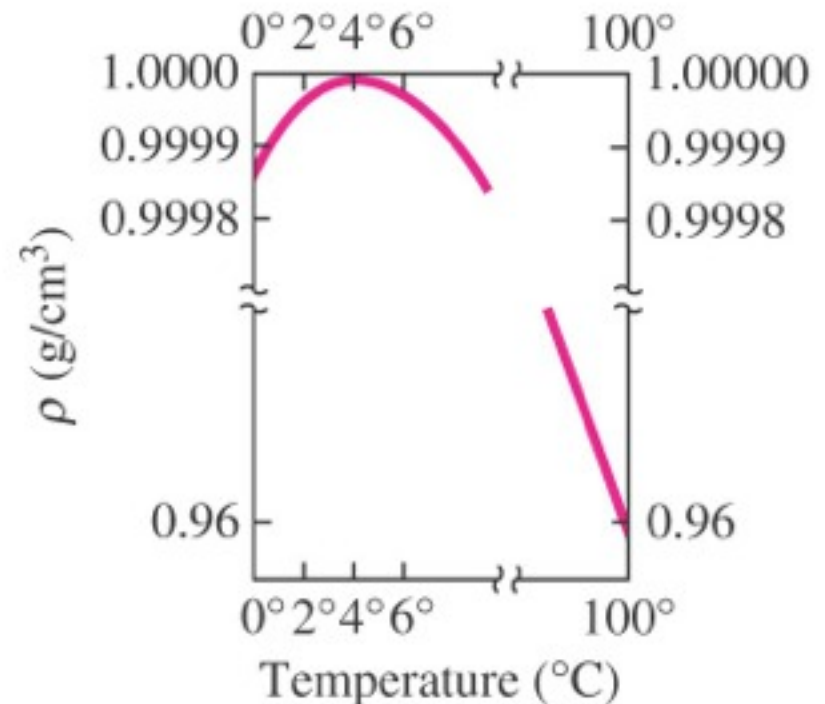
17-4 Thermal Expansion

Water behaves differently from most other solids—its **minimum volume** occurs when its temperature is 4°C . As it cools further, it **expands**, as anyone who leaves a bottle in the freezer to cool and then forgets about it can testify.

Volume



Density



A mole (mol) is defined as the number of grams of a substance that is numerically equal to the molecular mass of the substance:

1 mol H₂ has a mass of 2 g.

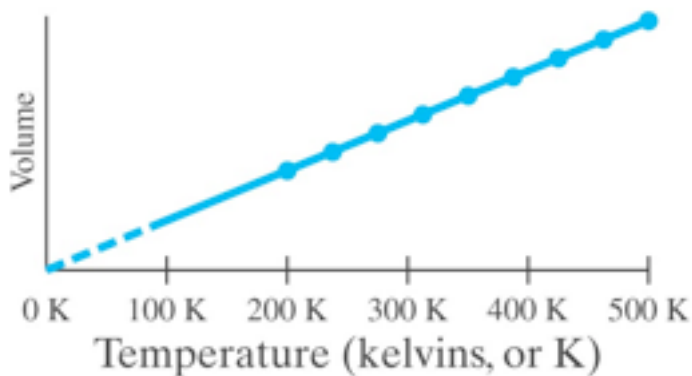
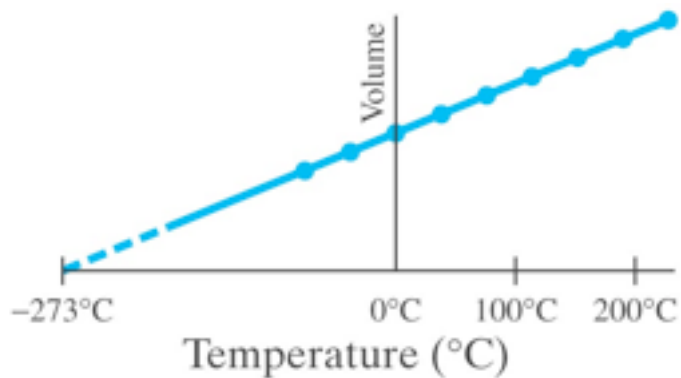
1 mol N₂ has a mass of 28 g.

1 mol CO₂ has a mass of 44 g.

The number of moles (mol) in a certain mass of material:

$$n \text{ (mole)} = \frac{\text{mass (grams)}}{\text{molecular mass (g/mol)}}.$$

17-6 The Gas Laws and Absolute Temperature



$$V \propto T$$

At fixed pressure, the **volume is linearly proportional to the temperature**, as long as the temperature is somewhat above the **condensation point**. Extrapolating, the volume becomes zero at **-273.15°C**; this temperature is called **absolute zero**

Guillaume Amontons, 1702
Jacques Charles, 1787
Joseph Gay-Lussac, 1808



1592 Galileo's thermoscope



1643 Torricelli makes first barometer

1662 Boyle's Law Published



1702 Amontons' Experiment

1714 Fahrenheit's Thermometer

1734 Bernoulli's KMT

$$P \propto T$$

1787 Charles' Law

$$V \propto \frac{1}{P}$$

$$V \propto T$$



1801 Dalton's Law of Partial Pressure

1802 Gay-Lussac's Balloon Ride

1811 Avogadro's Principle Published



The ideal gas law is

$$PV = nRT,$$

where n is the number of moles and R is the universal gas constant

$$\begin{aligned} R &= 8.314 \text{ J}/(\text{mol} \cdot \text{K}) \\ &= 0.0821 \text{ (L} \cdot \text{atm)} / (\text{mol} \cdot \text{K}) \\ &= 1.99 \text{ calories}/(\text{mol} \cdot \text{K}). \end{aligned}$$

or $PV = NkT$ where k is Boltzmann's constant N is the number of molecules, and N_A is Avogadro's number



$$k = \frac{R}{N_A} = \frac{8.314 \text{ J/mol} \cdot \text{K}}{6.02 \times 10^{23} / \text{mol}} = 1.38 \times 10^{-23} \text{ J/K.}$$

Using the Ideal Gas Law

Standard temperature and pressure (**STP**):

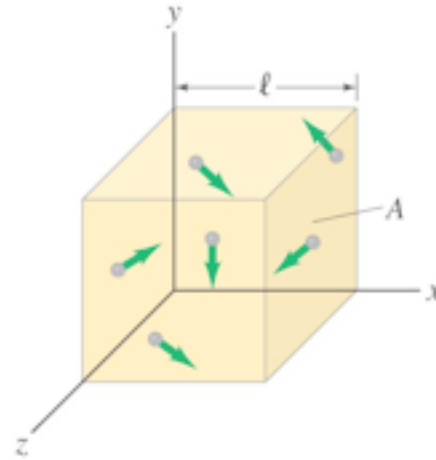
$$T = 273 \text{ K (0}^\circ\text{C)}$$

$$P = 1.00 \text{ atm} = 1.013 \times 10^5 \text{ N/m}^2 = 101.3 \text{ kPa.}$$

Determine the volume of 1.00 mol of any gas, assuming it behaves like an ideal gas, at STP.

