Classical Physics

- at end of the 19th century:

  • Mechanics - Newton’s Laws
  • Electromagnetism - Maxwell’s Eqns
  • Optics - Geometric (particles) vs. Physical (waves)
  • Thermodynamics - Four Laws (0-3)
  • Gas Laws - Kinetic Theory

- overlaps often led to important discoveries:

  • Maxwell’s Eqns $\rightarrow$ EM radiation (optics)

  • Newton’s laws / kinetic theory $\rightarrow$
    microscopic/atomic description of macroscopic gas laws
- around 1900, Theoretical problems:

1) What is EM medium? → Relativity

2) Blackbody Radiation → Quantum Physics

- Experimental discoveries:

1895 X-rays
1896 Radioactivity
1897 The electron

Quantum Physics
Relativity
Atomic Physics
Nuclear Physics
Particle Physics

But first...
Heat and Thermodynamics

- study of Thermal Energy of systems

**Temperature:** a measure of thermal energy, units of **Kelvins**

Room Temp ~ 290 K

Temperature of an object is measured by the change in some physical property.

Measuring device is called a **thermometer**.
Zeroth Law of Thermodynamics

If bodies $A$ and $B$ are each in thermal equilibrium with a third body $T$, then they are in thermal equilibrium with each other.

Thermal equilibrium: all measurable properties unchanging.

Objects in thermal equilibrium are at the same temperature.
Temperature Scales

• Daniel Fahrenheit (1686-1736)
  0°F     = mixture of ice, water, salt
  100°F  = Human body temp (~98.6°F)

• Anders Celsius (1701-1744)
  0°C     = Freezing point of H₂O
  100°C   = Boiling point of H₂O

• Lord Kelvin (1824-1907)

  H₂O boil :          100°C = 212°F = 373 K
  H₂O freeze :        0°C = 32°F = 273 K
  Absolute zero :     -273°C = -460°F = 0 K

  T_C = T_K - 273.15

  T_F = (9/5)T_C + 32
**Constant-Volume Gas Thermometer**

- measure pressure of gas at fixed volume

![Diagram of constant-volume gas thermometer]

**Pressure** = Force/Area \( (N/m^2=Pa) \) (Pascals)

1 atm = \(1.01 \times 10^5\) Pa = 14.7 lb/in\(^2\) = 760 mm of Hg = 760 torr

\[ T \text{ P at fixed V} \]

![Graph showing pressure vs. temperature]
Ideal-Gas Temperature

\[ T_k = (\text{constant}) \times P \quad \text{at fixed } V \]

- Need one point:
  Triple point of H\(_2\)O
  (ice/water/steam coexist)

\[ T_3 = 273.16 \, \text{K} \]

- Problem: different gases give different \( T \)

But as mass of gas reduced (\( m \to 0 \)) and \( P_3 \to 0 \), they agree (approach “ideal” gas)
Temperature and Heat

If system $S$ and environment $E$ are at different temperatures:

Energy will transfer until their temperatures become equal.

The transferred energy is called **Heat** (symbol $Q$).

*If $T_E > T_S$, $Q > 0$*

Heat absorbed by $S$

*If $T_S > T_E$, $Q < 0$*

Heat lost by $S$
Defn: Require $\Delta Q = 1 \text{ calorie}$ to raise 1 gm of H$_2$O by $\Delta T = 1^\circ C$.

1 calorie = 4.186 joules
(heat is a form of energy)

**Specific Heat**

Amount of heat needed to raise the temperature of $m$ grams of a substance by $\Delta T$ is

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

$\Delta = \text{final} - \text{initial}$

where $c$ is the specific heat (cals/g·°C)

Specific heat of water = 1 cal/g·°C
= 4186 J/kg·K
Molar Specific Heat

Can specify amount of substance in moles:

\[ 1 \text{ mole} = 6.02 \times 10^{23} \text{ units} \]
\[ = N_A \text{ units (Avogadro's number)} \]

(1 mole of Al = 6.02 \times 10^{23} \text{ atoms}
1 mole of CO\textsubscript{2} = 6.02 \times 10^{23} \text{ molecules})

The mass of a substance (in grams) is

\[ m = n \times A \]

where \( n \) = (# moles) and
\( A \) is the atomic (molecular) weight of the substance.

