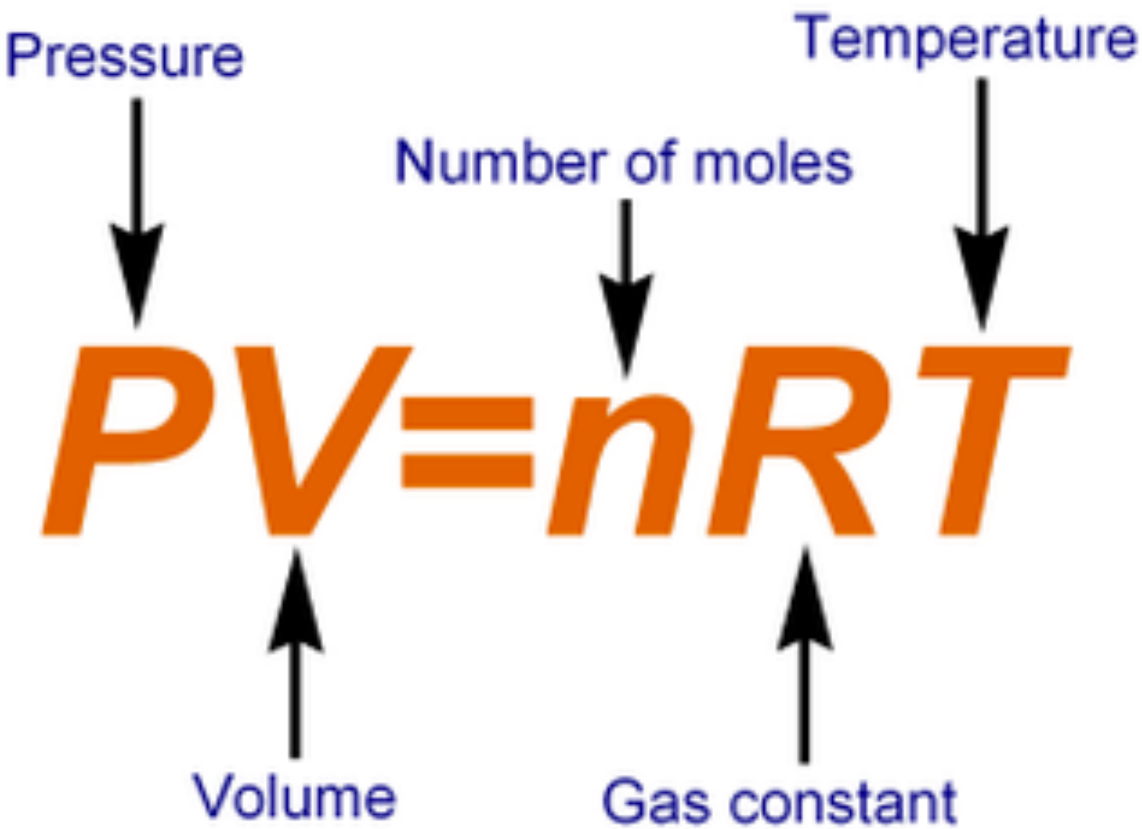
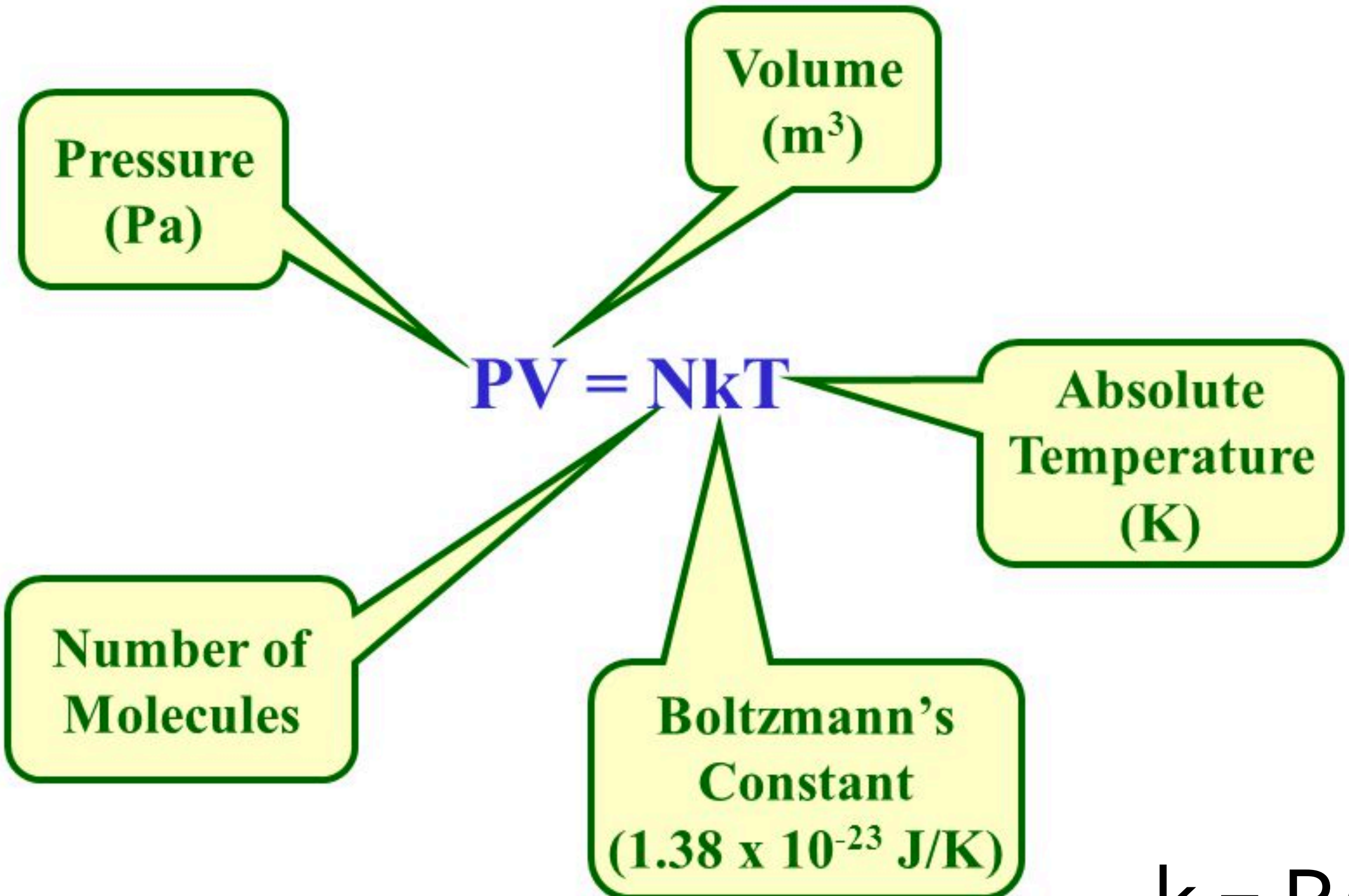
College Physics I: 1511 Mechanics & Thermodynamics

Professor Jasper Halekas
Van Allen Lecture Room 1
MWF 8:30-9:20 Lecture

Ideal Gas Law (Form 1)