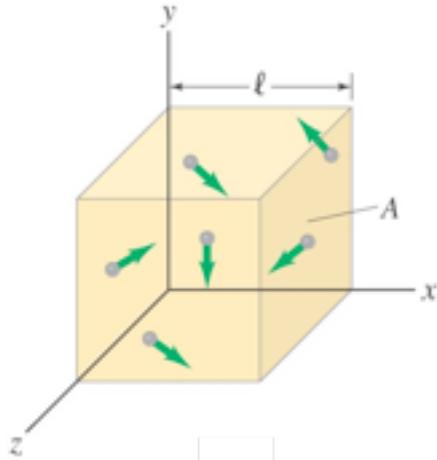
$$\begin{aligned} V &= RT/P = (8.314 \text{ J/mol K}) (273\text{K}) / (1.013 \times 10^5 \text{ N/m}^2) \\ &= 22.4 \times 10^{-3} \text{ m}^3 = 22.4 \text{ L} \end{aligned}$$

Assumptions of kinetic theory:



- **large number of molecules, moving in random directions with a variety of speeds**
- **molecules are far apart, on average**
- **molecules obey laws of classical mechanics and interact only when colliding**
- **collisions are perfectly elastic**

18-1 The Ideal Gas Law and the Molecular Interpretation of Temperature



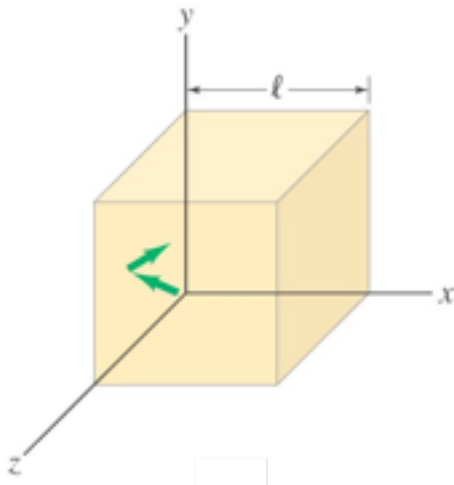
Pressure $P = \text{Force}/\text{Area} = NkT/V$.

The **force** exerted on the wall by the collisions of one molecule is

$$F = \frac{\Delta(mv)}{\Delta t} = \frac{2mv_x}{2\ell/v_x} = \frac{mv_x^2}{\ell}.$$

Then the force due to **all** N molecules colliding with that wall is

$$F = \frac{m}{\ell} N \overline{v_x^2}.$$



Daniel Bernoulli (1700-1782)

The averages of the squares of the speeds in all three directions are equal: $\overline{v_x^2} = \overline{v_y^2} = \overline{v_z^2} = \overline{v^2}/3$,

where $\overline{v^2} = \overline{v_x^2} + \overline{v_y^2} + \overline{v_z^2}$. Therefore

$$F = \frac{m}{\ell} N \overline{v_x^2} \quad \text{implies that} \quad F = \frac{m}{\ell} N \frac{\overline{v^2}}{3}.$$

So the pressure $P \equiv F/A$ is
$$P = \frac{1}{3} \frac{Nm \overline{v^2}}{V}.$$

Rewriting, $PV = \frac{2}{3} N \left(\frac{1}{2} m \overline{v^2} \right)$,

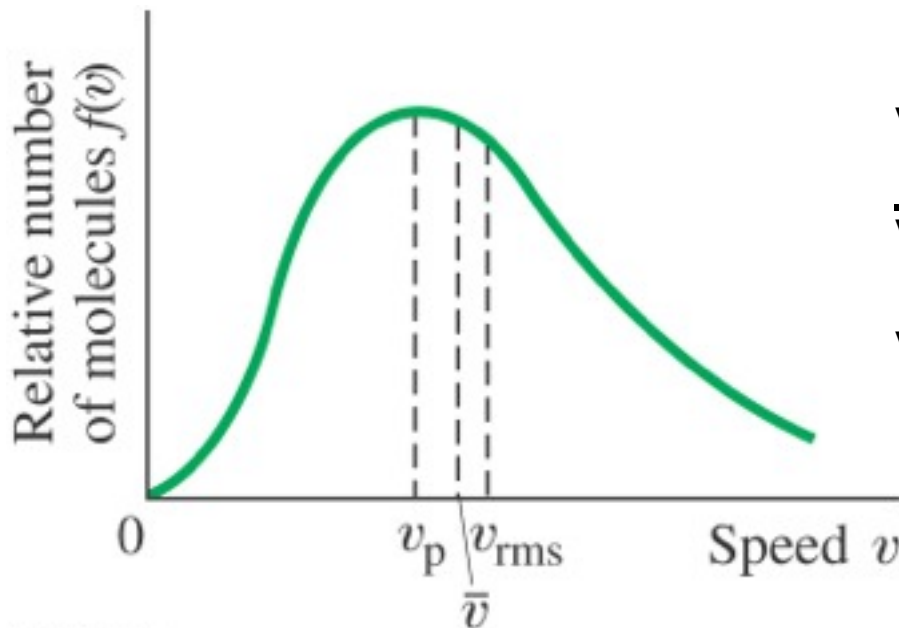
but the Ideal Gas Law says $PV = NkT$, so the average kinetic energy is determined by the temperature:

$$\overline{K} = \frac{1}{2} m \overline{v^2} = \frac{3}{2} kT.$$

18-2 Distribution of Molecular Speeds

The molecules in a gas will not all have the same speed; their distribution of speeds is called the Maxwell distribution:

$$f(v) = 4\pi N \left(\frac{m}{2\pi kT} \right)^{\frac{3}{2}} v^2 e^{-\frac{1}{2} \frac{mv^2}{kT}} .$$