1 mole of Carbon-12 has \( m = 12 \) grams.
### Some Examples:

<table>
<thead>
<tr>
<th>Element</th>
<th>Spec. Heat (J/kg·K)</th>
<th>A (g)</th>
<th>Mol. Sp. Ht. (J/Mole·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>128</td>
<td>207</td>
<td>26.5</td>
</tr>
<tr>
<td>Tungsten</td>
<td>134</td>
<td>184</td>
<td>24.8</td>
</tr>
<tr>
<td>Silver</td>
<td>236</td>
<td>108</td>
<td>25.5</td>
</tr>
<tr>
<td>Copper</td>
<td>386</td>
<td>63.5</td>
<td>24.5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>900</td>
<td>27</td>
<td>24.4</td>
</tr>
</tbody>
</table>

Note the relative consistency

\[
\Delta Q = m \cdot c \cdot \Delta T
\]

\[
\Delta Q = n \cdot C \cdot \Delta T
\]

\[
C = c \cdot \frac{m}{n} = c \cdot A
\]

\[
A(Pb) = 0.207 \text{ kg} = 207\text{g}
\]
Heats of Transformation

Heat may also change the phase (or state) of a substance (at constant T).

Matter exists in 3 common states:

• Solid

• Liquid

• Gas (or vapor)
Heating Curve

A - solid
B - solid/liquid
C - liquid
D - liquid gas
E - gas

Freezing
Melting
Condensation
Vaporization

Heat added

Image: http://library.thinkquest.org
Solid | Liquid | Gas

- melt -> boil
- freeze ← condense

"fusion" | "vaporization"

Requires energy | Releases energy

Amount of energy/unit mass is
Heat of transformation, \( L \).

e.g. for water:

**Heat of fusion**
\( L_F = 79.5 \text{ cal/g} = 333 \text{ kJ/kg} = 6.01 \text{ kJ/mole} \)

**Heat of vaporization**
\( L_V = 539 \text{ cal/g} = 2256 \text{ kJ/kg} = 40.7 \text{ kJ/mole} \)
Heat and Work

Consider this system:

Pressure = Force/Area \quad (P=F/A)

If piston moves \( ds \), then work done by the gas:

\[ dW = F \, ds = P \, A \, ds = P \, dV \]

Total work done by the gas in moving from \( V_i \) to \( V_f \):

\[ \int_{V_i}^{V_f} P \, dV \]
**P-V Diagrams**

Study effects of heat added/work done by plotting $P$ vs $V$ of gas:

The area under the curve is the work done.

The work done depends on the specific path from $i$ to $f$. 

---

**A**

---

**B**

---
Thermodynamic Cycles

If volume decreases, the work done (by the gas) is negative.

If we go from $i \rightarrow f$ and back to $i$, the net work done by the gas is the area inside the curve.
First Law of Thermodynamics

Heat $\Delta Q$ added to the system can have two effects:

• Increase the internal energy of the system
• Cause the gas to do work

Conservation of Energy says:

$$\Delta Q = \Delta U + \Delta W$$

where

$U$ is the internal energy of the system.

$\text{1$^{st}$ Law of Thermodynamics.}$
Energy Conservation: A Parable from Feynman

**Count** sugar cubes directly

Deduce number hidden in a box

Even dissolved in a pond

Count those that passed through a window

(named \( W \) or \( Q \))

That’s defining the system boundary!

Locality is assumed: cubes don’t just re-materialize outside the windows: must pass through the windows

Learned to calculate various forms of internal energy.

Can’t *derive* conservation of \( E \): must deduce that it’s plausible, learn to account for different forms of \( E \), and then measure that it works, with your chosen definitions and calculation methods.
State Functions

A property of the state of the system is often called a “State Function”.

P, V, and T are state functions. So is U (the internal energy).

Heat and Work are not. They are path-dependent, i.e. they depend on how we go from i to f.

However the combination \( \Delta Q - \Delta W = \Delta U \) does not depend on the path.
Various System Changes

Constant Volume (isochoric)

Constant Temp (isothermal)

Cyclical Process (returns to original state)
All previous cases are “quasi-static”:

Change occurs slow enough that thermal equilibrium can be considered true at all times.

A non-quasi-static process:

Adiabatic, free expansion:

\[ Q = 0 \quad \text{(adiabatic)} \]
\[ W = 0 \quad \text{(nothing to work against)} \]
\[ U = 0 \]
Heat Transfer Mechanisms

How does heat exchange occur?

• Conduction
• Convection
• Radiation
Conduction

• Occurs in systems where atoms stay in a fixed region.

