Thermodynamic equilibrium

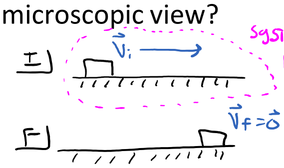
Select LEARNING OBJECTIVES:

- Develop a microscopic model of a gas where each particle has a different speed but the distribution of speeds is predictable at a given temperature.
- Make the connection between the microscopic particle speeds and the macroscopic temperature.
- Connect the average kinetic energy per particle to the overall total thermal energy - realizing that thermal energy is simply the summation of all of the microscopic KE of each particle.
- Understand the concept of equilibrium as a state where the energy gradient is zero.
- Using the concept of energy equilibrium to manifest as constant temperature.
- Define the Equipartition Theorem - specifically for gasses

TEXTBOOK CHAPTERS:

- Giancoli (Physics Principles with Applications 7th) :: 13-3
- Knight (College Physics : A strategic approach 3rd) :: 11.3
- BoxSand :: [Kinetic Theory of Gases]

WARM UP: A box slides across a table and comes to a rest due to friction. Include the table and the box in your system. What energy transformations occur within your system? Can you describe this from a microscopic view?



$KE_{Box} \longrightarrow E^{TH}_{Box+TABLE}$

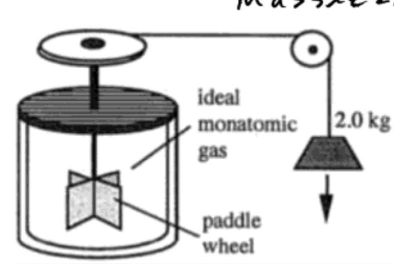
MACROSCOPIC: WE SEE THE TEMPERATURE OF BOTH BOX AND TABLE RISE

MICRO?

ATOMS OF THE BOX AND TABLE ARE VIBRATING BACK AND FORTH MORE RAPIDLY

PRACTICE: A paddle wheel frictionally adds thermal energy to 5.0 moles of an idea monatomic gas in a sealed isolated container. The paddle wheel is driven by a cord connected to a falling object as shown in the figure. If all the loss of gravitational potential energy from the object goes into the thermal energy of the gas, how far has the 2.0 kg object fallen when the temperature of the gas increases by 10 K?

massless



SYSTEM: MASS + GAS + EARTH

ENERGY TRANSFORMATION $U^g \longrightarrow E^{TH}$

$$U^g_i + E^{TH}_i = U^g_f + E^{TH}_f$$

$$\Delta U^g = \Delta E^{TH}$$

$$mg\Delta y = \frac{3}{2} N k_B \Delta T$$

MOLES TO N? ... CONVERSION

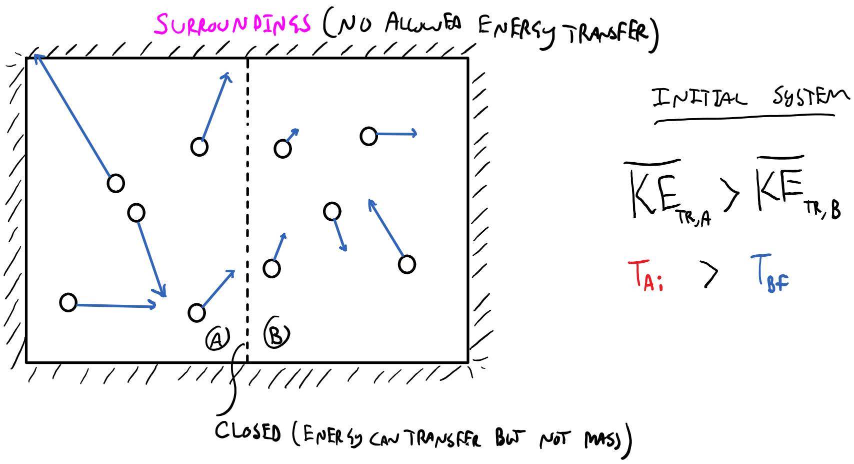
$$N k_B = nR \qquad R = 8.31 \frac{J}{mol\,K}$$