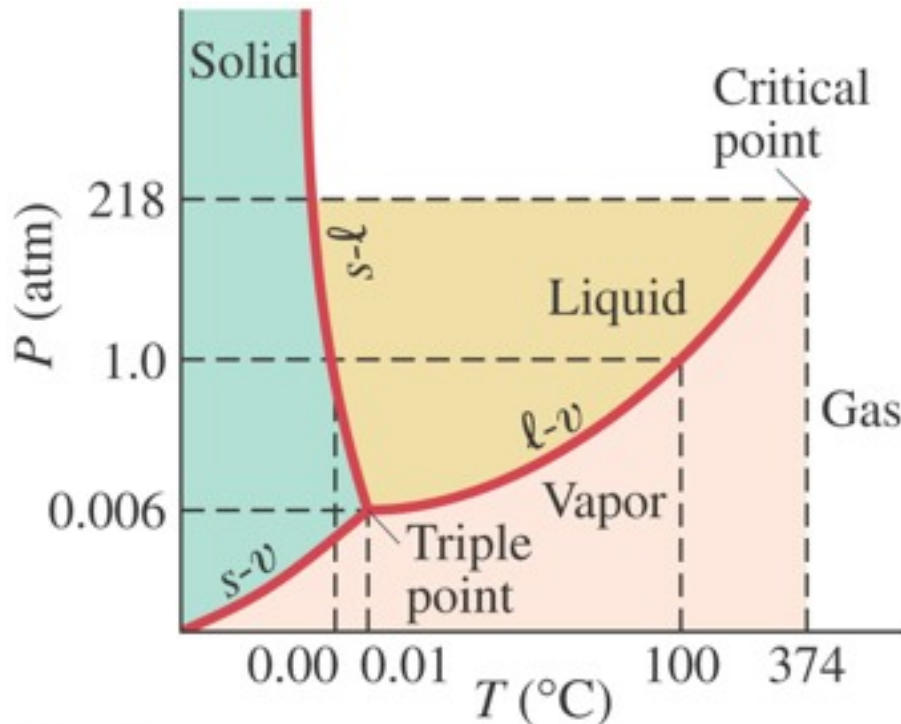
v_p = most probable speed = mode

\bar{v} = average speed

$v_{rms} = (\bar{v}^2)^{1/2}$ = root-mean-square speed

18-3 Real Gases and Changes of Phase

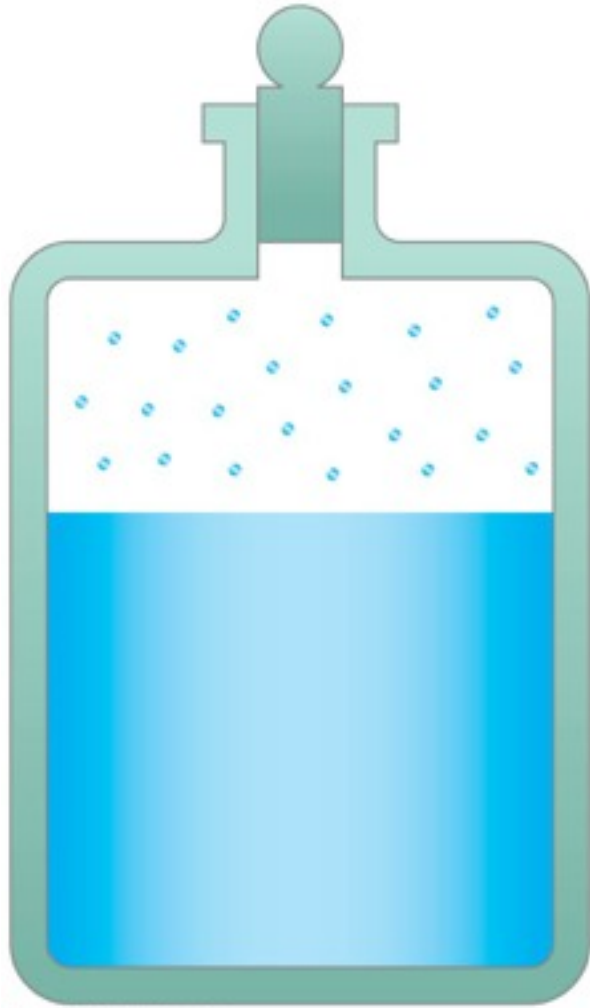
A PT diagram is called a **phase diagram**; it shows all three phases of matter. The **Triple point** is the only point where all three phases can coexist in equilibrium.



Phase diagram of water (note nonlinear axes).

$$\begin{aligned}P_{\text{tp}} &= 4.58 \text{ torr} \\ &= 0.0604 \text{ atm} \\ T_{\text{tp}} &= 273.16 \text{ K}\end{aligned}$$

18-4 Vapor Pressure and Humidity



An open container of water can **evaporate**, rather than boil, away. The **fastest** molecules are escaping from the water's surface, so evaporation is a **cooling** process as well.

The inverse process is called **condensation**.

When the evaporation and condensation processes are in **equilibrium**, the vapor just above the liquid is said to be **saturated**, and its pressure is the **saturated vapor pressure**.

18-4 Vapor Pressure and Humidity

TABLE 18–2 Saturated Vapor Pressure of Water

Temp-erature (°C)	Saturated Vapor Pressure	
	torr (= mm-Hg)	Pa (= N/m ²)
–50	0.030	4.0
–10	1.95	2.60×10^2
0	4.58	6.11×10^2
5	6.54	8.72×10^2
10	9.21	1.23×10^3
15	12.8	1.71×10^3
20	17.5	2.33×10^3
25	23.8	3.17×10^3
30	31.8	4.24×10^3
40	55.3	7.37×10^3
50	92.5	1.23×10^4
60	149	1.99×10^4
70 [†]	234	3.12×10^4
80	355	4.73×10^4
90	526	7.01×10^4
100 [‡]	760	1.01×10^5
120	1489	1.99×10^5
150	3570	4.76×10^5

[†]Boiling point on summit of Mt. Everest.

[‡]Boiling point at sea level.

The saturated vapor pressure increases with temperature.

Boiling point on summit of Mt. Everest

Boiling point in airplane

Boiling point at sea level

18-4 Vapor Pressure and Humidity



A liquid boils when its saturated vapor pressure equals the external pressure.

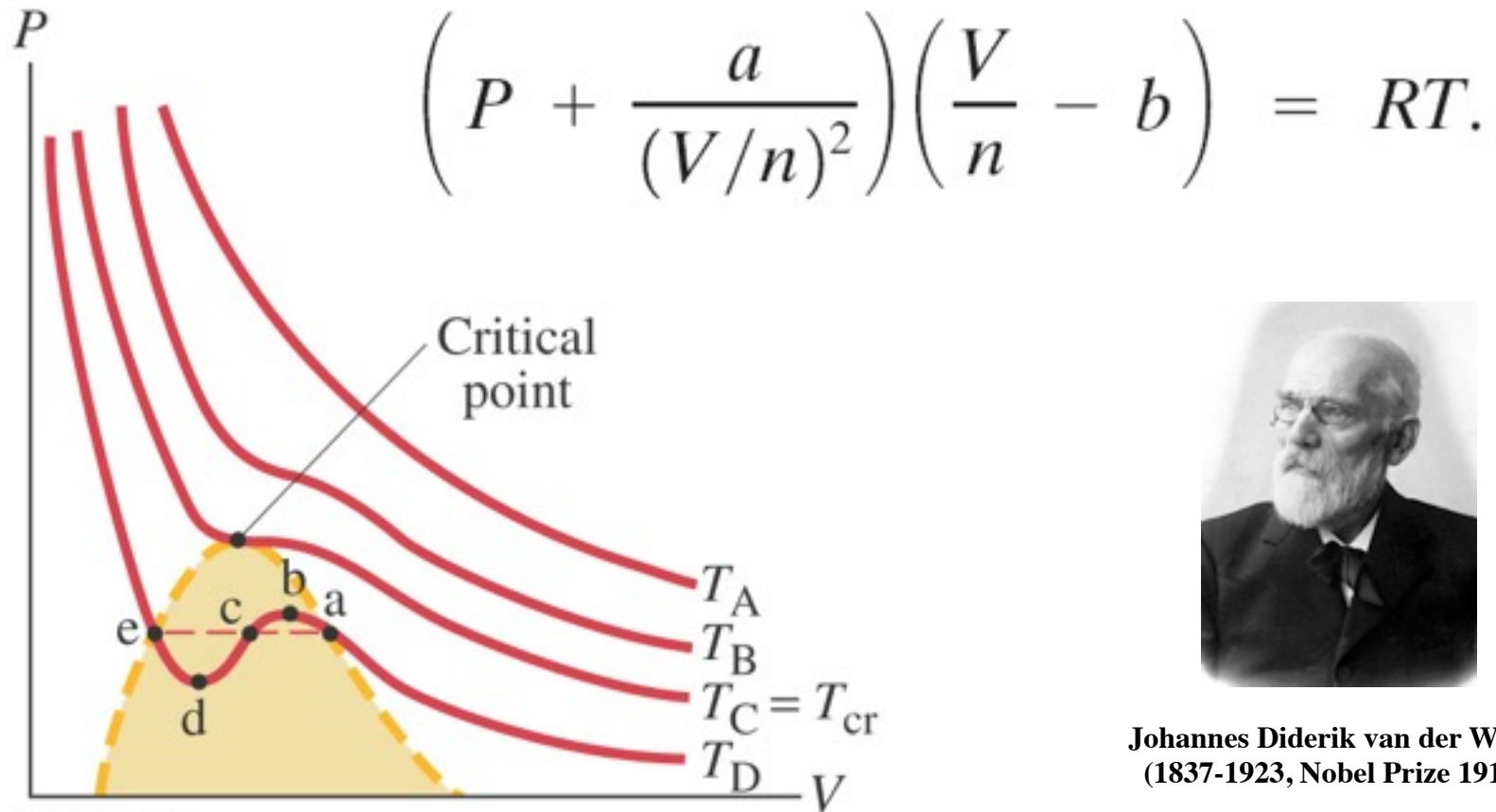
18-5 Van der Waals Equation of State

We assume that some fraction b of the volume per mole is unavailable due to the finite size of the molecules. We also expect that the pressure will be reduced by a factor proportional to the square of the density, due to interactions between the molecules. This gives the Van der Waals equation of state; the constants a and b are found experimentally for each gas:

$$\left(P + \frac{a}{(V/n)^2} \right) \left(\frac{V}{n} - b \right) = RT.$$

18-5 Van der Waals Equation of State

The PV diagram for a Van der Waals gas fits most experimental data quite well.

