Chapter 2 Atoms and Heat

• Moving atoms
• Motion, heat, and energy
• Converting motion into heat
• Changing temperature
  – expansion & contraction
• Transferring heat and energy
Quandaries

• Why? How does kinetic energy turn into heat? What is heat? How did this lead to an explosion?

• How can two objects be the same temperature and yet one feels cooler? What mistaken assumption are we making?

• Pump heat from the cold outdoors? This sounds like nonsense.
Atoms

• The stuff around us is composed of about 100 kinds of atoms.
Air

• Air is composed of \( \text{N}_2 \) (80\%) and \( \text{O}_2 \) (20 \%)
• The molecules are only about \( 10^{-10} \) m across!
• The molecules move about randomly with typical speed 330 m/s at room temperature.
• At higher temperature the molecules move with a faster mean speed and bear more energy.
Speed of sound and light

- Sound travels ~ 330 m/s
  \[(330 \text{ m/s})(3.281 \text{ ft/m}) = 1080 \text{ ft/s} \sim 1100 \text{ ft/s}\]
- 100 yards in ~ 1/3 sec
- 1 mile in \((5280\text{ ft})/(1080\text{ ft/s})=4.88\text{ s} \sim 5\text{ s}\)
- How fast does light travel?
  - \(3 \times 10^8\text{ m/s}\)
- How long for light to travel a mile?
  - \((1610\text{ m/mi})/(3 \times 10^8\text{ m/s}) = 5.36 \times 10^{-6}\text{ s}\)
Energy in heat

• We can store energy in a container of gas by increasing the KE and mean speed of the individual molecules.

• Suppose all molecules were moving in the same direction?
Hiss and noise

- Electrons in a conducting wire behave like a hot gas of particles confined within the wire.
- Normal electronics operates with smooth electron flow. The random thermal velocity atop the desired velocity is responsible for noise in electronic systems.
Temperature

- For an (ideal) gas of noninteracting atoms, temperature is simply a measure of the kinetic energy of random motion.
Why does temperature matter?

Temperature is related to the energy of a macroscopic object.

- Energy shows up as random motion.
- Coldest temperature — zero motional (kinetic) energy!

<table>
<thead>
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<th>Fahrenheit</th>
<th>Celsius</th>
<th>Kelvin</th>
<th>comments</th>
</tr>
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<tr>
<td>212</td>
<td>100</td>
<td>373.15</td>
<td>water boils</td>
</tr>
<tr>
<td>32</td>
<td>0</td>
<td>273.15</td>
<td>water freezes</td>
</tr>
<tr>
<td>-300.42</td>
<td>-195.79</td>
<td>77.36</td>
<td>liquid nitrogen boils</td>
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<td>-452.11</td>
<td>-268.95</td>
<td>4.2</td>
<td>liquid helium boils</td>
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<tr>
<td>-459.67</td>
<td>-273.15</td>
<td>0</td>
<td>absolute zero</td>
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</tbody>
</table>
Temperature scales: F, C, K

• 100 deg C or K between freezing and melting points of water
• 100 deg F between freezing and melting points of another liquid
• $T_C = (T_F - 32)(5/9)$
• The coldest temperature is that at which the molecules of a gas have zero kinetic energy
• Absolute 0 = -273 C = 0 K
Temperature conversion

• If room temperature is about 70 F, what is its value in K?

70 F is about 25 C

32 F = 0 C = 273 K

70 F = 300 K
Motion into heat

- Columbia space shuttle tragedy
  - Broke apart on re-entry
  - Large kinetic energy turned into heat
  - Kinetic energy = \( \frac{1}{2}mv^2 \)
- Mach 1 = speed of sound
- Corresponds to room temperature (300K)
- Convert all to heat
  - \( T=300M^2 \)
Hydrogen escapes from atmosphere

• KE = (1/2) mv^2 so at the same temperature lighter molecules have higher speeds.
• It is possible to throw something so fast up that it never returns (escape speed)
• The hydrogen in our atmosphere escaped by virtue of its thermal speed while oxygen (16 times heavier) remains.
Thermal expansion

• Increased jiggling causes solids and liquids to generally expand upon heating and contract upon cooling.

