Thermal Physics

Overmugged

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- ❑ Temperature and Thermal Equilibrium
- ❑ Temperature Scales
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- ❑ The Ideal Gas Equation
- ❑ Kinetic Energy of a Molecule
- ❑ Specific Heat Capacity and Specific Latent Heat
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Temperature

Symbol: T
SI unit: Kelvin (K)   (not °C)
Scalar

- is a base quantity that measures average kinetic energy of the molecules of a substance.
- higher temperature indicates that a substance has molecules with higher KE.

Heat

- is energy transferred between two objects due to the temperature difference between them.

- This occurs as molecules undergo **collisions** with one another.
- Kinetic energy is **transferred** from faster-moving molecules (in the **high-temperature** object) to slower-moving molecules (in the **low-temperature** object).
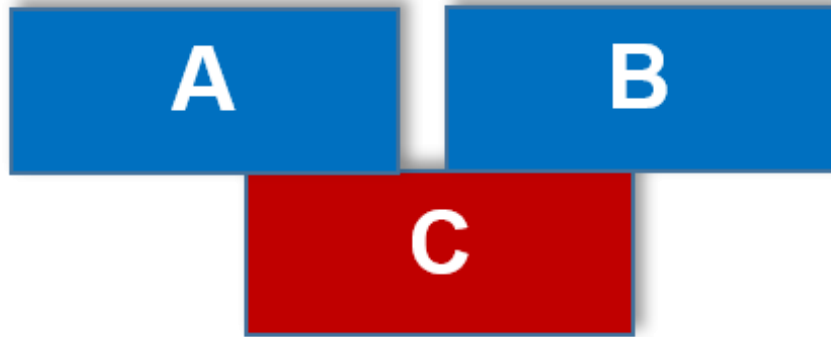- Heat tends to equalize the temperatures between the two bodies in contact.

Thermal Equilibrium
Two objects are said in thermal equilibrium: 1. when there is **no net flow of heat** between two objects in thermal contact.   2. if and only if they are at the same **temperature.**

Zeroth Law of Thermodynamics

If two objects A and B are each in thermal equilibrium with a third object C, then A and B are in **thermal with each other**.

Thermometric Property

- temperature scales (thermometers) measure temperature of a substance which rely on measuring physical property (known as **thermometric property**) of a substance that varies with temperature.

Thermometer	Thermometric Property
Liquid-in-gas	Volume of a fixed mass of liquid
Platinum resistance	Resistance of a metal
Constant volume gas	Pressure of a fixed mass of a gas at constant volume
Thermocouple	e.m.f produced between junctions of dissimilar metals that are at different temperature

Three Criteria for a Thermometric Property

A suitable thermometric property should:

1. **vary uniquely** with temperature (different values for different temperatures).
2. **change appreciably** with temperature.
3. **be reproducible** and can be accurately measured over a wide range of temperature.

Temperature Scale

Kelvin Temperature Scale

- The thermodynamic temperature scale (an **absolute scale** of temperature).
- does not depend on the thermometric property of any particular

Kelvin

- is defined as $\dfrac{1}{273.16}$ of the thermodynamic temperature of the triple point of water.

The Celsius Scale

Unit: degree Celsius (°C)
- commonly used in everyday life, science, and industry

$$T_K = T_C + 273.15$$

The Fahrenheit Scale

Unit: degree Fahrenheit ($°F$)
- commonly used in the United States.

$$T_C = \frac{5}{9}[T_F - 32]$$

$$T_F = \frac{9}{5}T_C + 32$$

| Special Temperatures to Remember	
Ice Point	▪ also known as freezing point **0°C** or 273.15 K → Temperature of liquid water turns to ice (solid).
Steam point	**100 °C** or 373.15 K → Temperature at which *water* vapor condenses at a pressure of one atmosphere.
Triple point of water	**0.01 °C** or **273.16 K** → Temperature at which water can coexist at three different state (solid, liquid, and gas) at the saturated vapor pressure of water 611.2 Pa.
Absolute Zero	▪ is defined as the zero point (**0 K**) of the thermodynamic temperature scale. ▪ Theoretically, this is at which the molecules of a substance have the **lowest energy,** hence the substance has minimum internal energy.