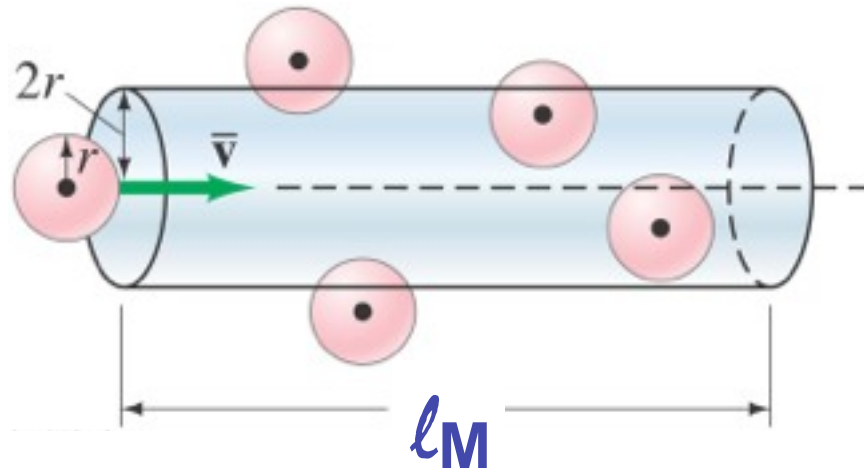


Johannes Diderik van der Waals
(1837-1923, Nobel Prize 1910)

18-6 Mean Free Path

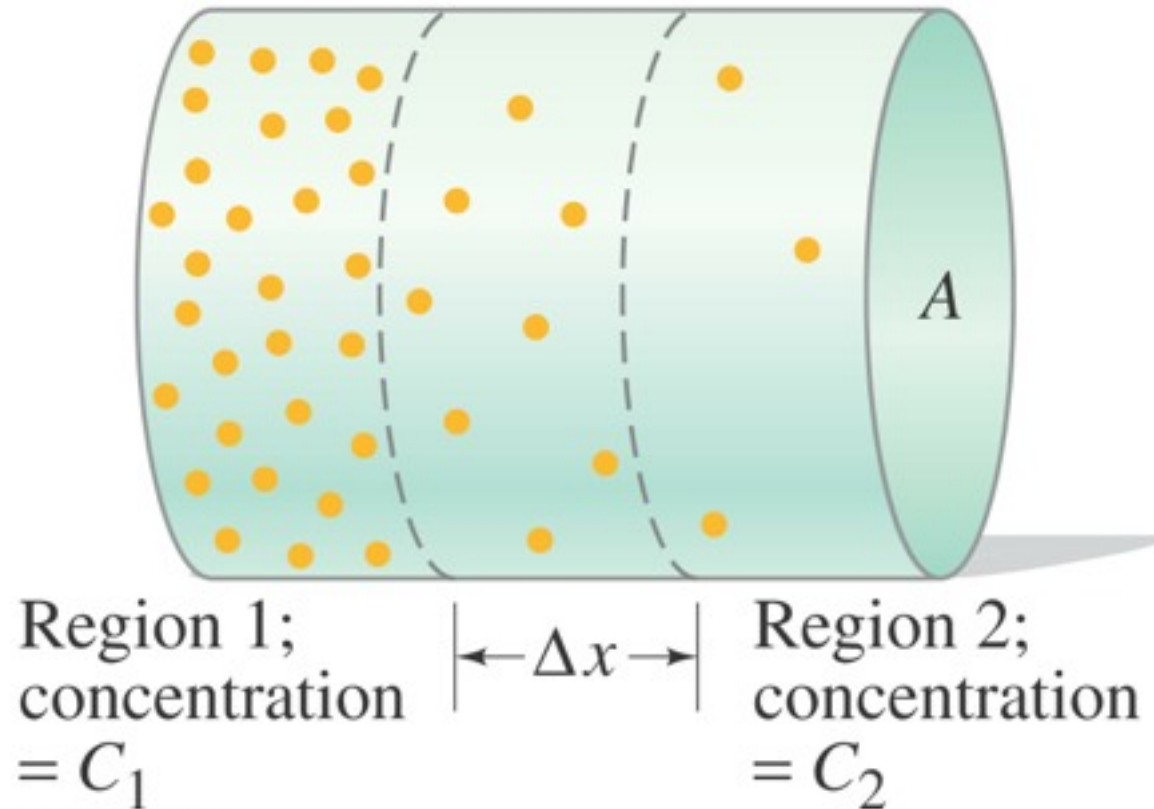
The mean free path can be calculated, given the average speed, the density of the gas, the size of the molecules, and the relative speed of the colliding molecules. The result, now including the motion of all the particles, is changed by $\sqrt{2}$:

$$\ell_M = \frac{1}{4\pi\sqrt{2}r^2(N/V)}.$$



18-7 Diffusion

Diffusion occurs from a region of **high concentration** to a region of **lower concentration**.



The **rate** of diffusion is given by: $J = DA \frac{dC}{dx}$.

19-1 Heat as Energy Transfer



We often speak of **heat** as though it were a **material** that flows from one object to another; it is not. Rather, it is a form of **energy transfer**.

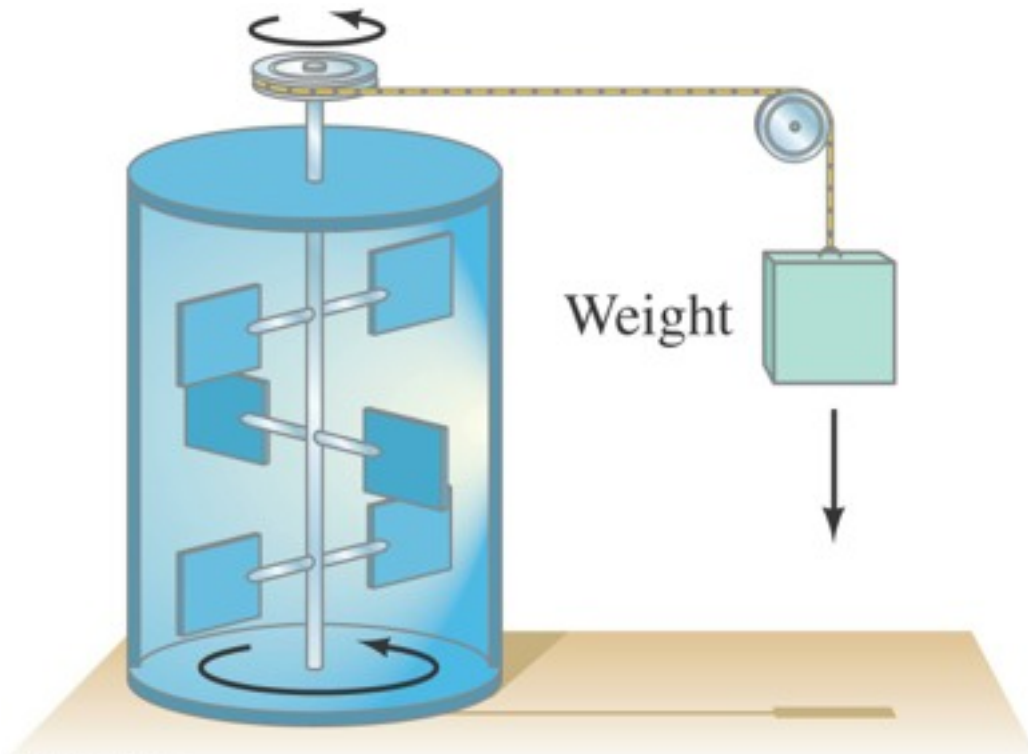
Unit of heat: calorie (cal)

1 cal is the amount of heat necessary to raise the temperature of **1 g** of water by **1 Celsius** degree.

Don't be fooled—the calories on our food labels are really **kilocalories (kcal or Calories)**, the heat necessary to raise **1 kg** of water by **1 Celsius** degree.

19-1 Heat as Energy Transfer

If **heat** is a form of **energy**, it ought to be possible to equate it to other forms. The experiment below found the **mechanical equivalent of heat** by using the falling weight to heat the water:



$$4.186 \text{ J} = 1 \text{ cal}$$

$$4.186 \text{ kJ} = 1 \text{ kcal}$$



James Prescott Joule
1818-1889

19-4 Calorimetry

Definitions:

Closed system: no mass enters or leaves, but energy may be exchanged

Open system: mass may transfer as well

Isolated system: closed system in which no energy in any form is transferred

For an isolated system,

energy out of one part = energy into another part,

or:

heat lost = heat gained.

