Important Concepts

• One of the most important concepts to recognize in this section is the difference between heat, temperature, and energy
  • These are all related concepts, but physically they are distinct

• Heat
  • energy transferred because of a temperature difference

• Temperature
  • a quantitative measure of how “hot” or “cold” something is. Related to the average (translational kinetic) energy of particles

• Internal Energy
  • the sum of the kinetic energies of all of the constituent particles, plus the sum of all the potential energies of interaction among these particles
Specific Heat

- **Matter’s resistance to temperature change** is characterized by an index, called the **specific heat**.
  - The symbol lower case “c” is commonly used and its value gives the energy required for every 1 kg of mass to increase in temperature by 1 K. (Units: J / K•kg)
  
  \[ Q = Mc\Delta T \]

- For instance
  - the specific heat of water is 4190 J/K•kg
    - If I give 1kg of water 4190 J of energy from heating, it will increase its temperature by 1 Kelvin (1 cal (calorie) = 4.186 J)
  - the specific heat of copper is 390 J/K•kg

- **Molar heat capacity (“C”)** is the same concept but with moles
  - \( n \) is the number of moles
    
    \[ Q = nC\Delta T \]
Specific Heat for an Ideal Gas

• Recall from last lecture that for an ideal gas, the average kinetic energy of a particle is related to the temperature via:

\[ \frac{1}{2}m(v^2)_{\text{avg}} = \frac{3}{2}k_B T \]

• For many (N) particles, this means

\[ NK_{\text{avg}} = K_{\text{tot}} = \frac{3}{2}Nk_B T \]

• For an ideal gas, the kinetic energy is directly related to the temperature. Therefore, adding energy (via heat) will change the temperature in the same way

\[ \Delta Q = \frac{3}{2}Nk_B \Delta T \]

• and therefore:

\[ c = \frac{3}{2} \frac{N}{M} k_B \leftrightarrow C = \frac{3}{2} R \]
Specific Heat for Other Gasses

- $3/2R = 12.47$, which is the heat capacity for He and Ar

- Why do other gasses differ?
  - If the molecules are not simple, rotational and vibrational modes can also get excited
  - (heat) energy need not go directly into translational kinetic energy
  - The more different “degrees of freedom” a molecule has, the more heat is required to increase its temperature (hence a higher specific heat)

<table>
<thead>
<tr>
<th>Type of Gas</th>
<th>Gas</th>
<th>$C_V$ (J/mol · K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monatomic</td>
<td>He</td>
<td>12.47</td>
</tr>
<tr>
<td></td>
<td>Ar</td>
<td>12.47</td>
</tr>
<tr>
<td>Diatomic</td>
<td>$H_2$</td>
<td>20.42</td>
</tr>
<tr>
<td></td>
<td>$N_2$</td>
<td>20.76</td>
</tr>
<tr>
<td></td>
<td>$O_2$</td>
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<td></td>
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<td>28.46</td>
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<tr>
<td></td>
<td>$SO_2$</td>
<td>31.39</td>
</tr>
<tr>
<td></td>
<td>$H_2S$</td>
<td>25.95</td>
</tr>
</tbody>
</table>
Specific Heat for Hydrogen Gas

Equipartition of energy: Each degree of freedom: $C = \frac{R}{2}$

- Translation: 3
- Rotation of diatomic molecules: 2
- Vibration of diatomic molecules (kinetic + potential): 2

Below 50 K, H₂ molecules undergo translation but do not rotate or vibrate. Appreciable rotational motion begins to occur above 50 K. Appreciable vibrational motion begins to occur above 600 K.
Two identical glasses contain different samples of water. Glass A contains 500mL of water, and Glass B contains 250mL of water. The water in Glass A has twice the thermal (internal) energy as the water in Glass B.

The temperature of Glass A is _____________ the temperature of Glass B.

A. Greater than  
B. Less than  
C. Equal to  
D. Not Enough Information
Glass Temperatures (II)

Two different glasses contain different samples of water. Glass A contains 500 grams of water, and Glass B contains 750 grams of water. The water in Glass B has twice the thermal (internal) energy as the water in Glass A.

The temperature of Glass A is _____________ the temperature of Glass B.

A. Greater than  
B. Less than  
C. Equal to  
D. Not Enough Information
Phase Changes

• When matter changes phase (e.g., between solid and liquid or between liquid and gas) that phase change has energy associated with it
  • The **latent heat of transformation** is the energy required to complete the phase change for every kg of the substance.
  • The symbol upper case “L” is commonly used, and its units are (J/kg)

\[
Q = \pm ML
\]

• Again here, the key concept to recognize is that temperature is not the same thing as internal energy
• During a phase change, the **temperature remains constant**, even though the **internal energy is changing** to transform the phase of the material
Phase Changes

- Triple point of water
  - \( T_t = 273.16 \text{ K} \), \( p_t = 6.1 \times 10^2 \text{ Pa} \)
- Critical point of water: (critical opalescence)
  - \( T_c = 647.4 \text{ K} \), \( p_c = 221.2 \times 10^5 \text{ Pa} \)

At the triple point, solid, liquid, and vapor coexist.

The slope of this curve is negative for water!
• Latent heat of water fusion: $L_f=79.6 \text{ cal/g}$
• Latent heat of water vaporization: $L_v=73.9 \text{ cal/g}$
(1 cal (calorie) = 4.186 J: heat 1g water by 1 K)
40 g of water at 100 °C and 60 g of water at 0 °C are mixed together. When the mixture reaches thermal equilibrium, the final temperature will be:

a) greater than 50 °C.

b) equal to 50 °C.

c) less than 50 °C.
50 g of steam at 100 °C and 50 g of liquid water at 80 °C are mixed together in an insulated container. When the combination reaches thermal equilibrium, the final temperature will be:

a) greater than 90 °C .
b) equal to 90 °C .
c) less than 90 °C .
The objects shown have been sitting untouched on a bedside table overnight. The room they are in has been at a constant temperature of 25°C.

A. The objects will all be at the same temperature as the room.
B. The scissors will be coldest, then the mirror glass, then the mirror frame, and then the hairbrush handle.
C. The temperatures will be different, but depend on mass so it’s hard to say. The mirror and metal will be colder than the plastic and wood.
D. The scissors will be coldest, the handle will be warmest, and the mirror frame and glass are in contact so will be at the same temperature in between.
Heat Transfer

- **Conduction** is the transfer of heat through kinematic interactions in a material
  - Metals can conduct heat in much the same way that they conduct current (electrons that move freely within the atomic lattice)
    - Don’t confuse conductivity with heat capacity

- **Convection** is the transfer of heat by the movement of fluid from one region to another

- **Radiation** is the transfer of heat by electromagnetic waves such as visible light, infrared, and ultraviolet radiation
An Ideal Gas

- The distribution of molecular speeds in a sample of N\textsubscript{2} gas at 20°C

\[
\frac{1}{2} m (v^2)_{\text{avg}} = \frac{3}{2} k_B T
\]

14 \times m(H\textsubscript{2}) = m(N\textsubscript{2})

Earth’s escape speed = 11,200 m/s
Maxwell-Boltzmann Distribution

• The probability density to find a particle in a gas at a given velocity is given by the equation

\[ f(v) = 4\pi \left( \frac{m}{2\pi k_B T} \right)^{3/2} v^2 \exp \left( -\frac{mv^2}{2k_B T} \right) \]

Maxwell-Boltzmann Molecular Speed Distribution for Noble Gases

![Graph showing the Maxwell-Boltzmann distribution for different noble gases at 25 °C](attachment:image.png)