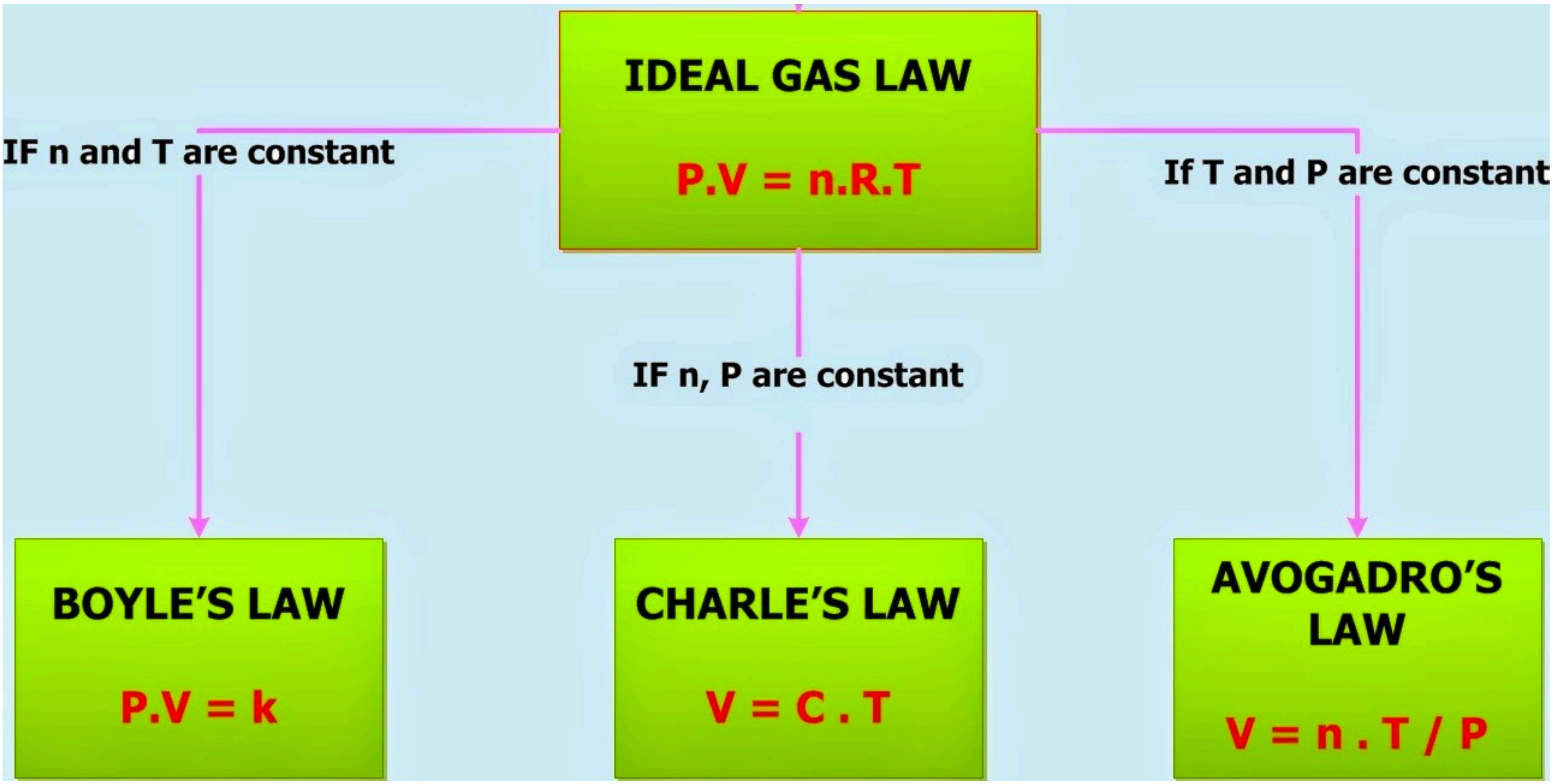


Ideal Gas Law (Form 2)



$k = R/N_A$

Special Cases of Ideal Gas Law

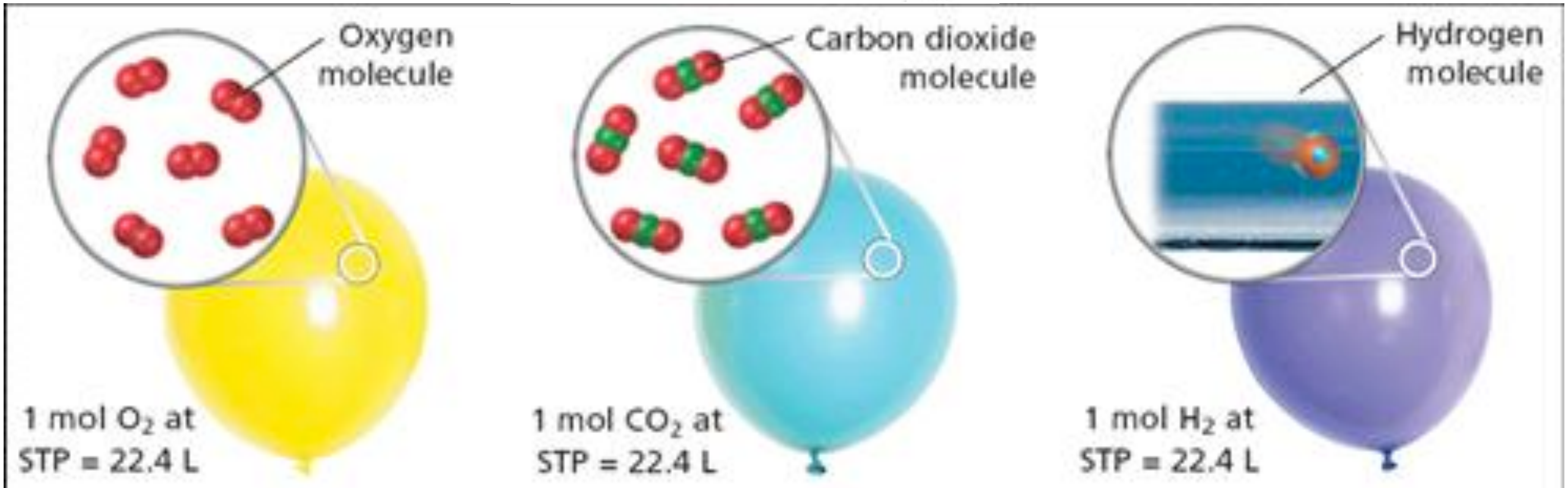


Avogadro's Law (Isobaric, Isothermal)