Using a digital thermometer, you measured your body temperature and it registered to be at 36.5 °C. What is this in absolute and Fahrenheit scale?
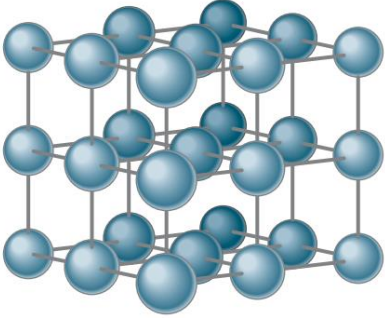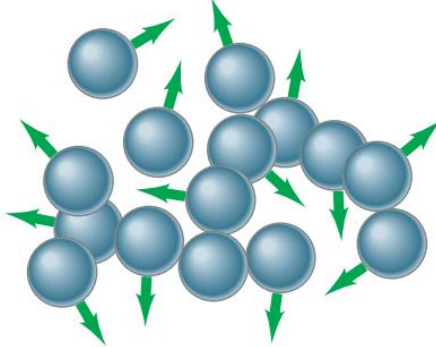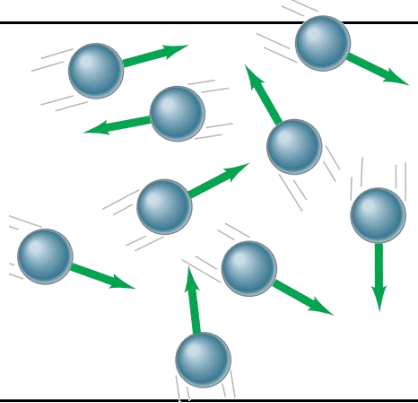
What temperature in both Celsius and Fahrenheit scale give a numerical reading of $T_C = T_F$?
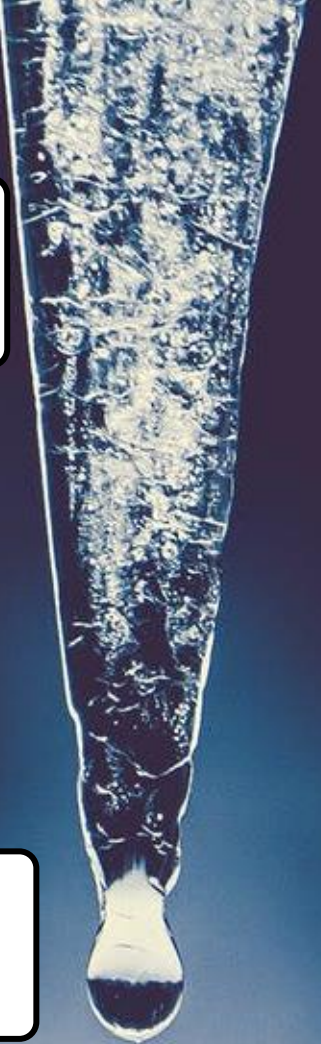
Kinetic Model of Matter

▪ Matter is made up of huge number (in the order of 10^{23}) of atoms/molecules, whose dimension are in the order of 10^{10} m.

▪ Depending on the distance between molecules, as well as on how fast they are moving relative to each other, molecules can form three states of matter: **solid**, **liquid**, and **gas**.

	Solid	Liquid	Gas
Packing arrangement of Molecules	Molecules are closely packed in a regular and geometrical pattern called a lattice structure.	Molecules are slightly further apart than in solids, with no regular pattern	Molecules are very far apart, with no regular pattern
Intermolecular distance	$\approx 3 \times 10^{-10}$ m	$\approx 3 \times 10^{-10}$ m	$\gg 3 \times 10^{-10}$ m
Density	High	High	Low
Volume/Shape	Fixed volume and shape	Fixed volume but takes shape of container.	No fixed volume or shape. Fills entire container in which they are in.

Kinetic Model of Matter

	Solid	Liquid	Gas
Compression	Returns to their original shape when stretched or compressed. * to a certain extent	Almost incompressible	Easily compressed
Movement of Molecules	Limited to vibrations about their mean positions	Random motion	Random motion at high speeds
Intermolecular forces	Strong intermolecular attractive and repulsive forces	Attractive cohesive force *pulls back the molecules near the surface of the liquid, opposing their escape	Negligible attractive/repulsive forces *because they are very far apart
Kinetic energy Effect of Temperature	Vibrations of the atom/molecules reflect their kinetic energy		
	↑ Temp = ↑ vibration = ↑ average kinetic energy		

Ideal Gas

- is defined as a gas that is governed by the equation $pV = nRT$ where p is the pressure, V is the volume, and T is thermodynamic temperature of the gas.

$$pV = nRT$$

$$pV = NkT$$

p = pressure (in Pascals)
V = volume (in m³)
T = temperature (in Kelvin)

n = number of moles
N = number of particles
R = universal gas constant= 8.31 J/(mol · K)
k = Boltzmann constant= 1.38×10^{-23} kg/(m² s²K)

Assumptions

R-A-V-E-D:

1. **R**andom continuous motion of all molecules in an ideal gas.
2. **A**ttraction-Zero attraction between any molecules (hence 0 molecular P.E.)
3. **V**olume: The volume of a single molecule is negligible relative to the volume occupied by the gas (i.e., volume of container)
4. **E**lastic collisions between all molecules, and between molecules and the walls.
5. **D**uration of collision is much smaller than the time duration between collisions.

Empirical Gas Laws

- The ideal gas equation can be derived from the following empirical gas laws:

	Boyle's Law	Charles' Law	The Pressure Law
Relationship	$p \propto \dfrac{1}{V}$	$V \propto T$	$p \propto T$
Constants	n, T	n, p	n, V

Standard Temperature and Pressure

- Abbreviated as **STP.**
- Often referred as "standard conditions."

  - STP means

$$T = 273 \ K \ (0\,°C) \text{ and}$$

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

Practice Example 3

Calculate the number of molecules in a basketball of radius 24.0 cm at *standard temperature and pressure* (STP).

