From Mechanics to Applications

• Mechanics: behavior of systems of few bodies
  - Kinematics: motion vs time
    - Translational and rotational
  - Dynamics: Newton’s Laws
    - From forces and torques to accelerations
  - Conservation laws
    - Energy, momentum, angular momentum
Multi-Body Systems

- In real life, deal with collections of bodies
  - E.g. study behavior of matter
  - Microscopic description: atomic/molecular level
    - Apply mechanics at this level
    - Difficult to deal with analytically past 3-body states
  - Macroscopic description
    - Describe bulk properties of matter
    - Necessarily means averaging over individual atomic/molecular behavior
    - So basis is still in Newton’s mechanics, but observe collective phenomena
  - Already covered:
    - Statics and dynamics of fluids
    - Wave phenomena
  - Still to cover: internal energy and transformations
States of Matter

• Solid
  - Incompressible
    ➫ Atomic distances constant
  - Maintains shape (not fluid)

• Fluid: changes shape, can flow
  - Liquid
    ➫ Incompressible: const atomic distances
  - Gas
    ➫ Compressible: atomic distances can change
Macroscopic Quantities

• Define behavior of matter in bulk

  ▪ Average quantities:
    ▪ Density: average mass per unit volume
    ▪ Pressure: average force per unit surface area
    ▪ Flow rate: average volume flowing through the surface per unit time (so related to average velocity, etc.)
    ▪ Temperature: measure of internal energy
    ▪ Number density, molar number, molar mass: number of particles
Definitions

• Number Density
  \( n = \frac{N}{V} \text{ m}^{-3} \)
  Beware of symbols !!!
  - Number of molecules: large
    E.g. 6*10^{23} in 22 L of gas at STP
  - So number density is typically a large number
    3*10^{25} m^{-3} for a gas at STP

• More convenient: number of moles
  - Basic unit: \( N_A = 6.02 \times 10^{23} \) atoms/mole
    \( \nu = n = \frac{N}{N_A} \): number of moles
    Beware of symbols !!!
Atomic Number

- Chemical elements are identified by the number of electrons on the orbit
  - Or number of protons in the nucleus
    - Charge of the nucleus Z, location in periodic table

- Isotopes
  - Atoms of one chemical elements may have different nuclei
    - Differ by the number of protons N (again, beware of symbols)

- Atomic number
  - \( A = Z + N \)
  - Total number of nucleons (protons and neutrons) in the nucleus
Atomic Mass

- Mass of each atom is determined primarily by its atomic number

\[ m_p = 938.3 \text{ MeV}/c^2 = 1.673 \times 10^{-27} \text{ kg} \]
\[ m_n = 939.6 \text{ MeV}/c^2 = 1.765 \times 10^{-27} \text{ kg} \]
\[ m_e = 0.511 \text{ MeV}/c^2 = 9.109 \times 10^{-31} \text{ kg} \]

- Binding energy is relatively small: few MeV/nucleon

- So mass of the atom is roughly

\[ M = Z m_p + N m_n + Z m_e - E_{\text{bind}} \approx A m_p \]

- Standard definition:

\[ 1 \text{ a.u.} = m(^{12}\text{C})/12 = 1.661 \times 10^{-27} \text{ kg} \]

- So measure atomic mass A a.u.

\[ \text{Mass of the atom } m_0 = A \times 1.661 \times 10^{-27} \text{ kg} \]

\[ \text{Mass of one mole of the atoms } M = N_A m_0 = A \times 10^{-3} \text{ kg/mole} \]
Number of Moles Again

- So can relate number of moles and mass of the sample

\[ n = \frac{N}{N_A} = \frac{m}{M} \]
Three Kinds of Energy

• Kinetic energy
  □ Scalar quantity describing motion
    \[ K = \frac{1}{2}mv^2 \]

• Potential energy
  □ Scalar quantity describing potential to move (itself or other objects)
    \[ \text{Gravitational potential energy} \]

• Mass
  □ Einstein’s famous
    \[ E = mc^2 \]
    \[ \text{For example reaction } e^+ + e^- \rightarrow 2\gamma \text{ yields energetic photons} \]
Internal Energy

• In practice, classify energy into
  - Mechanical (potential+kinetic)
    - Motion of whole bodies
    - Collective (coherent) motion (waves)
  - Internal: total energy associated with individual atoms
    - Nuclear, chemical, mass energy
    - Kinetic energy of atoms: “thermal” energy

• Total energy is always conserved
  - Energy transformation
    - From mechanical to internal, and vice versa
Temperature