19-5 Latent Heat

The **total** heat required for a phase change depends on the **total mass** and the **latent heat**:

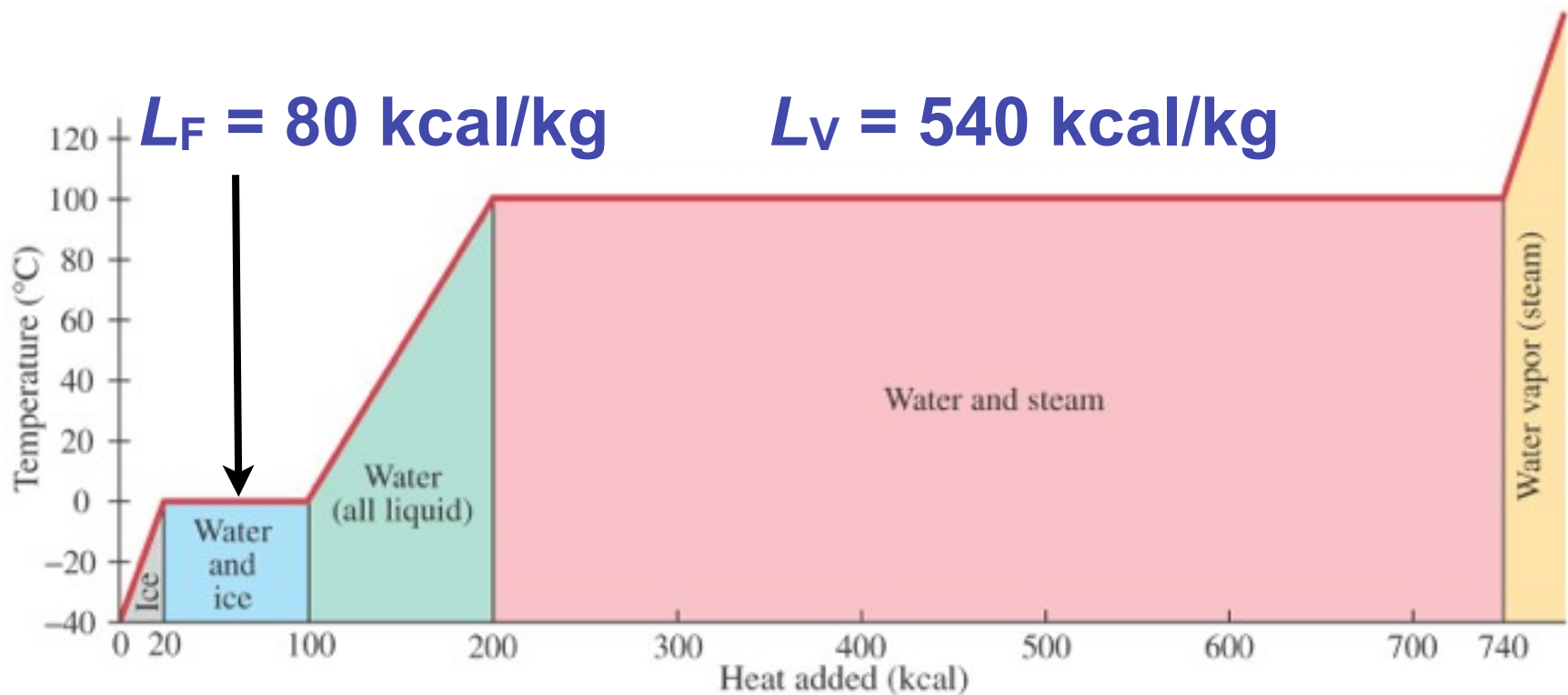
$$Q = mL.$$

The **latent heat of vaporization** is relevant for **evaporation** as well as **boiling**. The heat of vaporization of water rises slightly as the temperature decreases.

On a **molecular level**, the heat added during a change of state does not go to increasing the **kinetic energy** of individual molecules, but rather to **breaking the close bonds** between them so the next **phase** can occur.

19-5 Latent Heat

Energy is required for a material to change phase, even though its temperature is not changing. The diagram shows the latent heats of fusion L_F and vaporization L_V for water.



19-6 The First Law of Thermodynamics

The change in internal energy of a closed system will be equal to the energy added to the system minus the work done by the system on its surroundings.

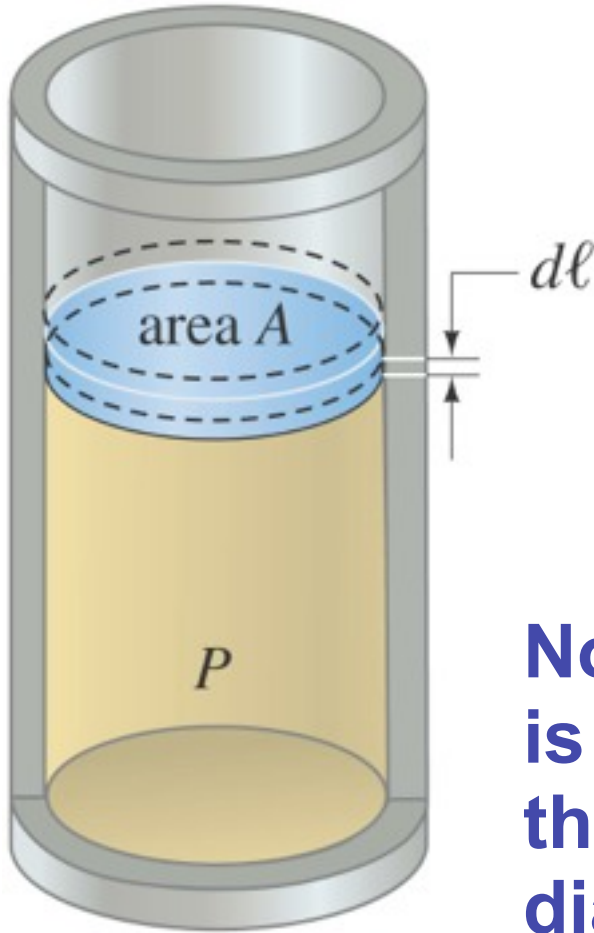
$$\Delta E_{\text{int}} = Q - W$$

This is the law of conservation of energy, written in a form useful to systems involving heat transfer.

The internal energy of an ideal monatomic gas is only dependent on the temperature T :

$$E_{\text{int}} = \frac{3}{2} NkT.$$

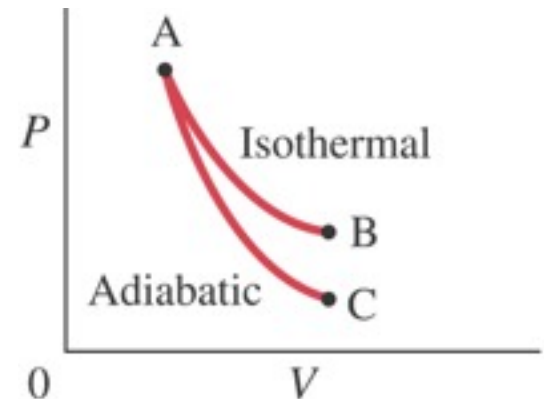
19-7 The First Law of Thermodynamics Applied; Calculating the Work