Practice Example 4

In a sealed car tire where the volume is constant, the pressure changes as the ambient temperature rises. In the morning where the temperature is 3.0 °C, the pressure inside the tire is 20.7 kPa. At noon where the sun warms the tire at 35 °C, find the pressure inside the tire.
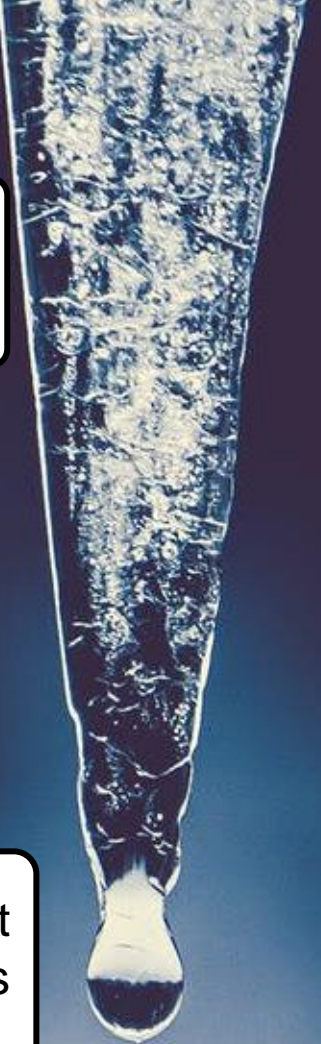
Kinetic Energy of a Molecule

Average Kinetic Energy

The average kinetic energy of molecules in random motion in an ideal gas is directly <u>proportional</u> to the <u>absolute</u> <u>temperature</u> of the gas.

$\langle E_K \rangle$ = energy of one gas molecule.

m = mass

$$\langle E_K \rangle = \frac{1}{2} m \langle c^2 \rangle = \frac{3}{2} kT$$

k = Boltzmann constant

$\langle c^2 \rangle$ = mean-square-speed of the gas molecules.

T = thermodynamic temperature (in Kelvin)

Mean-square-speed

Let c_x, c_y, and c_z be the velocity components of a molecule.

$$\langle c^2 \rangle = \langle c_x^2 \rangle + \langle c_y^2 \rangle + \langle c_z^2 \rangle$$
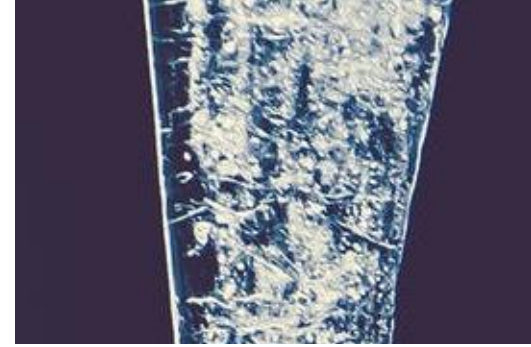
where $\langle c_x^2 \rangle = \dfrac{c_{x1}^2 + c_{x2}^2 + c_{x3}^2 + \cdots + c_{xN}^2}{N}$ (mean-square-speed in x-direction)

N= number of molecules

Root-mean-squared speed

$$c_{rms} = \sqrt{\langle c^2 \rangle} = \sqrt{\frac{c_1^2 + c_2^2 + c_3^2 + \cdots + c_N^2}{N}}$$
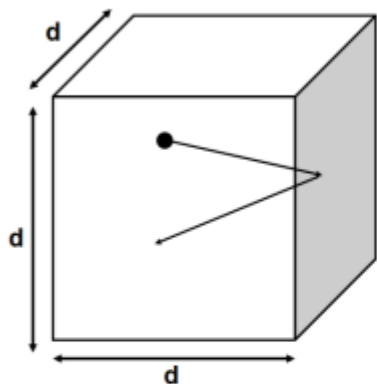
$$c^2 = c_x^2 + c_y^2 + c_z^2$$

Derivation

Consider a molecule, whose x-velocity is c_x, elastically colliding with the wall. The molecule travelled from another end of the box

Before collision

After collision

Change in momentum after collision:
$$\Delta P = \text{final} - \text{initial momentum}$$
$$\Delta P = (-mc_x) - mc_x = -2mc_x$$

Time between with the same wall
$$\Delta t = \frac{distance}{speed} = \frac{2d}{c_x}$$

Rate of change of momentum of the molecule
$$\frac{\Delta P}{\Delta t} = F_{on\ molecule} = \frac{-2mc_x}{2d/c\_x} = -\frac{mc_x^2}{d}$$

By Newton's 3rd Law, the force due to the molecule on the wall should be
$$F = -F_{on\ molecule} = \frac{mc_x^2}{d}$$

By considering N number of underlined identical molecules
$$F_{tot} = \frac{mc_{x1}^2}{d} + \frac{mc_{x2}^2}{d} + \frac{mc_{x3}^2}{d} + \cdots + \frac{mc_{xN}^2}{d} = \frac{m}{d}(c_{x1}^2 + c_{x2}^2 + c_{x3}^2 + \cdots + c_{xN}^2)$$
where c_{xi} x-velocity of ith molecule.

Using our definition for mean-square-speed in x-direction,
$$F_{tot} = N\frac{m}{d}\langle c_x^2 \rangle$$

The pressure p on the wall is this total force divided by the area d^2
$$p = \frac{F_{tot}}{d^2} = N\frac{m}{d^3}\langle c_x^2 \rangle = \frac{N}{V}m\langle c_x^2 \rangle$$
where we used the volume $V = d^3$ for the cubic container.