• Macroscopic description of internal energy
  ✑ Instead of adding up energies of individual atoms, assign a single quantity that describes the internal energy of atoms on average
    ✍ This quantity is temperature
    ✍ Formally, define $T \sim \langle K_{\text{atom}} \rangle$

• Informally, define temperature as a measure of being hot or cold, based on our experience
  ✑ Hot or cold on touch
  ✑ Effect of being hot or cold on other objects
    ✍ From latin *temperatura*: mixture
Zeros Law of Thermodynamics

Consider the top picture in the figure. We place a thermoscope (body T) in close contact with body A and the two objects are put inside a thick-walled insulated box. The reading of body T will eventually reach a constant value (137.04 in this example). We say that the two bodies are in thermal equilibrium. Every measurable parameter of body A and T is stable. In addition, the two bodies have the same temperature. Assume now that bodies T and B are placed in close contact as shown in the middle picture, and that the reading of T is still 137.04.

If we now place bodies A and B in close contact we find experimentally that they are at thermal equilibrium with each other. If bodies A and B are each in thermal equilibrium with body T, then A and B are in thermal equilibrium with each other. The statement above is known as the "zeroth law of thermodynamics"
The Galileo Thermometer

In the figure is shown a constant volume gas thermometer. It consists of a glass bulb containing a gas. The bulb is connected to a mercury manometer. The temperature $T$ of the bath surrounding the bulb is measured as follows: The mercury reservoir is raised or lowered so that the mercury level is at mark A. This insures that the volume of the gas is constant. The gas pressure $p$ is given by the equation: $p = p_o - \rho gh$. Here $\rho$ is the density of mercury and $h$ is the height difference between point A and the mercury surface in the open end of the manometer.

Define (calibrate) as a function of $p$
Scale where $T \sim p$ is the Kelvin scale
The Triple Point of Water

In this section we will define the temperature on the Kelvin scale. Then we calibrate a thermoscope and thus convert it into a thermometer. Although the temperature of a body does not have an upper limit, it does have a lower limit which we define it to be the zero of the Kelvin scale.

To set up a temperature scale we pick a reproducible thermal phenomenon and arbitrarily assign a Kelvin temperature to its environment. Examples are the freezing point and the boiling point of water at atmospheric pressure. It turns out that the triple point of water is easier to reproduce and is thus chosen to define the Kelvin scale. The triple point of water is defined as the coexistence of solid, liquid and gaseous forms of water at a certain temperature and pressure. The temperature at this point is taken to be

\[ T_3 = 273.16 \text{ K} \]
Temperature Scales

Lord Kelvin (W. Thomson) 1824-1907

Anders Celsius 1701-1744

Gabriel Fahrenheit 1686-1736
Temperature Scales

The Kelvin temperature scale is used in basic scientific work. For more practical everyday applications the Celsius scale is widely used. The Celsius degree has the same size as the Kelvin. The zero of the Celsius scale is shifted so that:

\[ T_C = T - 273.15 \degree \]

\( T_F = \frac{9}{5} T_C + 32 \degree \)

The Fahrenheit scale used in the US employs a smaller degree than the Celsius scale and a different zero: \( 0 \degree C = 32 \degree F \)

The relationship between the two temperature scales is given by the equation:

\[ T_F = \frac{9}{5} T_C + 32 \degree \]
## Temperature Scales

<table>
<thead>
<tr>
<th>Temperature</th>
<th>T(°C)</th>
<th>T(K)</th>
<th>T(°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute zero</td>
<td>-273</td>
<td>0</td>
<td>-460</td>
</tr>
<tr>
<td>Boiling point of LN2</td>
<td>-196</td>
<td>77</td>
<td>-321</td>
</tr>
<tr>
<td>Freezing point of H₂O</td>
<td>0</td>
<td>273</td>
<td>32</td>
</tr>
<tr>
<td>Room temperature</td>
<td>20</td>
<td>293</td>
<td>68</td>
</tr>
<tr>
<td>Normal human body</td>
<td>36.6</td>
<td>309.9</td>
<td>98.6</td>
</tr>
<tr>
<td>Boiling point of water</td>
<td>100</td>
<td>373</td>
<td>212</td>
</tr>
<tr>
<td>Melting point of Fe</td>
<td>1538</td>
<td>1811</td>
<td>2800</td>
</tr>
</tbody>
</table>
Thermal Expansion

\[ \Delta L = \alpha L \Delta T \]

**Linear expansion**

If the temperature of a metal rod of length \( L \) is increased by an amount \( \Delta T \), its length also increases by an amount \( \Delta L = \alpha L \Delta T \)

The term \( \alpha \) is known as the **coefficient of linear expansion** and it depends on the material of the rod.