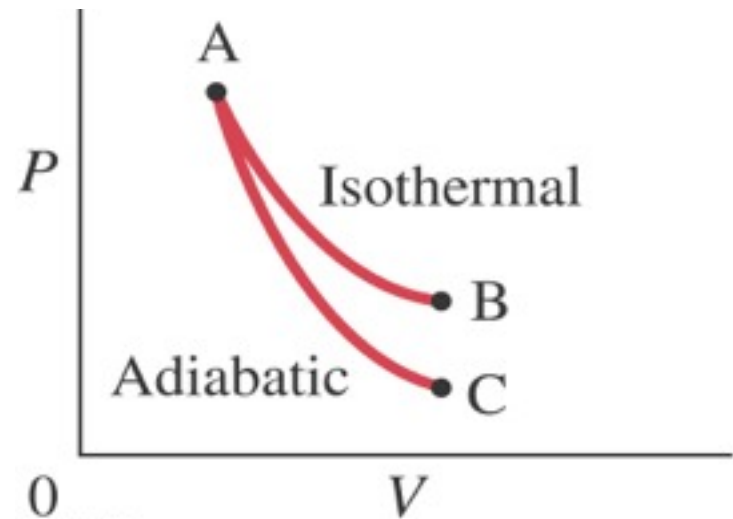
The work done in moving a piston by an infinitesimal displacement is:

$$dW = \vec{\mathbf{F}} \cdot d\vec{\ell} = PA d\ell = P dV.$$

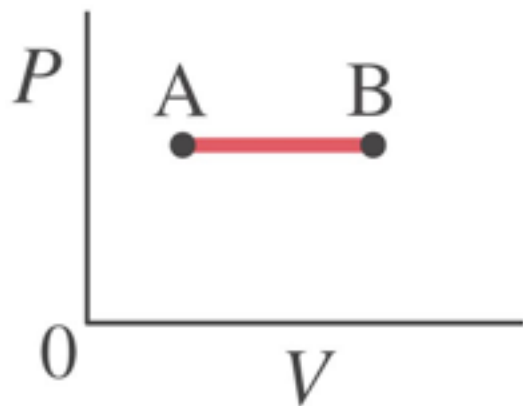
Note: $W = \int P dV$ is the area under the curve on a P - V diagram.



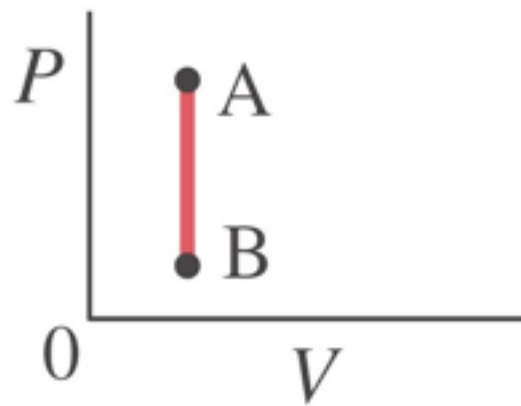
An **isothermal** process occurs at constant temperature, an **adiabatic** process is one in which there is no heat flow into or out of the system.



An **isobaric** process occurs at constant pressure; an **isovolumetric** one occurs at constant volume.



Isobaric



Isovolumetric

19-7 The First Law of Thermodynamics Applied; Calculating the Work

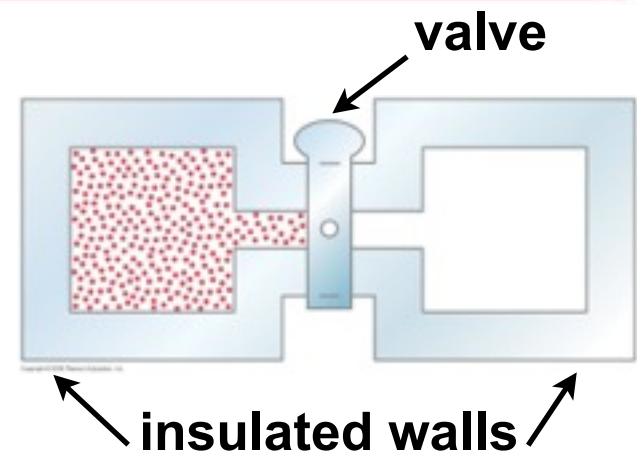
$$\Delta E_{\text{int}} = Q - W$$

The following is a simple summary of the various thermodynamic gas processes:

TABLE 19–3 Simple Thermodynamic Processes and the First Law

Process	What is constant:	The first law predicts:
Isothermal	$T = \text{constant}$	$\Delta T = 0$ makes $\Delta E_{\text{int}} = 0$, so $Q = W$
Isobaric	$P = \text{constant}$	$Q = \Delta E_{\text{int}} + W = \Delta E_{\text{int}} + P \Delta V$
Isovolumetric	$V = \text{constant}$	$\Delta V = 0$ makes $W = 0$, so $Q = \Delta E_{\text{int}}$
Adiabatic	$Q = 0$	$\Delta E_{\text{int}} = -W$

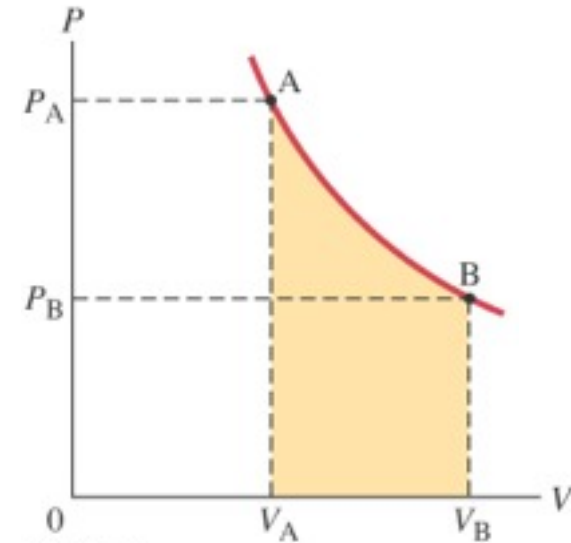
Free expansion is an adiabatic process: when the valve is opened, the gas expands with no change in its internal energy: $W = 0$, $Q = 0$, so $\Delta E_{\text{int}} = 0 \Rightarrow$ for an ideal gas $\Delta T = 0$.



19-7 The First Law of Thermodynamics Applied; Calculating the Work

For an ideal gas expanding isothermally, $P = nRT/V$. Integrating to find the work done in taking the gas from point A to point B gives:

$$W = \int_{V_A}^{V_B} P dV = nRT \int_{V_A}^{V_B} \frac{dV}{V} = nRT \ln \frac{V_B}{V_A}.$$



19-8 Molar Specific Heats for Gases, and the Equipartition of Energy

For gases, the molar specific heat depends on the process—the isobaric (constant pressure) molar specific heat C_P is different from the isovolumetric one C_V .

$$Q = nC_V\Delta T$$

$$Q = nC_P\Delta T$$



n = number of moles

19-8 Molar Specific Heats for Gases, and the Equipartition of Energy

In this table, we see that the specific heats for gases with the same number of molecules are almost the same, and that the difference $C_P - C_V$ is almost exactly equal to 2 cal/mol-K in all cases.

TABLE 19-4 Specific Heats of Gases at 15°C

Gas	Specific heats (kcal/kg · K)		Molar specific heats (cal/mol · K)		$C_P - C_V$ (cal/mol · K)	$\gamma = \frac{C_P}{C_V}$
	c_V	c_P	C_V	C_P		
Monatomic						
He	0.75	1.15	2.98	4.97	1.99	1.67
Ne	0.148	0.246	2.98	4.97	1.99	1.67
Diatomic						
N ₂	0.177	0.248	4.96	6.95	1.99	1.40
O ₂	0.155	0.218	5.03	7.03	2.00	1.40
Triatomic						
CO ₂	0.153	0.199	6.80	8.83	2.03	1.30
H ₂ O (100°C)	0.350	0.482	6.20	8.20	2.00	1.32

19-8 Molar Specific Heats for Gases, and the Equipartition of Energy

1st Law: $\Delta E_{\text{int}} = Q - W$; ideal gas: $P\Delta V + V\Delta P = R\Delta T$ for one mole ($n=1$).

For an ideal gas in a constant-volume process, no work is done, so $\Delta E_{\text{int}} = Q_V = C_V \Delta T$.