To generalize this, we use the three components of the velocity c: c_x, c_y, and c_z.
$$c^2 = c_x^2 + c_y^2 + c_z^2$$
$$\langle c^2 \rangle = \langle c_x^2 \rangle + \langle c_y^2 \rangle + \langle c_z^2 \rangle$$

Pressure (averaged over the three directions):
$$p = \frac{N}{V}m\frac{\langle c_x^2 \rangle + \langle c_y^2 \rangle + \langle c_z^2 \rangle}{3} = \frac{N}{V}m\frac{\langle c^2 \rangle}{3}$$

or
$$pV = \frac{1}{3}Nm\langle c^2 \rangle$$

Combining this with the ideal gas equation $pV = NkT$
$$\frac{1}{3}Nm\langle c^2 \rangle = NkT$$
$$\Rightarrow \frac{1}{2}m\langle c^2 \rangle = \frac{3}{2}kT$$

The RHS is **the average kinetic energy** ($\frac{1}{2}mv^2$)
$$\langle E_K \rangle = \frac{3}{2}kT$$

Practice Example 5

(a) The temperature of an ideal gas is 100 °C. Calculate the average kinetic energy of the molecules in the gas.

(b) What is the mean-square speed of the gas molecules if a gas molecule weighs 4.0 u? ($1u = 1.66 \times 10^{-24} g$)

Practice Example 6

The mean kinetic energy of the molecules in an ideal gas at 750°C is 0.75×10^{-20} J.

a) Suppose the molecules travel slower, a quarter of the speed, what is new the mean kinetic energy of the molecules

b) At a quarter of the speed, what is the temperature of gas molecules in Celsius scale?

Specific Capacity and Specific Latent Heat

Heat Capacity

Symbol: C
SI unit: Joule per Kelvin [J/K]
Scalar

- The **numerical value** of the heat capacity of a body is the quantity of **heat** required to **raise** the **temperature** of the body by **one degree**

$$C = \frac{Q}{\Delta T}$$

$Q =$ quantity of heat
$\Delta T = T_f - T_i =$ change in temperature

* ΔT in Celsius degree is the same as the ΔT in Kelvin. So, there is no need to convert to Kelvin if temperatures are given in the Celsius scale

Specific Heat Capacity

Symbol: c
SI unit: Joule per kilogram per Kelvin [J/(kg K)]
Scalar

- The **numerical value** of the heat capacity of a substance is the quantity if the heat required to raise the temperature of unit mass of the substance by one degree.
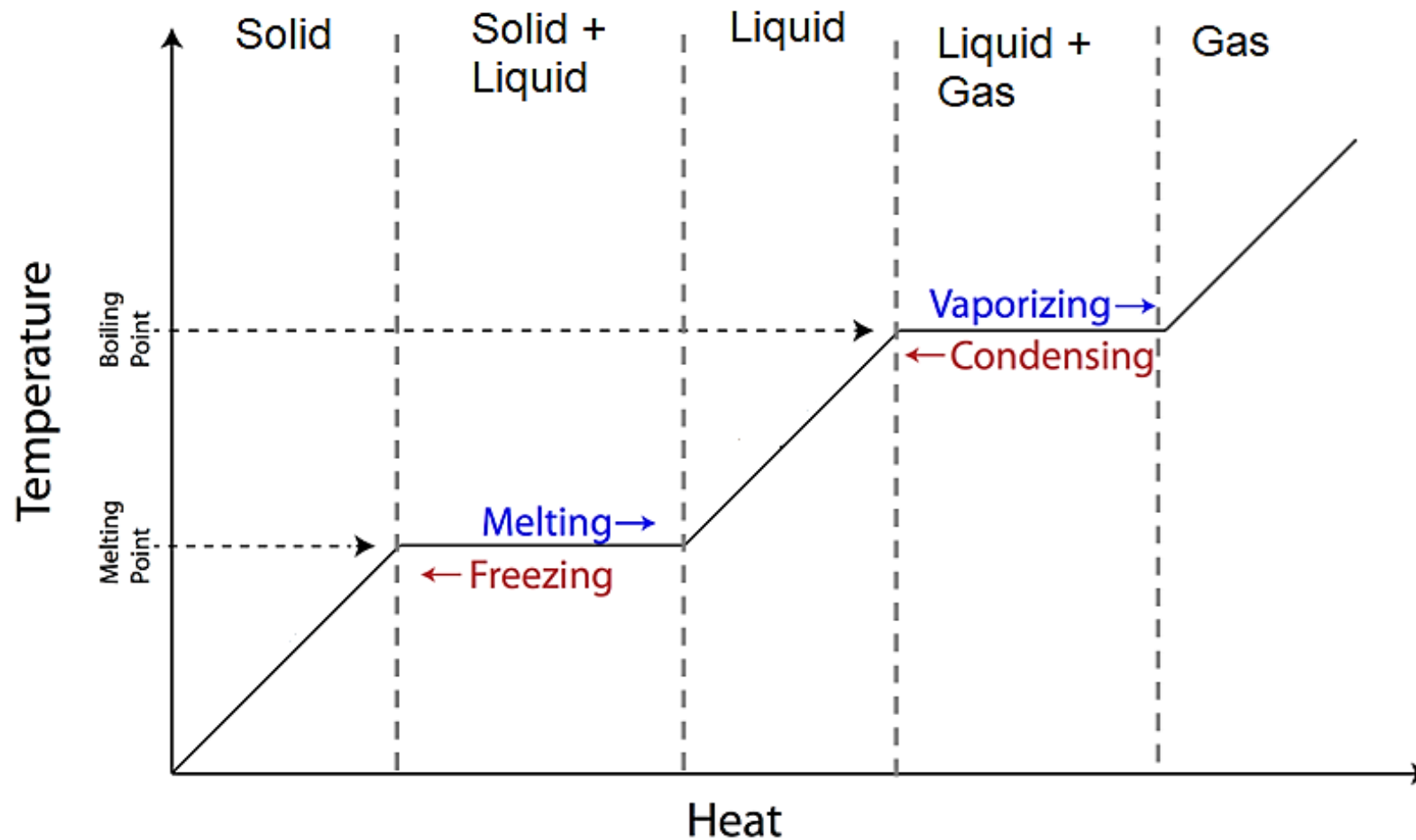
$$c = \frac{Q}{m\Delta T}$$