$$\frac{V_1}{n_1} = \frac{V_2}{n_2}$$

V_1 V_2 are Volumes of gas

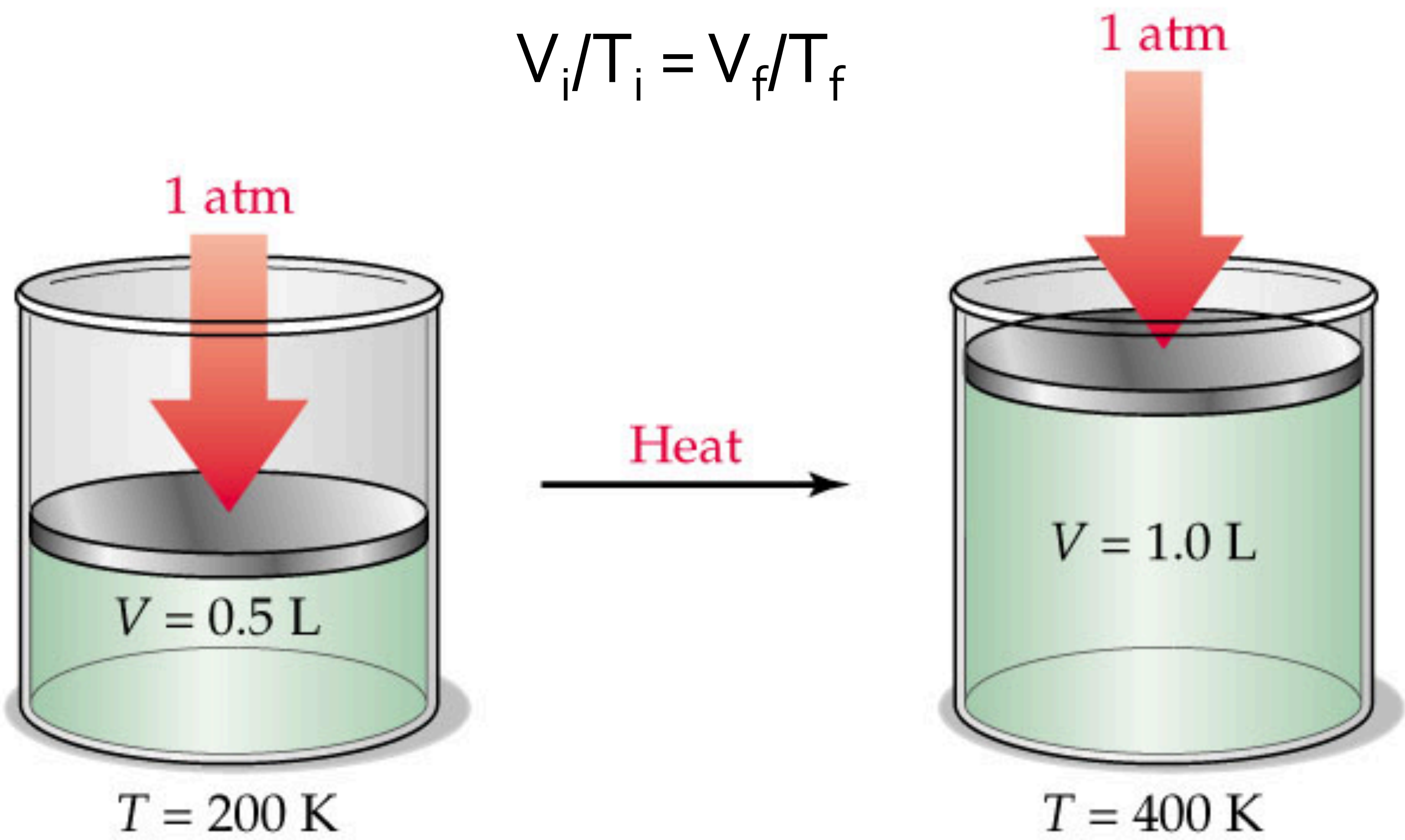
n_1 n_2 are amount of gas



At the same temperature and pressure, balloons of equal volume have equal numbers of molecules, regardless of which gas they contain.

Charles' Law (Isobaric Gas)

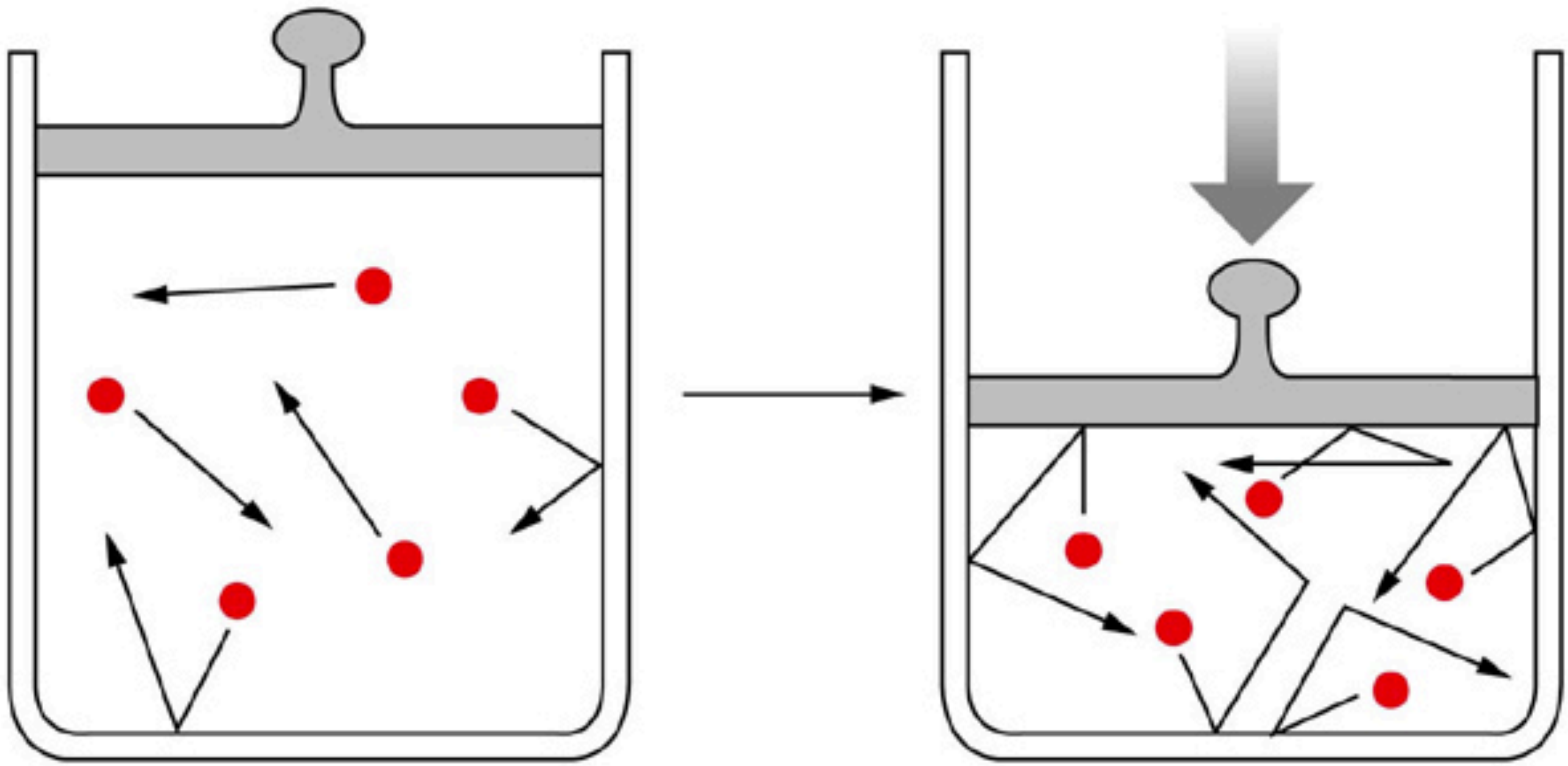
$$V_i/T_i = V_f/T_f$$



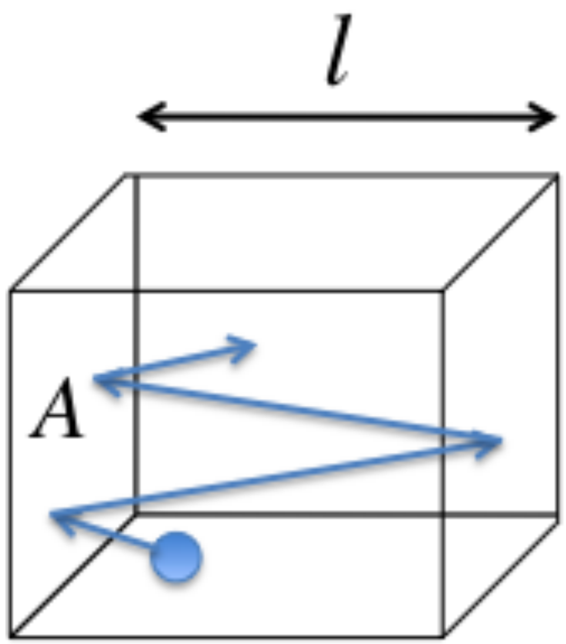
Boyle's Law (Isothermal Gas)

Boyle's Law: $P_1V_1 = P_2V_2$

Decreasing volume increases collisions and increases pressure.