$$mg\Delta y = \frac{3}{2} nR\Delta T$$

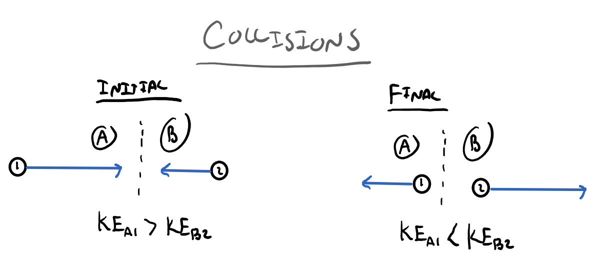
$$\Delta y = \frac{3nR\Delta T}{2mg} = 31.8\ m$$

Recall back to ph201 where we studied systems in mechanical equilibrium as well as dynamic systems. In fact, Newton's laws of motion gave us a definition for what mechanical equilibrium meant, and the dynamics portion was what happened when our system deviated from its equilibrium state. An example was a rocket in space moving at some constant velocity (its engines are off). The rocket was said to be in dynamic mechanical equilibrium since it is moving but isn't changing its velocity. What happens when the rocket fires up its engines? It accelerates, which is now a dynamics type of problem (i.e. it is no longer in equilibrium). In thermodynamics we also have equilibrium and non-equilibrium (dynamic) conditions, however these conditions are different than our mechanical equivalent which we studied in ph201 as discussed above.

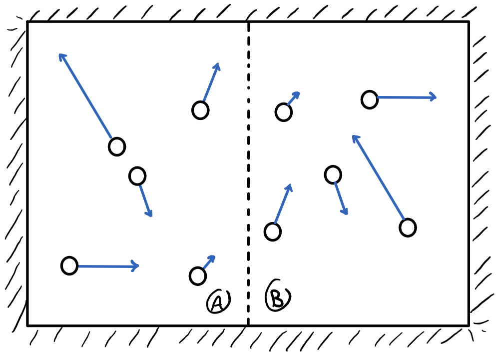
Thermodynamic equilibrium of a system is defined as the same average translational kinetic energy per particle. A consequence of this condition is that the temperate is also the same within the system. To help illustrate this condition of thermodynamic equilibrium let's consider a closed system with 2 regions (A and B) that are isolated from the surrounding. Recall closed means energy can be transferred by mass cannot, and isolated means that both energy and mass cannot be transferred. Initially region A has a larger average translational kinetic energy than region B, so our system is not in equilibrium. Let's also assume the mass of all the particles are the same in both regions, this is not necessary but it will help visualize the scenario since the length of the velocity vectors will be an indication of translational kinetic energy of each particle and the overall average translational kinetic energy of each region.



Recall that mechanical systems will tend towards equilibrium. We saw this behavior when studying energy with the case study of a ball placed in a U-shaped ramp. The ball oscillated back and forth around its stable equilibrium location, and eventually because of friction the ball worked its way to the equilibrium condition where it was at a constant velocity at the equilibrium location. Thermodynamic systems also tend towards equilibrium. Thus over time the system shown above will reach thermodynamic equilibrium (i.e. the system will have the same average translational kinetic energy). How does this system do that? To help answer this we will look at collisions between particles at the barrier. Consider just two particles, one from each region. If we pick these particles at random then we will most likely have a larger translational kinetic energy particle from region A.



Before the collision, the particle 1 in region A has a larger translational kinetic energy than the particle 2 in region B. When they collide, we will assume a completely elastic collision so that no energy is lost but energy is transferred from particle 1 to particle 2. Thus after the collision particle 1 in region A will now be moving slower than before, and particle 2 in region B will be moving faster than before. This process happens between many particles until the average translational kinetic energy of the particles in region A equals the average translational kinetic energy of the particles in B. So in thermodynamic equilibrium the system might look like the figure below, where each region has a distribution translational kinetic energy per particle but the average translational kinetic energy in each region is the same.