The constant \( \alpha \) does not change very much with temperature. Thus for most practical purposes it can be taken as a constant.

**Volume Expansion.**

All three dimensions of a solid expand with temperature, and thus the volume also expands. For liquids this is the only meaningful expansion parameter. For a liquid of volume \( V \), an increase \( \Delta T \) in temperature results in an increase in volume \( \Delta V = \beta V \Delta T \)

The term \( \beta \) is known as the coefficient of volume expansion.

For a solid \( \beta = 3\alpha \)
# Coefficients of Expansion

## TABLE 18-2

<table>
<thead>
<tr>
<th>Substance</th>
<th>$\alpha \left(10^{-6} / \degree C\right)$</th>
<th>Substance</th>
<th>$\alpha \left(10^{-6} / \degree C\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice (at 0°C)</td>
<td>51</td>
<td>Steel</td>
<td>11</td>
</tr>
<tr>
<td>Lead</td>
<td>29</td>
<td>Glass (ordinary)</td>
<td>9</td>
</tr>
<tr>
<td>Aluminum</td>
<td>23</td>
<td>Glass (Pyrex)</td>
<td>3.2</td>
</tr>
<tr>
<td>Brass</td>
<td>19</td>
<td>Diamond</td>
<td>1.2</td>
</tr>
<tr>
<td>Copper</td>
<td>17</td>
<td>Invar$^b$</td>
<td>0.7</td>
</tr>
<tr>
<td>Concrete</td>
<td>12</td>
<td>Fused quartz</td>
<td>0.5</td>
</tr>
</tbody>
</table>

a) Room temperature values except for the listing for ice.
b) This alloy was designed to have a low coefficient of expansion. The word is a shortened form of “invariable.”
Water is Special

Maximum density = 1 g/cm\(^3\) at 3.98 °C (39.16 °F)

Density at 0 °C (water) = 0.999 g/cm\(^3\)

Density at 0 °C (ice) = 0.917 g/cm\(^3\)

Density at 10 °C = 0.9997 g/cm\(^3\)

Density at 20 °C = 0.9981 g/cm\(^3\)

Density slowly increasing as heat is removed

A - Abrupt decrease in density with freezing

E - Note break in density scale.

04/16/2007 YGK, Physics 8A
Heat and Work

• What needs to happen for the temperature of the object to increase?
  - Remember that temperature is a measure of average energy of the molecules:
    \[ T \sim \langle K \rangle \]
  - So if the temperature of the object increases, the total internal energy of the object increases
    \[ E_{\text{int}} = N(\langle K \rangle + \langle U \rangle) = CnT \] where \( n \) is the number of moles and \( C \) is some constant (to be defined later)

• Where does this energy come from?
  - Energy can be transferred to object by two means:
    - Thermal: heat from external sources (also includes any chemical or nuclear transformations)
    - Mechanical: work from external sources
1st Law of Thermodynamics

• Write energy conservation for a system
   “System”: a substance in question of finite mass that can undergo a thermal process
   As opposed to environment, which is usually considered to have infinite mass
    ✈ \( \Delta E_{\text{int}} = Q - W \)
    ✈ Here \( \Delta E_{\text{int}} \) is the change in internal energy, \( Q \) is the heat delivered to system, and \( W \) is the work done by the system
    » N.B. : this convention may be opposite to chemistry. I.e. by convention, physicists count the work done by system, e.g. a thermal engine. It is opposite to work done by the environment on the system (3rd Newton’s Law)
      ✈ \( W = - W_{\text{external}} \)

• It may be more obvious to rewrite this as
  ✈ \( E_{\text{final}} + W = E_{\text{initial}} + Q \)
2nd Law of Thermodynamics

• Conventional formulation (Kelvin):
  - Heat travels from hot objects to cold, but not in reverse
    - More on this later (next week)
    - But this is what you would expect
  - Define
    - $Q > 0$ when heat is delivered to system
    - $Q < 0$ when heat flows from system
Heat Capacity.
If an object whose initial temperature is $T_i$ absorbs an amount $Q$ of heat, its temperature increases to a value $T_f$ according to the equation:

$$Q = C\Delta T = C(T_f - T_i).$$

The proportionality constant $C$ is known as the object's "heat capacity".