Gas Exerts a Force (Pressure) Through Collisions



Change in momentum on left wall

$$\Delta(mv) = mv_x - (-mv_x) = 2mv_x$$

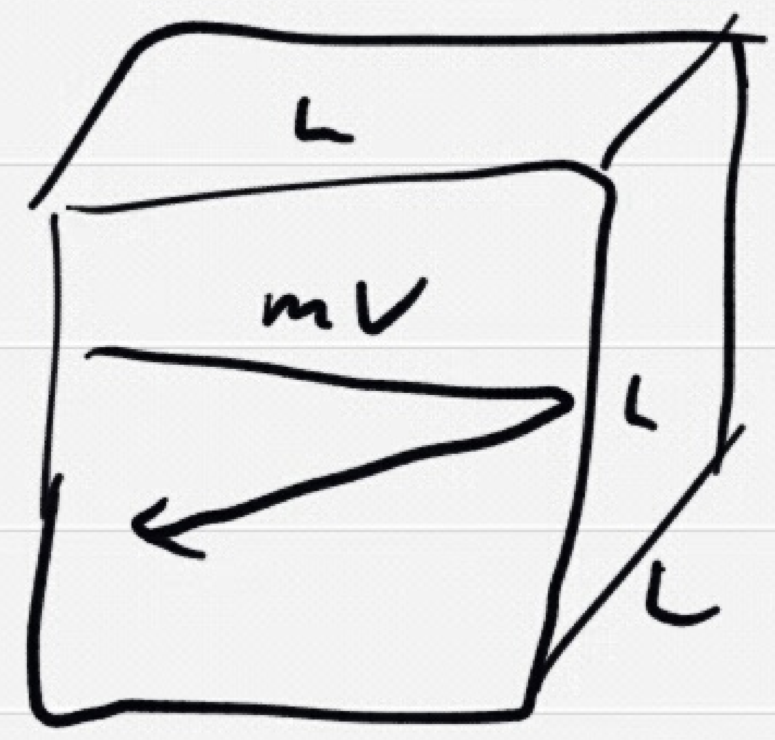
Time between collisions on left wall

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

$F\Delta t = \Delta p \Rightarrow \langle F \rangle = \langle m v_x^2/L \rangle = \langle 1/3\ mv^2/L \rangle$

$P = F/A = N\langle F \rangle/A = N\ 1/3\ m \langle v^2 \rangle/L^3 = N\ 2/3 \langle 1/2\ mv^2 \rangle/V$

$$\Delta p = F \Delta t$$



$$\Delta p_x = 2 m v_x$$

$$\Delta t = 2L / v_x$$

$$F_x = \Delta p_x / \Delta t = \frac{2 m v_x}{2L / v_x} = \frac{m v_x^2}{L}$$

$$\langle v^2 \rangle = \langle v_x^2 \rangle + \langle v_y^2 \rangle + \langle v_z^2 \rangle$$

$$\Rightarrow \langle v_x^2 \rangle = \langle v^2 \rangle / 3$$

$$\langle F \rangle = \left\langle \frac{m v_x^2}{L} \right\rangle = \left\langle \frac{m v^2}{3L} \right\rangle$$

$$P = N \langle F \rangle / A = \frac{N \langle m v^2 \rangle}{3 L \cdot L^2}$$

$$= \frac{N}{L^3} \cdot \frac{1}{3} \cdot 2 \cdot \langle \tfrac{1}{2} m v^2 \rangle$$

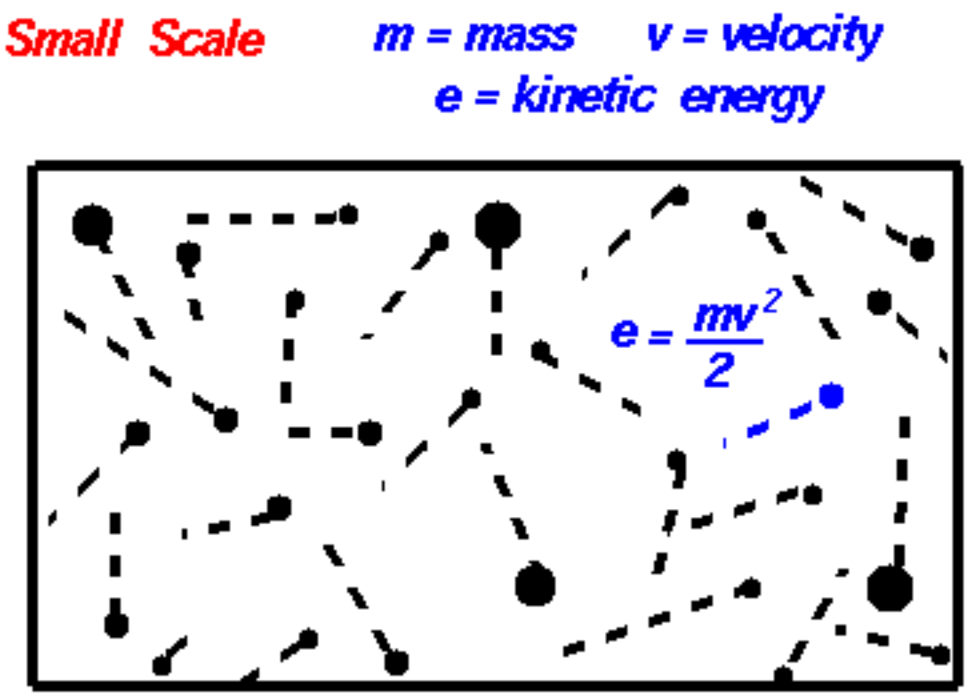
$$= \frac{N}{V} \cdot \frac{2}{3} \cdot \langle \tfrac{1}{2} m v^2 \rangle$$

$$= \tfrac{2}{3} N/V \langle KE \rangle$$

Ideal Gas Law and Kinetic Energy

- Macroscopic: $PV = NkT$
- Kinetic: $PV = N (2/3 \langle 1/2\, mv^2 \rangle) = N (2/3 \langle KE \rangle)$
- $\langle KE \rangle = 3/2\, kT$
- There is a direct relationship between the macroscopic quantity T and the average kinetic energy of the individual gas particles

Kinetic View of Temperature



Temperature is a measure of the average kinetic energy of translation of the gas molecules.

$$\left[\frac{1}{2}mv^2\right]_{average} = \frac{3}{2}kT$$

defines the kinetic temperature

k = Boltzmann constant

Concept Check

- Two sealed containers A and B are at the same temperature and each contain the same number of moles of an ideal monatomic gas. Container A is twice as big as container B. Which one of the following statements concerning these containers is true?