$Q =$ quantity of heat
$m =$ mass of the body
$\Delta T =$ change in temperature

Change of Phase

- Transition from one phase to another is not instantaneous.
- During transition, the two phases coexist until the transition is completed

Change of Phase

	Melting	Boiling
Transition	Solid to liquid	Liquid to gas
Intermolecular interaction	Lattice structure must break.	All bonds between atoms/molecules have to be <u>completely</u> broken.
At melting point or boiling point	Molecules have enough energy to vibrate so violently that attractive forces cannot hold them together	Thermal energy supplied is used to overcome the attractive forces between molecules
Energy supplied	**Latent heat of Fusion**	**Latent heat of vaporization**
Temperature	At melting point and boiling point, the **temperature remains constant**. *This indicates that thermal energy supplied to the body is used to break the bonds	

Change of Phase

Evaporation	Boiling
Both represent a change of phase from liquid to gas	
Can take place at any temperature	Takes place at fixed temperature
Takes place at the **surface** of the liquid	Occurs **in the body** of the liquid.

Latent Heat

Symbol: L_f, L_v
Si unit: Joule per kilogram
Scalar

- the amount of heat to bring about a change of phase

Latent heat of fusion   (solid → liquid)

$$L_f = \frac{Q}{m}$$

Latent heat of vaporization   (liquid → gas)

$$L_v = \frac{Q}{m}$$

Vat made of iron is used to color cotton, linens, and other cellulosic fibers with cool blue-gray color. The vat weighs 15 kg. $\left(c_{iron} = 450\frac{J}{kg \cdot K}\right), \left(c_{water} = 4200\frac{J}{kg \cdot K}\right)$

a) Suppose you want the vat's temperature to be at 95°C, how much heat is required to make the temperature rise from 20°C?
b) Adding water to the vat increases the required heat for the temperature increase. Calculate the total heat needed.

Practice Example 8

In an insulated flask containing liquid nitrogen, you drop a 30-g ice cube which is at its melting point. Upon dropping, the nitrogen starts to evaporate. If the nitrogen's boiling point is -196°C, and its the latent heat of evaporation is 200 kJ/kg, calculate how much nitrogen has evaporated.

$\left(c_{ice} = 2100\frac{J}{kg \cdot K}\right)$ Assume that specific of ice is equal to its value near its melting point.

Internal Energy

Symbol: U
SI unit: Joule [J]
Scalar

- sum of the microscopic **kinetic** (translational, rotational, and vibrational) and **potential energies** of the molecules of the system.

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

The internal energy U of an ideal gas is purely kinetic

Notes

- Molecules have *kinetic energy* because they are in constant motion.
- Molecules have *potential energy* due to the interactions between them.
- Rise in temperature increases the ave. KE of the molecules which in turn increases the internal energy of the system.
- U is **state-dependent** and **path independent** (i.e the order of expansion/contraction of a gas does not change U.)

First Law of Thermodynamics

The **increase** in the **internal energy** of a system is equal to the sum of the **heat supplied to** the system and the **work done on** the system.

The internal energy of a system depends only on its state.

$$\Delta U = Q + W$$

| INCREASE in internal energy of the system ΔU | = | Heat Q SUPPLIED to the system | + | Work W done ON the system |

	Positive (+)	Negative (-)
$\boldsymbol{\Delta U}$	**Increased** in U	**Decreased** in U
$\boldsymbol{Q}$	Heat **absorbed** by the system	Heat **lost** by the system
$\boldsymbol{W}$	Work done **on** the system (Compression)	Work done **by** the system (Expansion)