For a gas at constant pressure, $Q_P = \Delta E_{\text{int}} + P\Delta V$.

Comparing these two processes for a monatomic gas when ΔT is the same gives $Q_P = C_P \Delta T = C_V \Delta T + R\Delta T$, so dividing by ΔT gives

$$C_P - C_V = R,$$

which is consistent with the measured values (note that $R = 1.99 \text{ cal/mol-K}$).

19-8 Molar Specific Heats for Gases, and the Equipartition of Energy

In addition, since for a monatomic gas

$$\Delta E_{\text{int}} = \frac{3}{2} nR \Delta T = nC_V \Delta T,$$

we expect that

$$C_V = \frac{3}{2} R.$$

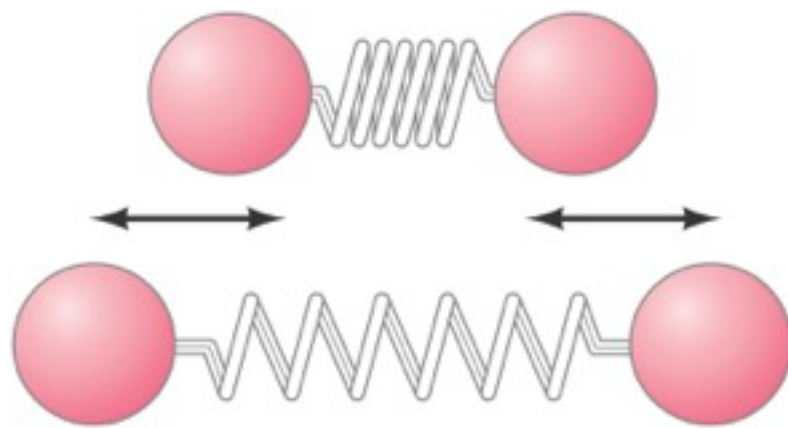
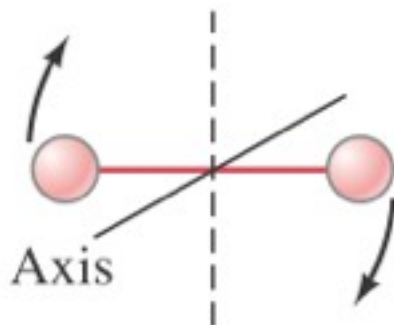
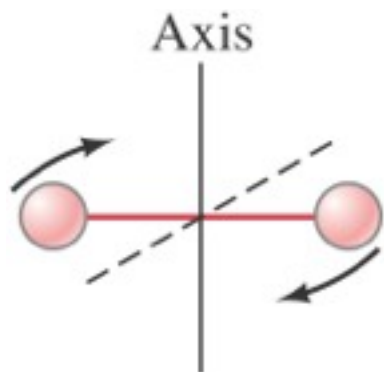
This is also in agreement with measurements for monatomic gases.

TABLE 19-4 Specific Heats of Gases at 15°C

Gas	Specific heats (kcal/kg · K)		Molar specific heats (cal/mol · K)		$C_P - C_V$ (cal/mol · K)	$\gamma = \frac{C_P}{C_V}$
	c_V	c_P	C_V	C_P		
Monatomic						
He	0.75	1.15	2.98	4.97	1.99	1.67
Ne	0.148	0.246	2.98	4.97	1.99	1.67
Diatomic						

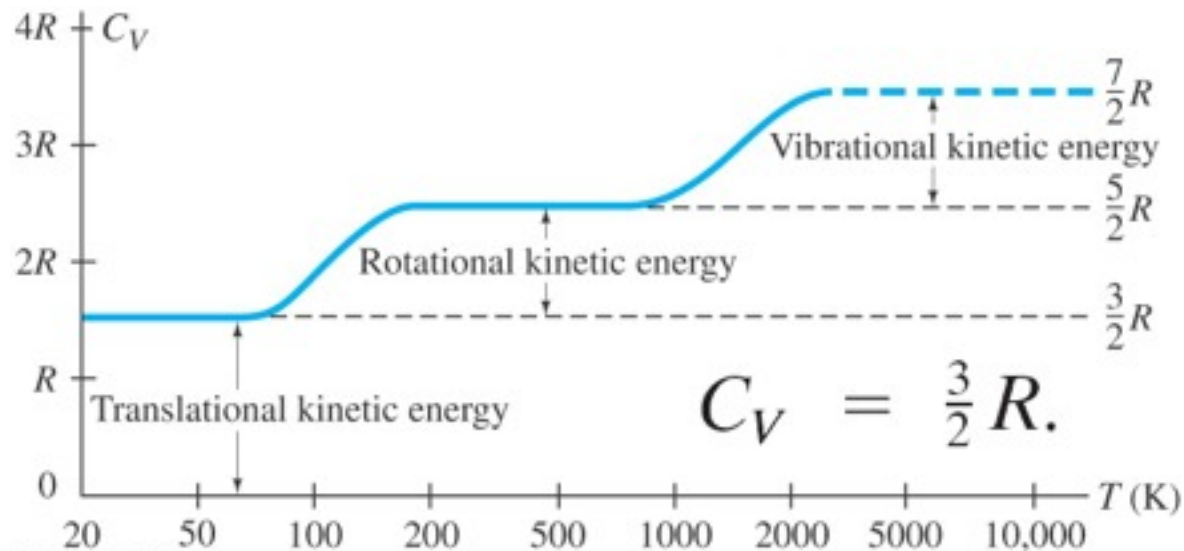
19-8 Molar Specific Heats for Gases, and the Equipartition of Energy

For a gas consisting of more complex molecules (diatomic or more), the molar specific heats increase. This is due to the extra forms of internal energy that are possible (rotational, vibrational).



19-8 Molar Specific Heats for Gases, and the Equipartition of Energy

Each mode of vibration or rotation is called a **degree of freedom**. The equipartition theorem states that the total internal energy is shared equally among the active degrees of freedom, each accounting for $\frac{1}{2} kT$. The actual measurements show a more complicated situation.



19-9 Adiabatic Expansion of a Gas

For an adiabatic expansion, $dE_{\text{int}} = -PdV$, since there is no heat transfer.

From the relationship between the change in internal energy and the molar heat capacity, $dE_{\text{int}} = C_V dT$ for one mole ($n=1$).

From the ideal gas law, $PdV + VdP = RdT$.

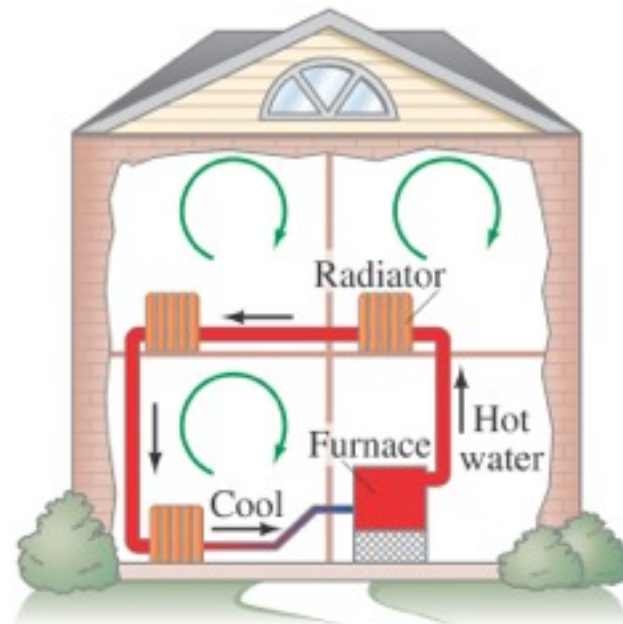
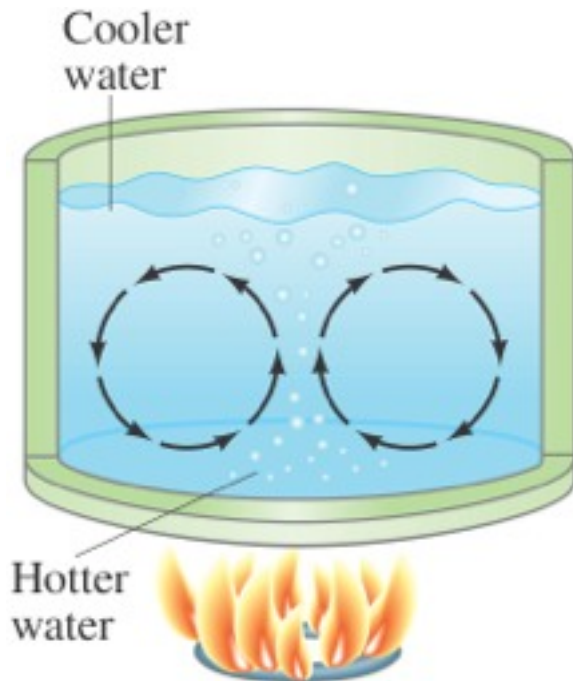
Combining and rearranging gives $(C_P/C_V)PdV + VdP = 0$, or $\gamma dV/V + dP/P = 0$, where we