A. The average (RMS) speed of gas atoms is greater in B
B. The frequency of collisions of the atoms with the walls of container B are greater than that for container A
C. The kinetic energy of the gas atoms is greater in B
D. The pressure within container B is less than that in A

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$$V_A = 2V_B$$

$$T_A = T_B = T$$
$$n_A = n_B = n$$

$$p_A \cdot V_A = nRT$$
$$p_B \cdot V_B = nRT$$

$$p_A V_A = p_B V_B$$

$$p_B / p_A = V_A / V_B = 2$$

T constant

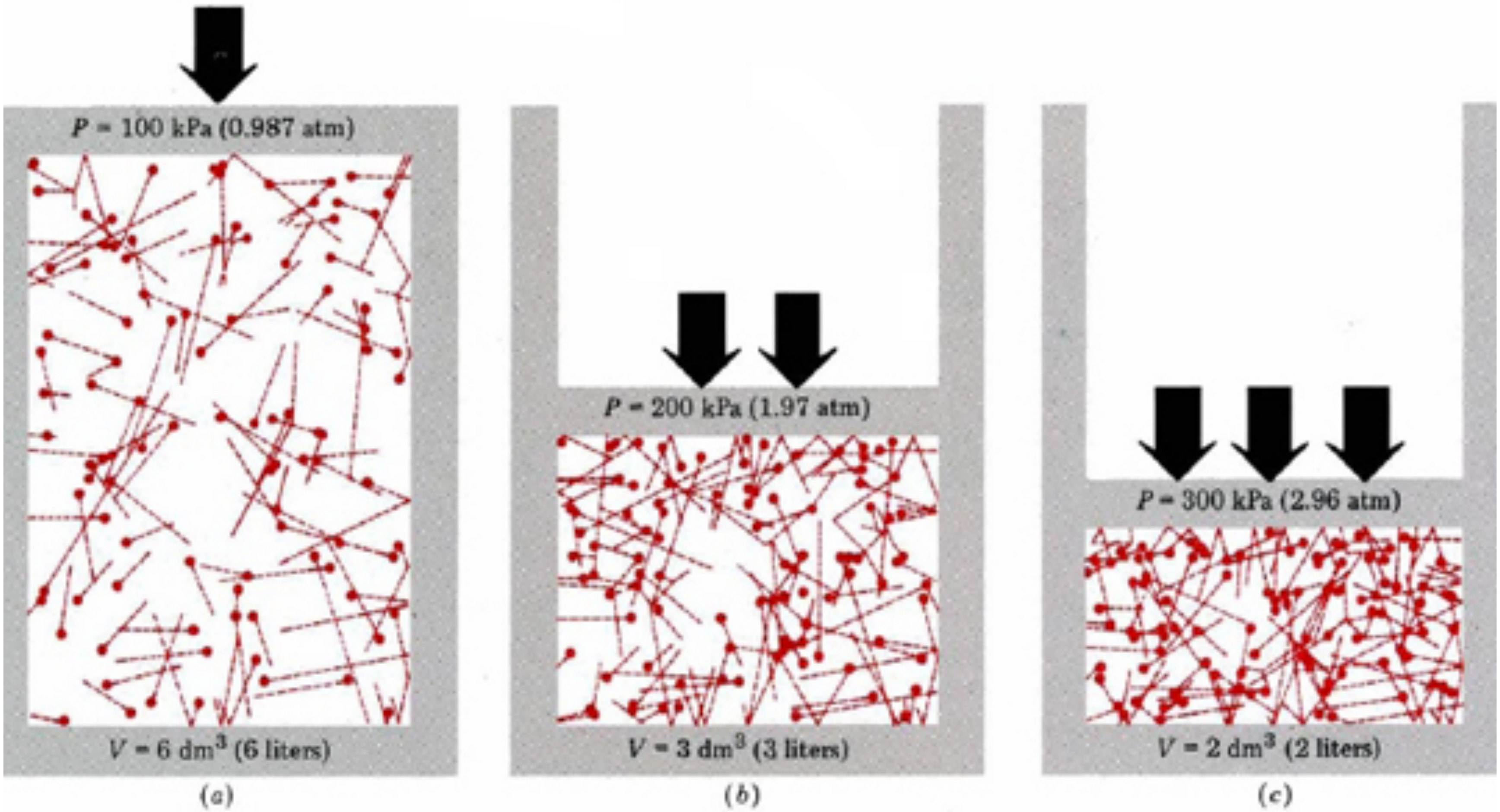
$\Rightarrow$ $\langle KE \rangle$ constant

$\Rightarrow$ $\langle \frac{1}{2} m v^2 \rangle$ constant

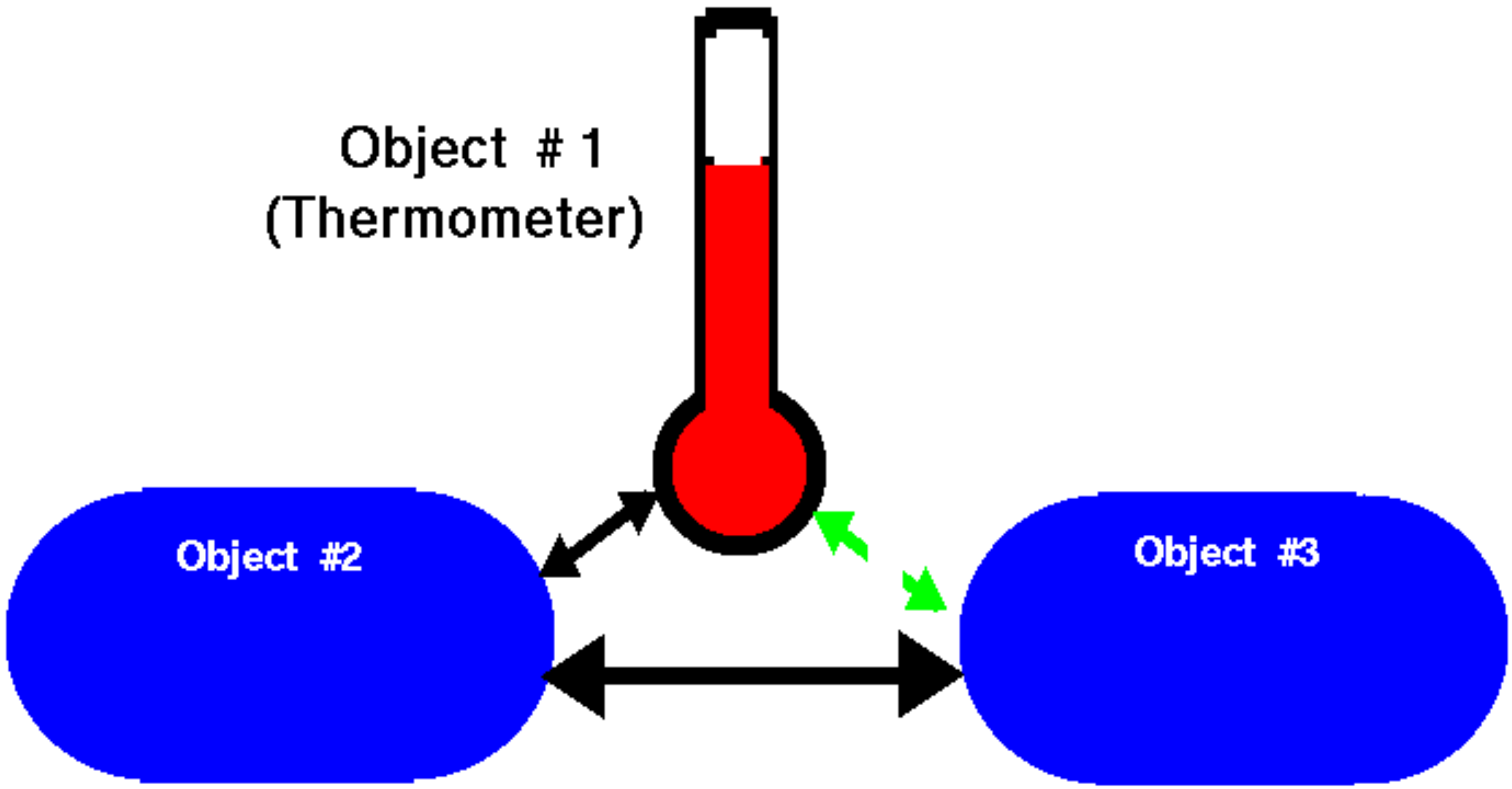
$\Rightarrow$ $\langle v^2 \rangle$ constant