• The reason is that it is easier to pull atoms apart from their equilibrium separation in condensed matter than to compress them.

• The amount is about $10^{-3} – 10^{-5}$ per degree C.
Thermal expansion force

- Consider the force it might take to compress a bar of steel by hand by 1%.
- This is more easily done by cooling it.
- Conversely if the bar is heated by few degrees while constrained in length, it will exert a huge force, equivalent to that required to mechanically compress it.
- Look out!
Global warming and sea level rise

- If the Earth mean temperature rises a few deg, the oceans will expand just a tiny amount, but enough to flood coastlines.
- Water thermal expansion $2 \times 10^{-4} / \text{deg C}$
- Average ocean depth : 12,000 ft
- Assume 2.5°C temp rise in global warming.
  - $2.5 \times (2 \times 10^{-4}/\text{deg C})(12,000\text{ft}) = 6\text{ft}$
Pressure, volume, and temperature

• Temperature
  – measure of internal energy

• Volume
  – space that gas takes up

• What is pressure?
  – Pressure = force / unit area
  – Molecules bounce against walls
  – Faster motion -> more force.

For an ‘ideal’ gas,
  PRESSURE x VOLUME proportional to TEMPERATURE
Example

• At constant temperature
  – PRESSURE proportional to $1/VOLUME$
  – VOLUME proportional to $1/PRESSURE$
Converting heat and motion

- Motion into heat
  - Space shuttle re-entry tragedy
- Heat into motion?
  - Cork launched by liquid nitrogen
  - What about continuous conversion of heat into motion?
  - Final state should be same as initial state
A simple steam engine

- pivot
- directional nozzle
- steam exhaust causes sphere to spin
- steam rises through tubes
- water vaporized in heated kettle

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More useful
Heat engines

• Thermal energy can be converted to mechanical work or electrical energy

• A hot gas is caused to push on a piston. The gas cools as it expands, the energy appearing in motion of the piston

• A clever cyclic process converts lumps of heat into mechanical motion
Laws of thermodynamics

• Two objects in contact are always found to reach the same temperature. This may be verified by putting each in contact with a gas thermometer.

• The objects share thermal energy via touching (and radiation) until in equilibrium.
Cyclic processes

Ideal Stirling Cycle
Processes 1-2 and 3-4 are isothermal: 
\( P V = m R T = \text{constant} \)
Cycle

Constant Volume, heating

Constant Temp

Constant Volume, cooling
Heat to electricity

- Sunpower EG-1000 demonstrated using sawdust pellets as the fuel
- Generates more than 1000W of electricity to a light panel.
Refrigerators, air conditioners, and heat pumps

• A refrigerator is the reverse of a heat engine. Mechanical work is done to move heat from a cold place to a warm place

• A heat pump refrigerates the outdoors to heat your house.
Refrigeration Cycle

The Refrigeration Cycle

Evaporator (Low Pressure) --|---|---|--|---|--
\[\text{Heat Source in}\] \[\text{Evaporator}\] \[\text{80}\%\] \[\text{Expansion Valve}\] \[\text{Heat Source out}\]

Condenser (High Pressure) --|---|---|--|---|--
\[\text{Compressor}\] \[\text{20}\%\] \[\text{Condenser}\]

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Heating Flow

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Heating Return
Wasted energy

• The conversion of heat to work is necessarily inefficient – some thermal energy always flows from a higher temperature source to a lower temperature heat sink
Heat pump
Refrigerator
Efficiency of heat engines and pumps

• The science of thermodynamics shows that transformations of heat are governed by universal laws.

• All thermal engines have a maximum ideal efficiency that depends only on the temperature of two heat baths, not on the mechanism of the engine.
Solid, liquid, gas, and plasma

- Matter exists in different forms at different temperatures (energy content)
- These forms differ in the amount of order known as entropy
- Changing from one form to the other requires energy, even if temperature does not change.
Laws of Thermodynamics

• 0th Law: objects in contact tend to reach the same temperature
• 1st Law: energy is conserved (if you consider all the forms, including heat)
• 2nd Law: you can’t extract heat energy without a temperature difference
• 3rd Law: nothing can reach the temperature of absolute zero
Heat flow

• How fast this happens depends on details!
• Thermal conduction
  – Copper : good thermal conduction