• Heat energy causes them to move, rotate, and/or vibrate.

• Energy is transferred to adjacent atoms by interactions/collisions.

Energy moves, not the atoms
Heat conduction rate is

\[ P_{\text{cond}} = \frac{Q}{\Delta t} = A \frac{dT}{\Delta x} \]

- \( \frac{dT}{\Delta x} = (T_H - T_C)/\Delta x \)
  is the Temperature gradient.

- \( P_{\text{cond}} \) is the Energy transferred per time (SI units: Watts),
  sometimes called thermal current, I.

- \( \Delta \) is the Thermal Conductivity
  (SI units: Watts/m•K).
## Some Thermal Conductivities

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity (W/m•K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>428</td>
</tr>
<tr>
<td>Copper</td>
<td>402</td>
</tr>
<tr>
<td>Aluminum</td>
<td>235</td>
</tr>
<tr>
<td>Lead</td>
<td>35</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>14</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.18</td>
</tr>
<tr>
<td>Helium</td>
<td>0.15</td>
</tr>
<tr>
<td>Dry Air</td>
<td>0.026</td>
</tr>
<tr>
<td>Window Glass</td>
<td>1.0</td>
</tr>
<tr>
<td>White Pine</td>
<td>0.11</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>0.048</td>
</tr>
<tr>
<td>Polyurethane Foam</td>
<td>0.024</td>
</tr>
</tbody>
</table>
Using the notation $I$ for $P_{\text{cond}}$, we can write

$$\Delta T = I \Delta x / (kA)$$

or

$$\Delta T = I R$$

where $R = \Delta x / (kA)$ is the thermal resistance.

Note the analogy with Ohm’s Law for electricity.

Note: $R_{\text{fishbane}} = \Delta x / \kappa = R A$

$R_{\text{fishbane}}$ = insulation “R-value”
  = material and thickness only
  can’t change size of attic
  can add more, or better, insulation
Two or more conductors (or insulators) in series:

Steady state thermal current is same through both slabs

\[
\begin{align*}
T_H - T_I &= I \cdot R_1 \\
T_I - T_C &= I \cdot R_2
\end{align*}
\]

\[
T_H - T_C = I (R_1 + R_2) = I \cdot R_{\text{equiv}}
\]

where

\[
R_{\text{equiv}} = R_1 + R_2 + \ldots
\]

(like resistances in series)
Conductors in parallel:
(multiple paths for heat flow)

\[ T_H - T_C = \Delta T: \text{ same for all paths but current flows (I) are different.} \]

\[ I_{\text{total}} = I_1 + I_2 + \ldots \]
\[ = \Delta T/R_1 + \Delta T/R_2 + \ldots \]
\[ = \Delta T \left( 1/R_1 + 1/R_2 + \ldots \right) \]
\[ = \Delta T/R_{\text{equiv}} \]

with

\[ 1/R_{\text{equiv}} = 1/R_1 + 1/R_2 + \ldots \]

(like resistances in parallel)
Convection

• Occurs in fluid systems. The energy flows along with the medium.

• Fluid near heat source becomes hot, expands, and rises. Surrounding cooler fluid takes its place. Etc.
Radiation

Here the energy is carried by electromagnetic waves. Called Thermal Radiation.

The Rate at which an object radiates is given by the Stefan-Boltzmann Law:

\[ P_{\text{rad}} = \varepsilon \sigma A T^4 \]

where

- \( P_{\text{rad}} \): Power radiated in Watts
- \( A \): Area of emitter (or absorber!)
- \( T \): Temperature of emitter in K
- \( \sigma \): Universal constant (\( S\)-B's constant)
  \[ \sigma = 5.6703 \times 10^{-8} \text{ W/(m}^2\text{K}^4) \]
- \( \varepsilon \): the emissivity of the emitter
  (\( 0 < \varepsilon < 1 \), depending on the composition of the surface)
The rate an object absorbs thermal radiation is given by the same formula:

\[ P_{\text{abs}} = \varepsilon A (T_{\text{env}})^4 \]

except that now \( T_{\text{env}} \) is the temperature of the environment.

The emissivity \( \varepsilon \) of an object is the same for radiation and absorption.

- Lighter objects reflect more. (smaller \( \varepsilon \))
- Darker objects absorb more. (larger \( \varepsilon \))
  They also emit more.

A surface with \( \varepsilon = 1 \) is called a Blackbody radiator.