Specific Heat.
The heat capacity $C$ of an object is proportional to its mass $m$.

Thus the equation above can be written as:  

$$Q = mc(T_f - T_i).$$

The constant $c$ is known as the "specific heat" and it depends on the material out of which the object is made.

Molar Specific Heat.
If we measure the heat capacity that corresponds to one mole of a substance, this is known as "molar specific heat". It is a convenient parameter because 1 mole of any substance contains the same number $(6.02 \times 10^{23})$ of atoms or molecules.
# Specific Heat

**TABLE 18-3**

Some Specific Heats and Molar Specific Heats at Room Temperature

<table>
<thead>
<tr>
<th>Substance</th>
<th>Specific Heat</th>
<th>Molar Specific Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cal</td>
<td>J</td>
</tr>
<tr>
<td><strong>Elemental Solids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>0.0305</td>
<td>128</td>
</tr>
<tr>
<td>Tungsten</td>
<td>0.0321</td>
<td>134</td>
</tr>
<tr>
<td>Silver</td>
<td>0.0564</td>
<td>236</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0923</td>
<td>386</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.215</td>
<td>900</td>
</tr>
<tr>
<td><strong>Other Solids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brass</td>
<td>0.092</td>
<td>380</td>
</tr>
<tr>
<td>Granite</td>
<td>0.19</td>
<td>790</td>
</tr>
<tr>
<td>Glass</td>
<td>0.20</td>
<td>840</td>
</tr>
<tr>
<td>Ice (− 10°C)</td>
<td>0.530</td>
<td>2220</td>
</tr>
<tr>
<td><strong>Liquids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mercury</td>
<td>0.033</td>
<td>140</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>0.58</td>
<td>2430</td>
</tr>
<tr>
<td>Seawater</td>
<td>0.93</td>
<td>3900</td>
</tr>
<tr>
<td>Water</td>
<td>1.00</td>
<td>4180</td>
</tr>
</tbody>
</table>
Heat of Transformation

- Need energy to change phase of the material (break chemical bonds)
  - Phase transformation (melting, boiling) happens at constant temperature
    - Define $Q = \pm L_m$.
    - Plus for vaporization/melting (energy added to matter)
    - Minus for condensation/fusion (energy released by matter)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Melting Point (K)</th>
<th>Heat of Fusion $L_f$ (kJ/kg)</th>
<th>Boiling Point (K)</th>
<th>Heat of Vaporization $L_v$ (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>14.0</td>
<td>58.0</td>
<td>20.3</td>
<td>455</td>
</tr>
<tr>
<td>Oxygen</td>
<td>54.8</td>
<td>13.9</td>
<td>90.2</td>
<td>213</td>
</tr>
<tr>
<td>Mercury</td>
<td>234</td>
<td>11.4</td>
<td>630</td>
<td>296</td>
</tr>
<tr>
<td>Water</td>
<td>273</td>
<td>333</td>
<td>373</td>
<td>2256</td>
</tr>
<tr>
<td>Lead</td>
<td>601</td>
<td>23.2</td>
<td>2017</td>
<td>858</td>
</tr>
<tr>
<td>Silver</td>
<td>1235</td>
<td>105</td>
<td>2323</td>
<td>2336</td>
</tr>
<tr>
<td>Copper</td>
<td>1356</td>
<td>207</td>
<td>2868</td>
<td>4730</td>
</tr>
</tbody>
</table>
Demo: Heat Capacity

**HEAT CAPACITY.**

Ball Race: Five different balls heated and placed on paraffin sheet.

A set of 5 balls (Lead, Glass, Zinc, Brass, Iron) are heated to 100°C in a boiling water bath, then released onto a sheet of paraffin wax. Iron melts through the paraffin first. Then brass. Zinc melts part way in. Lead and glass melt into the paraffin only a short distance.

<table>
<thead>
<tr>
<th></th>
<th>Lead</th>
<th>Glass</th>
<th>Zinc</th>
<th>Brass</th>
<th>Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass in grams</td>
<td>45</td>
<td>10</td>
<td>24</td>
<td>30</td>
<td>26</td>
</tr>
<tr>
<td>Thermal cap. (cal/gm°C)</td>
<td>.031</td>
<td>.160</td>
<td>.092</td>
<td>.092</td>
<td>.105</td>
</tr>
<tr>
<td>Heat to raise 1°C (cal)</td>
<td>1.39</td>
<td>1.60</td>
<td>2.20</td>
<td>2.76</td>
<td>2.94</td>
</tr>
</tbody>
</table>