Work done

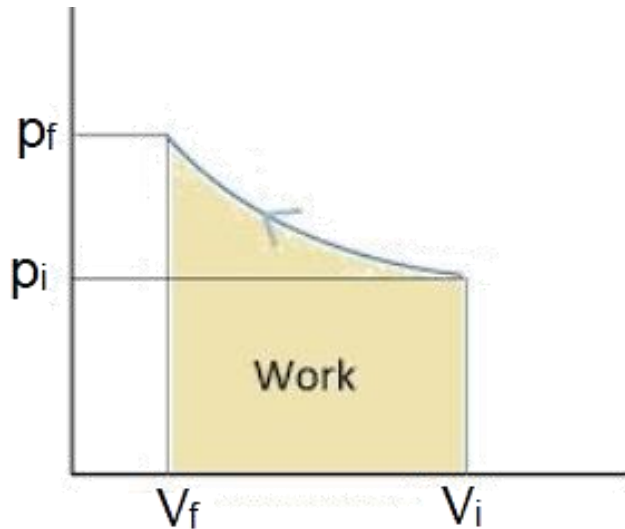Work on the gas:

$$W = -\int_{V_i}^{V_f} p \, dV$$

For constant pressure

$$W = -p(V_f - V_i)$$

p = pressure
V_i = initial volume
V_f = final volume of the container

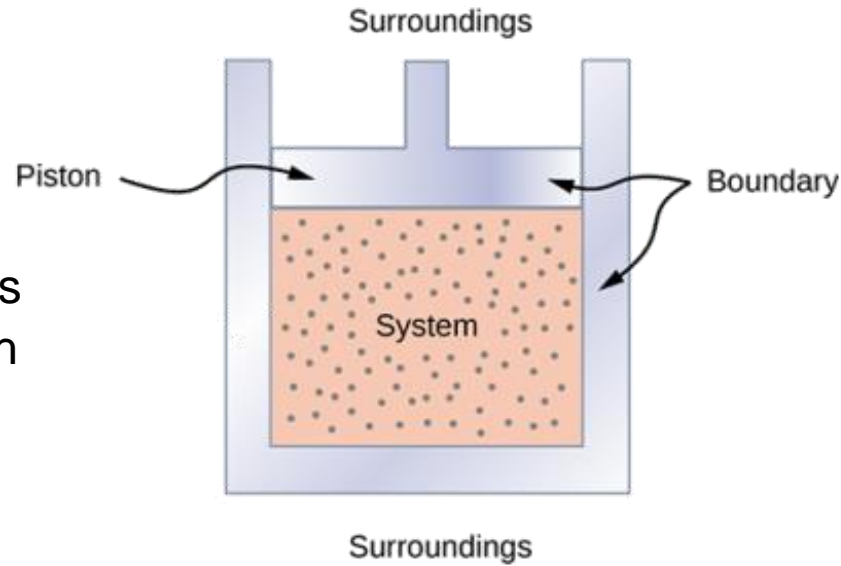Work done on the system is the area under the curve in a p vs V graph.

- +W for compressed gas

- -W for expanded gas

Special Processes

The following processes are special cases for a fixed amount of gas in a cylinder with a free moving piston.

Isothermal Process

Temperature T is constant.

- If the change in pressure and volume takes place without change in temperature.

$$T = constant$$
$$\Delta U = 0$$
$$p \propto \frac{1}{V}$$
$$Q = -W$$

Special Processes

Isobaric Process

Pressure p is constant.
If the volume change occurs at constant pressure.

$p = constant$
Work on the gas is **rectangular** in a p-V graph:
$$W = -p\Delta V$$

Isovolumetric/Isochoric Process

Volume V is constant.
If the change in pressure occurs without a change in volume.

No work done on or by the gas:
$$V = constant$$
$$W = 0$$
$$\Delta U = Q$$

Adiabatic Process

$$Q = 0$$
$$\Delta U = W$$

No heat transfer $Q = 0$.
When the change in pressure and volume occurs with no heat supplied to or lost from the system.
This can be achieved when:
1. The system is **insulated**.
2. The **change** in pressure and volume occurs **faster** than the exchange of heat with the surroundings.
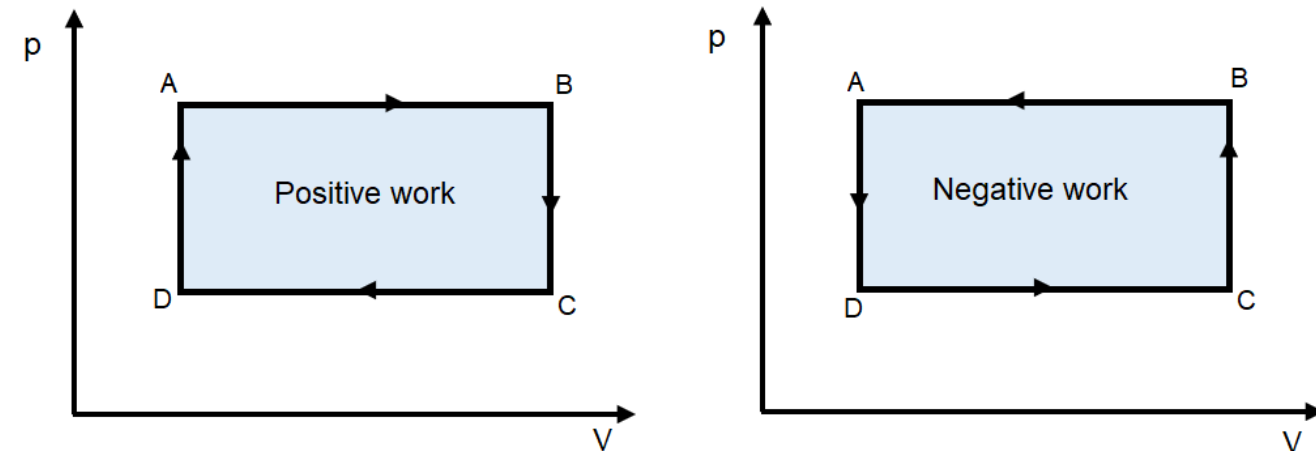
Special Processes

Cyclic Process

Constant internal energy (initially and finally).