$\Rightarrow$ $v_{rms} = \sqrt{\langle v^2 \rangle} = \text{constant}$

Kinetic View of Pressure



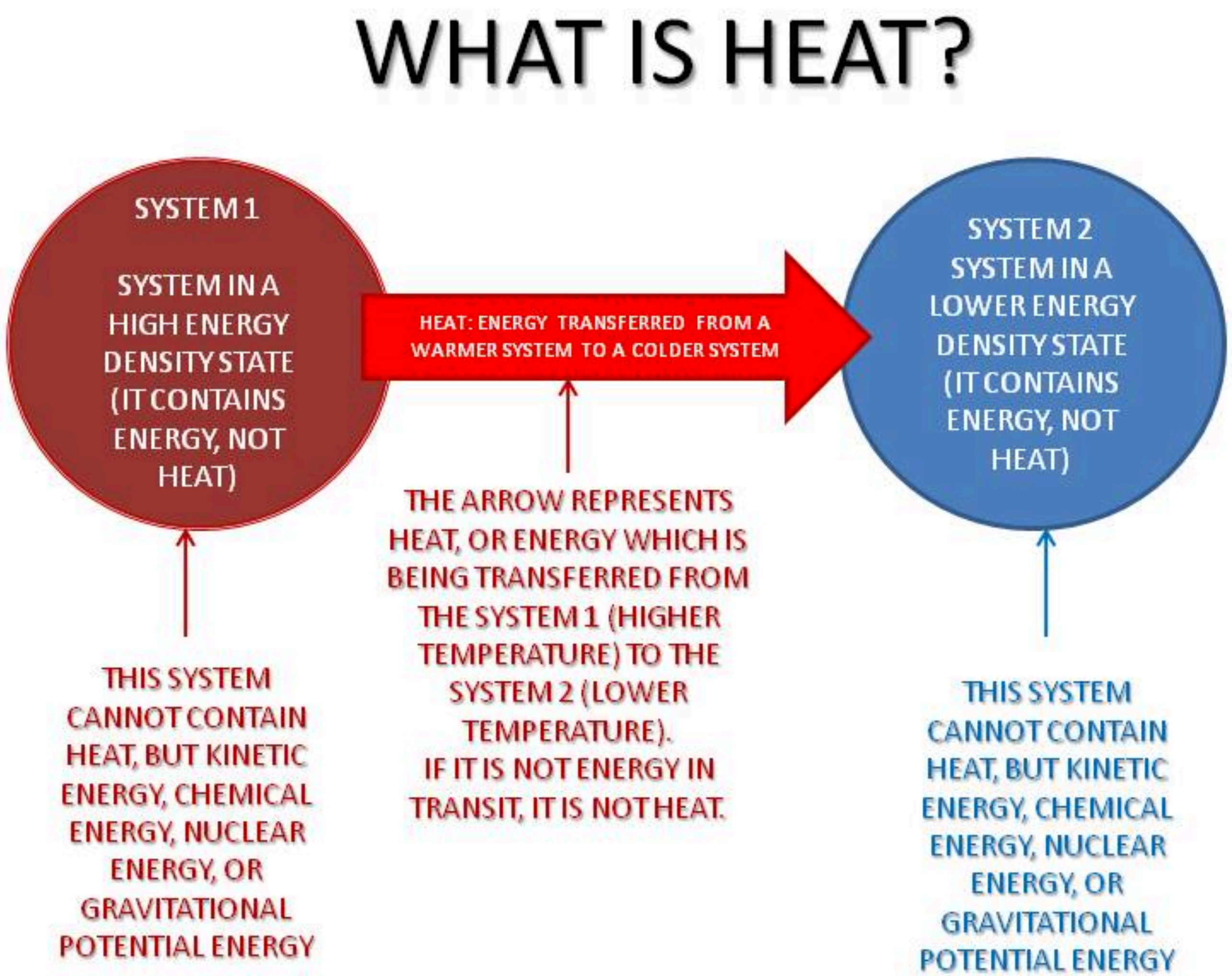
Thermal Equilibrium (Zeroth Law of Thermodynamics)



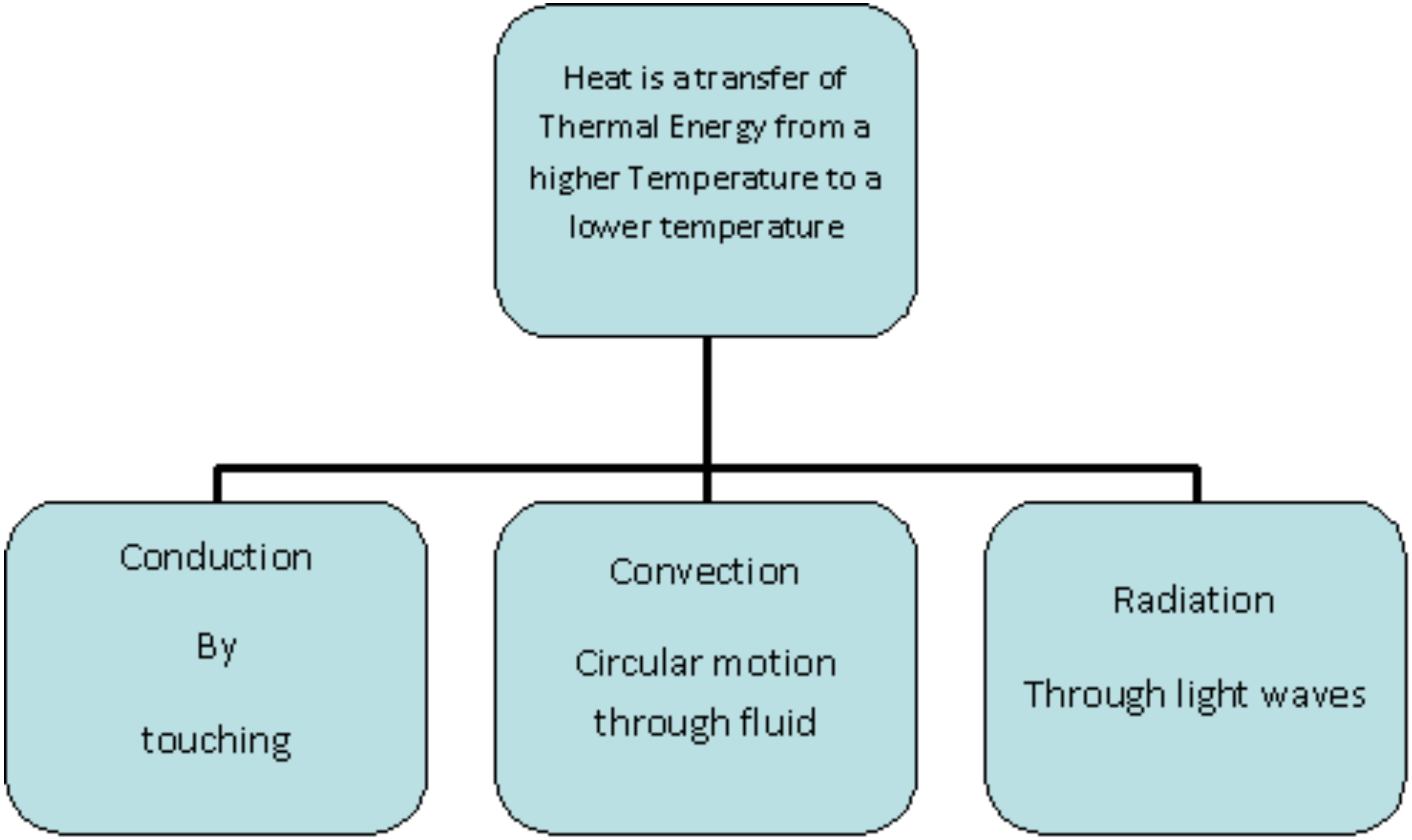
When two objects are separately in thermodynamic equilibrium with a third object, they are in equilibrium with each other.