define: $\gamma = \frac{C_P}{C_V}$. Integration then gives the

result: $PV^\gamma = \text{constant.}$

19-10 Heat Transfer: **Convection**, Radiation, Conduction

Convection occurs when heat flows by the mass movement of molecules from one place to another. It may be **natural** or **forced**; both these examples are natural convection.



Heat Transfer by **Radiation**

$$\frac{\Delta Q}{\Delta t} = \epsilon \sigma A T^4.$$

The constant σ is called the **Stefan-Boltzmann constant**:

$$\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4.$$

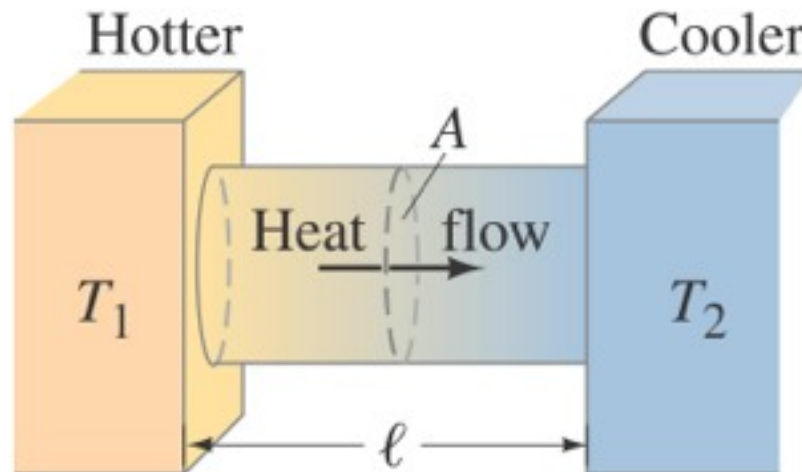
The **emissivity** ϵ is a number between 0 and 1 characterizing the surface; black objects have an emissivity near 1, while shiny ones have an emissivity near 0. It is the same for absorption; a good emitter is also a good absorber.

19-10 Heat Transfer: Convection, Radiation, **Conduction**

Heat conduction can be visualized as occurring through molecular collisions.

The heat flow per unit time is given by:

$$\frac{\Delta Q}{\Delta t} = kA \frac{T_1 - T_2}{\ell}.$$



20-1 The Second Law of Thermodynamics—Introduction

The second law of thermodynamics is a statement about which processes occur and which do not. There are many ways to state the second law; here is one:

Heat can flow spontaneously from a hot object to a cold object; it will not flow spontaneously from a cold object to a hot object. (Clausius statement of 2nd Law.)

20-2 Heat Engines

The **efficiency** of the heat engine is the ratio of the work done to the heat input:

$$e = \frac{W}{Q_H}.$$

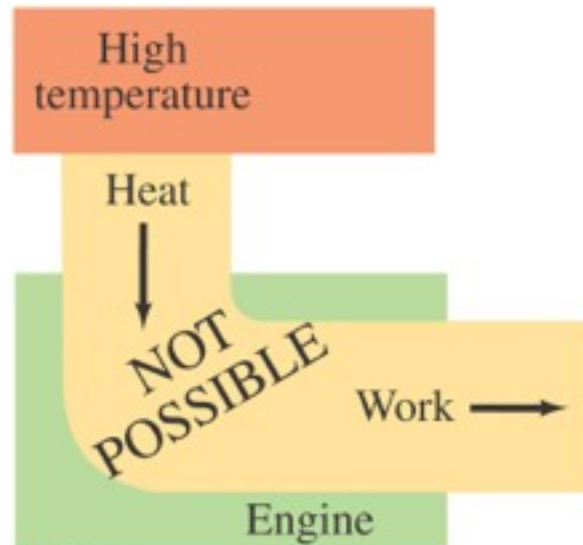
Using conservation of energy to eliminate W , we find:

$$\begin{aligned} e &= \frac{W}{Q_H} \\ &= \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}. \end{aligned}$$

20-2 Heat Engines

No heat engine can have an efficiency of 100%. This is another way of writing the second law of thermodynamics:

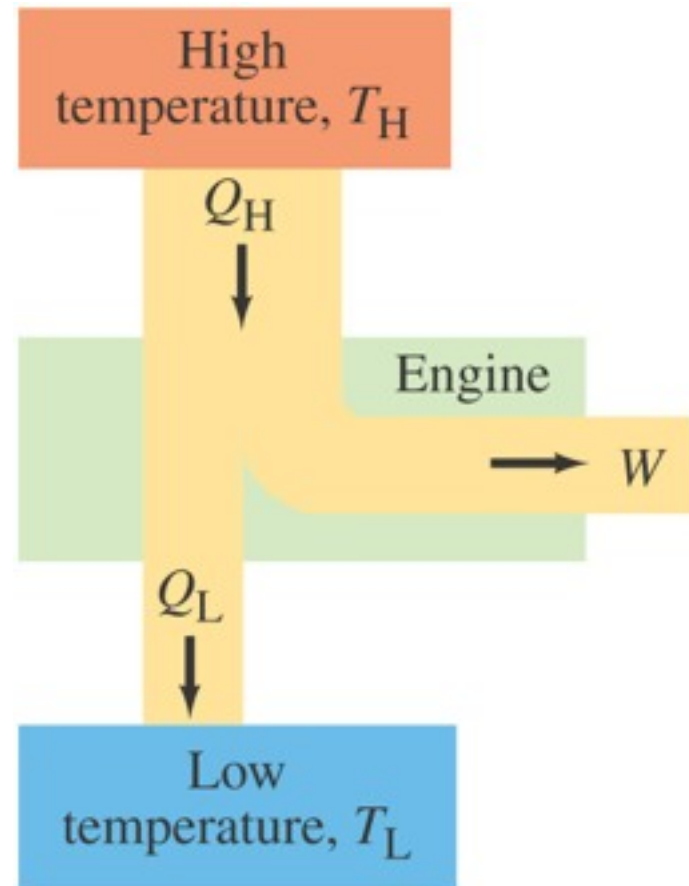
No device is possible whose sole effect is to transform a given amount of heat completely into work. (Kelvin-Planck version of 2nd Law.)



20-2 Heat Engines

It is easy to produce thermal energy using work, but how does one produce work using thermal energy?

This is a heat engine; mechanical energy can be obtained from thermal energy only when heat can flow from a higher temperature to a lower temperature.



20-2 Heat Engines

We will discuss only engines that run in a repeating cycle; the change in internal energy over a cycle is zero, as the system returns to its initial state.

The high-temperature reservoir transfers an amount of heat Q_H to the engine, where part of it is transformed into work W and the rest, Q_L , is exhausted to the lower temperature reservoir.

Thus

$$W = Q_H - Q_L$$

Note that all three of these quantities are positive.