It involves expansion and contraction of an ideal gas, that eventually returns the system to it original state (same pressure, volume, and hence temperature)

The **work** done can be calculated as the **area** <u>within the enclosed loop</u> of a cyclic process.

- Positive work is done by the gas if it expands at higher pressure (left figure). Path is clockwise - ABCD.

- Negative work is done by the gas if it compresses at higher pressure (right figure). Path is counterclockwise -ADCB.

Complete the table below by filling in the boxes with correct signs (+, -, or 0) for $\Delta U, Q$, and W. The system for A, B, and C are a.) air in the pump, b.) oil in the wok, and c.) air in the ball, respectively. So for A, you are asked to determine whether the heat of the air in the pump, work done on the air, and the corresponding change in internal energy is positive or negative.
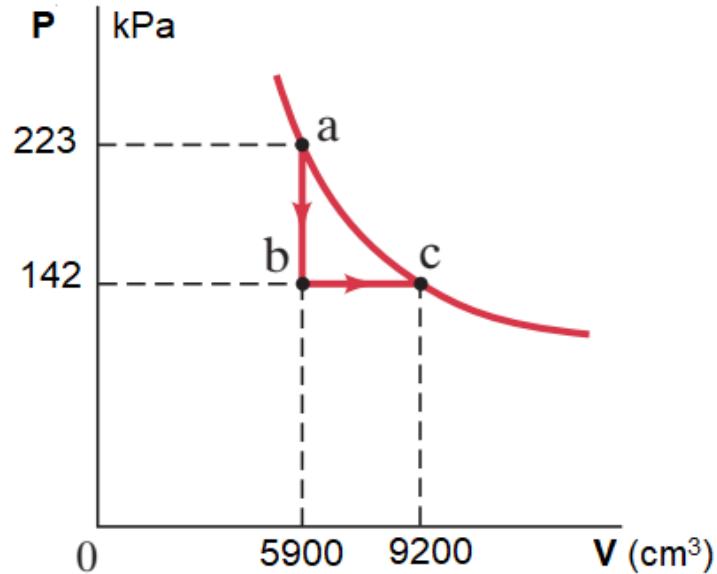
Explain your answers.

	Q	W	ΔU
A. Rapidly pumping a balloon			
B. Oil in a room-temperature wok sitting on a hot stove			
C. Air quickly leaking out of a beach ball			

P | kPa

223 ---- a

142 --- b   c

0   5900 9200   V (cm³)

Consider a $p - V$ diagram below wherein the process takes place in two steps. The system is an ideal gas in which heat can flow in or out. The pressure decreases from 223 kPa to 142 kPa at constant volume (**a**→ **b**), then this is followed by increase in volume from 5900 cm³ to 9200 cm³ at constant pressure (**b** → **c**).

a) Determine the total work done by the gas in the process.

b) Find the ΔU of the gas in the process.

c) Solve the total heat transferred into or out of the gas.

Suggested Solutions to Practice Examples

Practice Example 1

Kelvin Scale:

$$T_K = T_C + 273.15$$
$$T_K = 36.5 + 273.15 = 309.65K$$

Fahrenheit Scale:

$$T_F = \frac{9}{5}T_C + 32$$
$$T_F = \frac{9}{5}(36.5) + 32 = 97.7°F$$

Practice Example 2

$$T_F = \frac{9}{5}T_C + 32 \rightarrow T_F = \frac{9}{5}T_F + 32$$
$$\left(1 - \frac{9}{5}\right)T_F = 32$$
$$T_F = -40°F$$

Practice Example 3

We use equation (2) of the ideal gas law: $pV = NkT \rightarrow N = \frac{pV}{kT}$

At STP: $T = 0°C = 273.15K$, $p = 101.3\ kPa$

The volume of a sphere is

$$V = \frac{4}{3}\pi r^3 = \frac{4}{3}(3.14)(0.24)^3 = 57.9 \times 10^{-3}m^3$$

$$N = \frac{(101.3 \times 10^3)(57.9 \times 10^{-3})}{(1.38 \times 10^{23})(273.15)} = 1.56 \times 10^{24} \text{ molecules}$$

Practice Example 4

The tire is sealed, so the initial and final volume and number of moles in the tire is constant.

$$V_1 = V_2 \rightarrow \frac{n_1 R T_1}{p_1} = \frac{n_2 R T_2}{p_2}$$

The R and $n_1 = n_2$ cancels out: $\qquad p_2 = p_1 \frac{T_2}{T_1}$

We convert the temperatures: $\quad T_1 = 0°C = 273.15K; \qquad T_2 = 35°C = 308.15\ K$

The pressure at noon time is

$$p_2 = (20.7 \times 10^3)\frac{308.15}{273.15} = 23.4\ kPa$$

(a) Convert the temperature first into Kelvin.