Objects in thermodynamic equilibrium have the same temperature.

Heat


WHAT IS HEAT?
SYSTEM 1
SYSTEM IN A HIGH ENERGY DENSITY STATE (IT CONTAINS ENERGY, NOT HEAT)
HEAT: ENERGY TRANSFERRED FROM A WARMER SYSTEM TO A COLDER SYSTEM
SYSTEM 2
SYSTEM IN A LOWER ENERGY DENSITY STATE (IT CONTAINS ENERGY, NOT HEAT)
THIS SYSTEM CANNOT CONTAIN HEAT, BUT KINETIC ENERGY, CHEMICAL ENERGY, NUCLEAR ENERGY, OR GRAVITATIONAL POTENTIAL ENERGY
THE ARROW REPRESENTS HEAT, OR ENERGY WHICH IS BEING TRANSFERRED FROM THE SYSTEM 1 (HIGHER TEMPERATURE) TO THE SYSTEM 2 (LOWER TEMPERATURE).
IF IT IS NOT ENERGY IN TRANSIT, IT IS NOT HEAT.
THIS SYSTEM CANNOT CONTAIN HEAT, BUT KINETIC ENERGY, CHEMICAL ENERGY, NUCLEAR ENERGY, OR GRAVITATIONAL POTENTIAL ENERGY

Energy Transfer Mechanisms



Heat and Temperature

- Adding heat changes the temperature of an substance (usually)
- But, not all heat necessarily goes into changing temperature
- Heat can also do work, or can change the phase or other properties of a substance

Internal Energy of a Gas

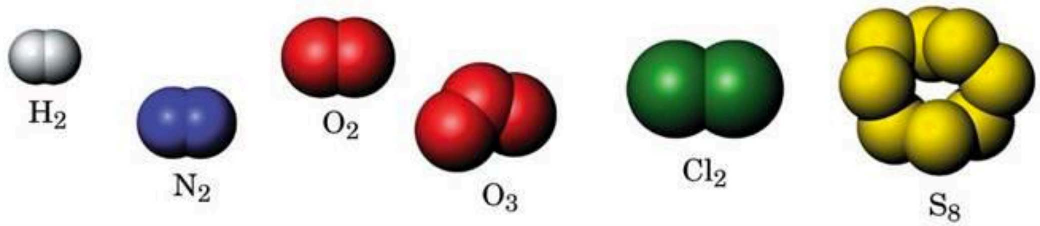
- Since <KE> = 3/2 kT, it is tempting to state that the total internal energy U of a gas is 3/2 NkT

- This is true for a monatomic ideal gas
  - Total internal energy U = 3/2 NkT = 3/2 nRT for a monatomic ideal gas

Types of Gas

Forms of the Elements

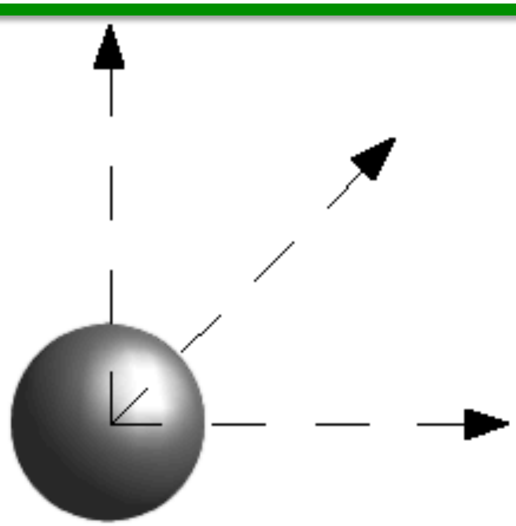
- A monatomic element consists of a single atom.
- A diatomic element exists as a molecule made up of two atoms.
- A polyatomic element exists as a molecule made up of three or more atoms.



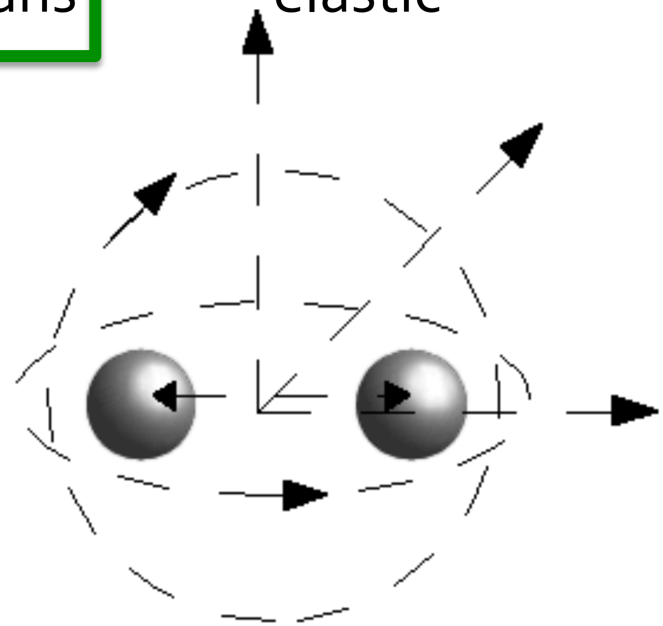
Internal Energy of Diatomic and Higher Gases

$$E = KE + PE$$

$$E = KE_{rot} + KE_{trans} + PE_{elastic}$$

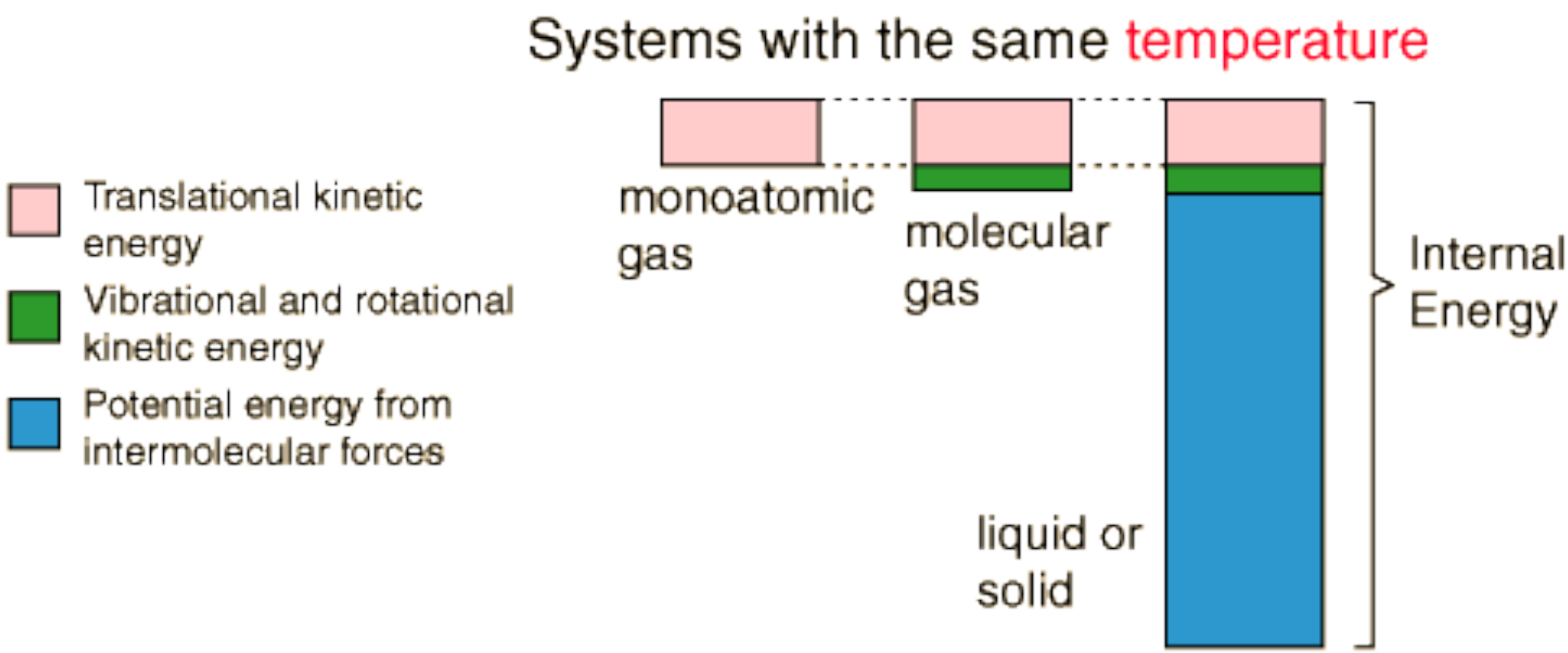


Monatomic: only translational degrees of freedom.