AT EQUILIBRIUM

$\overline{KE}_{TR,A} = \overline{KE}_{TR,B}$

... AND THUS $T_{A_{eq}} = T_{B_{eq}}$

$T_{B_i} < T_{A_{eq}} = T_{B_{eq}} < T_{A_i}$

To summarize, the initial system contained two regions with different average translational kinetic energies. To describe this situation, physicists say that there is an energy gradient (or energy difference) present. Anytime a system, mechanical or thermodynamic, has an energy gradient there are mechanisms that drive that system to equilibrium. For our thermodynamic case, equilibrium is reached once the average translational kinetic energy is the same; the consequence of this is that the temperature is also the same.

PRACTICE: You have two containers in contact with each other. One is full of helium gas. The other holds a large number of neon gas molecules. Both gasses are in equilibrium with each other. How does the temperature of the helium compare to the temperature of the nitrogen?

@ EQ $\overline{KE}_{He} = \overline{KE}_{Ne}$

(a) $T_{He} > T_{Ne}$
(b) $T_{He} < T_{Ne}$
(c) $T_{He} = T_{Ne}$

$\overline{KE}_{TR} = \frac{3}{2} k_B T$

$\therefore \overline{KE}_{He} = \overline{KE}_{Ne} = \frac{3}{2} k_B T_{He} = \frac{3}{2} k_B T_{Ne}$

THUS SAME TEMP... $T_{He} = T_{Ne}$

PRACTICE: You have two containers in contact with each other. One is full of helium gas. The other holds a larger number of neon gas molecules. Both gases are in equilibrium with each other. How does the total internal energy of the helium compare to the total internal energy of the nitrogen?

(a) $E^{Th}_{He} > E^{Th}_{Ne}$
(b) $E^{Th}_{He} < E^{Th}_{Ne}$
(c) $E^{Th}_{He} = E^{Th}_{Ne}$

@ EQ $\overline{KE}_{He} = \overline{KE}_{Ne}$

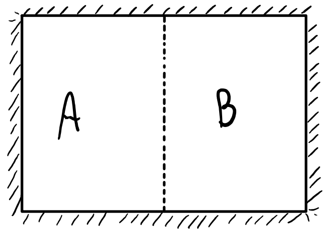
BOTH ARE MONATOMIC

$E^{TH} = N\overline{KE}$ $\quad E^{TH} = N \frac{3}{2} k_B T$

w/ $N_{He} < N_{Ne}$ & $E^{TH}_{He} < E^{TH}_{Ne}$

PRACTICE: A closed system with 2 regions (A and B) that are isolated from the surrounding contain two equally numbered moles of monatomic gas. They are in thermal equilibrium with each other and the molecular mass of A is 4 times that of B. Which of the following statements are true regarding this situation?

(a) The temperature of B is four times that of A.
(b) The temperature of B is equal to the temperature of A.
(c) The average molecular speed of B is equal to that of A.
(d) The average molecular speed of B is twice that of A.
(e) The average kinetic energy of A is a fourth that of B.
(f) The total internal thermal energy of A is equal to B.



@Eq $\overline{KE}_{TR,A} = \overline{KE}_{TR,B}$ $\quad E^{TH} = N\overline{KE}_{TR} = N\frac{1}{2}\overline{m}V_{rms}^2$ $\quad E^{TH} = \frac{3}{2}Nk_BT$

w/ $\overline{KE}_A = \overline{KE}_B$ AND $\overline{KE} = \frac{3}{2}k_BT$ $\Big\}$ $T_A = T_B$

w/ $\overline{KE}_A = \overline{KE}_B$ AND $\overline{KE} = \frac{1}{2}\overline{m}V_{rms}^2$ $\Big\}$ $m_AV_A^2 = m_BV_B^2$, w/ $m_A = 4m_B$ $\Big\}$ $4m_BV_A^2 = m_BV_B^2$, $2V_A = V_B$

w/ $\overline{KE}_A = \overline{KE}_B$ AND $N_A = N_B$ $\Big\}$ $E^{TH}_A = E^{TH}_B$

Questions for discussion:

(1) Does a diatomic gas have more, less, or an equal amount of thermal energy than a monatomic gas at the same temperature?