$$T_K = T_C + 273.15 = 373.15 \, K$$

$$\langle E_K \rangle = \frac{3}{2}(1.38 \times 10^{-23})(373.15) = 7.72 \times 10^{-21} J$$

(b) $m = 6.64 \times 10^{-24} g = 6.64 \times 10^{-27} kg$

$$\langle E_K \rangle = \frac{1}{2}m\langle c^2 \rangle \rightarrow \langle c^2 \rangle = \frac{2\langle E_K \rangle}{m} = \frac{2(7.72 \times 10^{-21})}{6.64 \times 10^{-27}}$$

$$\langle c^2 \rangle = 2.32 \times 10^6 m^2/s^2$$

$$\langle E_K \rangle = \frac{3}{2}kT \rightarrow T = \frac{2\langle E_K \rangle}{3k}$$

$$T = \frac{2}{3}\left(\frac{4.69 \times 10^{-23}}{1.38 \times 10^{-23}}\right) = 2.26K$$

$$T_C = T_K - 273.15 = -234.89°C$$

Practice Example 7

a) Take note that we do not need to convert the temperature in Kelvin because ΔT is the same whether K or °C is used.

$$c = \frac{Q}{m\Delta T} \to Q = mc\Delta T \Rightarrow Q_{vat} = (15)(450)(95 - 20) = 506 \; kJ$$

b) $Q = mc\Delta T \Rightarrow \quad Q_{water} = (15)(4200)(95 - 20) = 4725 \; kJ$

$$Q_{total} = Q_{vat} + Q_{water} = 5231kJ$$

Practice Example 8

The amount of heat out from the ice goes into the nitrogen, i.e. $Q_{ice} = -Q_N$. Also note $L_v = \frac{Q_N}{m_N}$.

$\Delta T_{ice} = T_f - T_i = -196 - 0 = -196K$ (melting point T_i is at 0°C)

$$Q_{ice} = -Q_N \Rightarrow \quad m_{ice}c_{ice}\Delta T_{ice} = -m_N L_v$$

$$(30 \times 10^{-3})(2100)(-196) = -m_N(200 \times 10^3)$$

$$m_N = \frac{(30\times10^{-3})(2100)(196)}{200\times10^3} = 6.2 \times 10^{-2} \; kg$$

Practice Example 9

|	Q	W	ΔU
A. Rapidly pumping a balloon	0	+	+
B. Oil in a room-temperature wok sitting on a hot stove	+	0	+
C. Air quickly leaking out of a beach ball	0	-	-

Explanation:

Q: For A and C, there is no heat transferred in or out of the system so Q=0. The oil in the wok is heating up so Q is positive.

W: Work is done on the system if it compresses. For A, the air in the pump compresses so +. For B, there is no volume or pressure change so W=0. Lastly, air in the tire expands as some escapes so negative.

ΔU: For A and C, Q=0 so $\Delta U = W$. For B, $\Delta U = Q$.
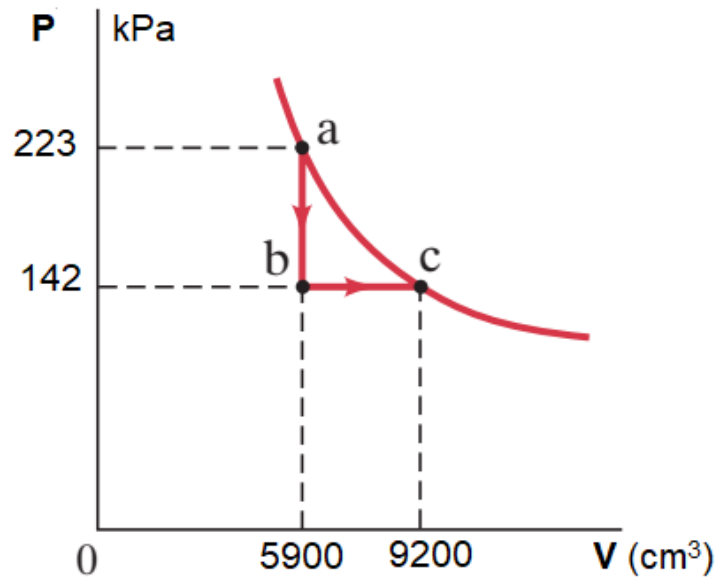
a.) 1st step: No work is done since V is constant.

2nd step: $W = p\Delta V = p(V_c - V_b)$

$$W_2 = (142 \times 10^3)(0.0092 - 0.0059) = 468.6 \, J$$

$$W = W_1 + W_2 = 486.6J$$

b.) There is no change in temperature so $\Delta U = 0$

c.) $\Delta U = Q + W \rightarrow Q = \Delta U - W$

$$Q = 0 - 468.6J = -468.6J$$

It is negative so heat is lost from the system.

For more notes & learning materials, visit:
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'A' levels crash course program

Professionally designed crash course to help you get a **condensed revision** before your 'A' Levels!

Each H2 subject will have **3 crash course modules** which will cover their entire H2 syllabus.

The **4 hour module** focuses on going through **key concepts** and **identifying commonly tested questions!**

The crash courses modules will begin in **June 2021 and last till Oct 2021**.

Pre-register now on our website and secure your slots!

Need help?

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(Private Tutor)

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(Telegram)

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