Diatomic: translational, rotational, and vibrational degrees of freedom.

Internal Energy



Adding Heat Changes Temperature

Specific Heat Capacity

- **<u>Specific Heat Capacity</u>** is the amount of heat per unit mass (kg) of a substance to change its temperature by one degree Celsius.

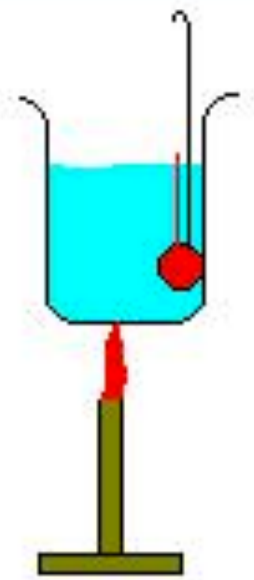
$$Q = c\, m\, \Delta T$$

Q = heat added (removed)

c = specific heat capacity

m = mass

ΔT = temperature change



c = 4,186 J/kg/C

for water at
T = 4 C

Work and Energy

Work Kinetic Energy Theorem

$$W_{net} = \Delta KE$$
$$W_{net} = \tfrac{1}{2} m v_f^2 - \tfrac{1}{2} m v_o^2$$

The W_{net} in the work-energy theorem is the work done **on/to** a moving object.

The work done **by** the object would be the negative of this.

First Law of Thermodynamics

The change in internal energy of a system is equal to the heat added to the system minus the work done by the system.

$$\Delta U = Q - W$$

Change in internal energy

Heat added to the system

Work done by the system

Concept Check

- When a solid object is heated, its internal energy (and temperature) changes. Its volume also changes, and this volume change can be used to do work. Which do you think is bigger?

A. The amount of heat that goes into internal energy
B. The amount of heat that goes into doing work
C. The two are equal

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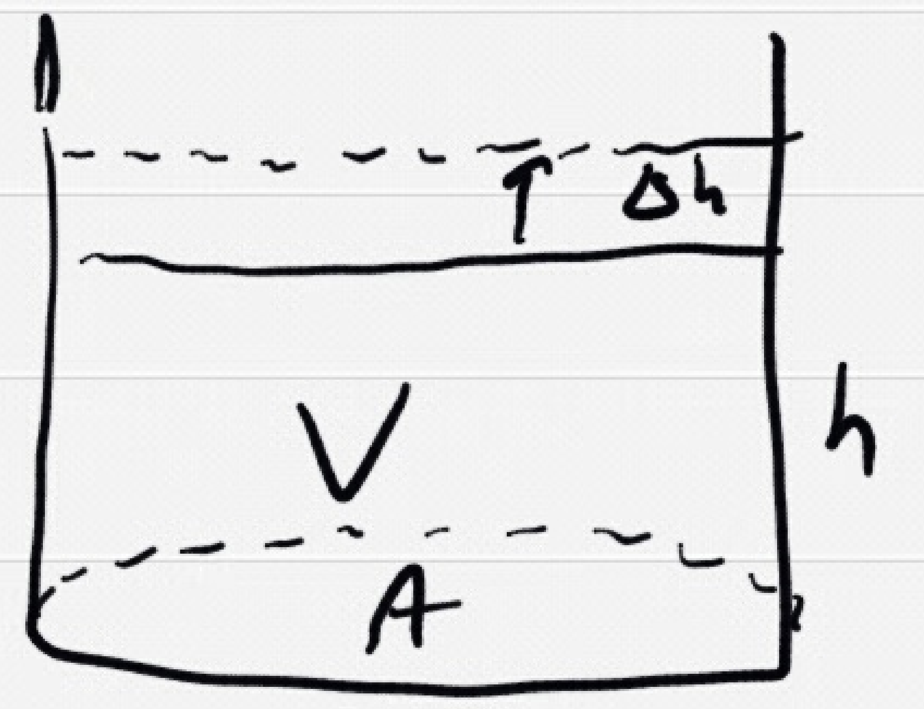
Example Problem

- Liquid water is heated in an open pan where the air pressure is one atmosphere. Determine the ratio of the work done by the water (on the surrounding atmosphere) to the heat transferred to the water.

- Mass density of water = 1000 kg/m^3
- Specific heat capacity c = 4200 J/(kg K)
- Coefficient of volume expansion $\beta = 2 \times 10^{-4}$
- Atmospheric pressure = 10^5 Pa

$$Q = mc\Delta T \Rightarrow \Delta T = Q/mc$$

$$\Delta V = \beta \Delta T V$$



$$V = A \cdot h$$
$$\Delta V = A \cdot \Delta h$$

$$\begin{aligned} W &= F\Delta h \\ &= PA\Delta h \\ &= P\Delta V \\ &= P(\beta \Delta T V) \\ &= P \cdot \left(\beta \cdot \frac{Q}{mc} \cdot V\right) \\ &= P \cdot \beta \cdot Q/c \cdot V/m \\ &= P \cdot \beta \cdot Q/c \cdot 1/\rho \\ &= 10^5 \cdot 2\times10^{-4} \cdot 1/4200 \cdot 1/1000 \cdot Q \end{aligned}$$

$$\sim 5 \times 10^{-6} \cdot Q$$

$$\Delta U = Q - W$$
$$\sim Q$$

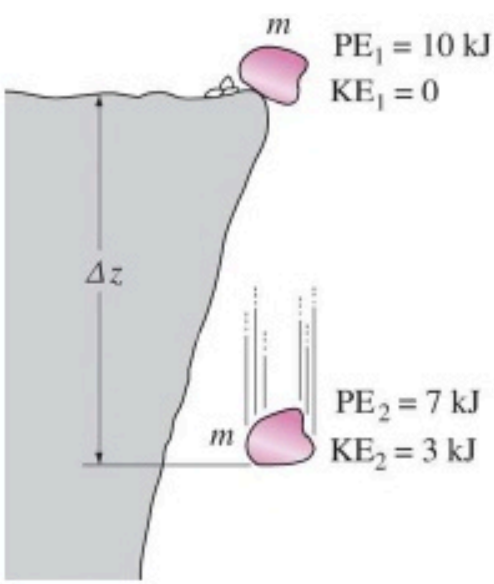
- Most heat goes to internal energy for a solid
- Similar for fluids

- Not so for gas!

First Law Restated

THE FIRST LAW OF THERMODYNAMICS

- The ***first law of thermodynamics*** (***the conservation of energy principle***) provides a basic to study the relationships among various forms of energy and energy interactions.
- The first law states that ***energy can be neither created nor destroyed during a process; it can only change forms***.



Energy cannot be created or destroyed; it can only change forms.

The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

Happy Thanksgiving!

- See you all again on Monday 11/28!