Today

• Announcements:
  – HW#5 is due by 8:00 am Wed. Feb. 25th.
  – Extra Credit Exam due by Tomorrow 8am.
• Work, Energy, Power loose ends
• Temperature
• Second Law of Thermodynamics
Energy and Power

- **Energy is the ability to do work**: Work = force x distance = F d
- Energy comes in two general forms
  - Kinetic (KE) – energy of motion
  - Potential (PE) – energy of position

- **Power** (measured in W = J/s) is the rate of change (or use) of energy

\[
KE = \frac{1}{2} mv^2
\]

m - mass
v - velocity
Some Forms of Energy

**Kinetic energy**: energy of motion

**Potential energy**: “stored” energy due to position

**Gravitational energy**: energy associated with a raised object

**Elastic energy**: energy of a stretched or deformed object

**Thermal energy**: energy in the form of heat due to the random microscopic motion of atoms and molecules
Forms of Energy

**Electromagnetic energy** – energy associated with electric and magnetic fields

**Radiant energy** – energy of electromagnetic waves such as light, infrared, and X-rays

**Chemical energy** – energy involved in chemical reactions

**Nuclear energy** – energy involved in nuclear reactions
The Law of Conservation of Energy

• The total energy of all the participants in any process remains unchanged throughout that process.

• That is, energy cannot be created or destroyed. Energy can be transformed (changed from one form to another), and it can be transferred (moved from one place to another), but the total amount always stays the same.

Holds true in ALL domains of Physics (relativity, quantum Mechanics, Newtonian motion, special relativity, String Theory,…)
Conservation of Energy

In nature certain quantities are “conserved”. Energy is one of these quantities. Charge is another.

Example: Ball on a hill

A 1.00 kg ball is rolled toward a hill with an initial speed of 5.00 m/s. If the ball roles without friction, how high, h, will the ball go?

\[ KE = \frac{1}{2}mv^2 \quad PE = mgh \quad g = 9.80 \frac{m}{s^2} \]

\[ \frac{1}{2}mv^2 = mgh \rightarrow h = \frac{v^2}{2g} = \frac{(5 \frac{m}{s})^2}{2 \cdot 9.80 \frac{m}{s^2}} = 1.28 \text{ m} \]
Time Travel

• Einstein's theory of General Relativity explains the origin of gravity by mass distorting space-time
• Time is a dimension in a 4-dimensional universe
• If time is a dimension like the other three, can we move back and forth in time? Why does time have a direction? Arrow of time
• If we can travel back in time, it would be possible for us to influence things so that we are not born.
• Three theories to resolve the paradox
  – Travel back in time is not possible
  – There are a very large number of parallel universes
  – Something about nature prevents us from influencing the past
What is Temperature?

Old definition:
Temperature is the thing measured by thermometers.

\[ ^\circ F = \left(\frac{9}{5}\right) ^\circ C + 32 \]
\[ K = ^\circ C + 273.1 \]
What is Temperature?

• Modern Idea: Temperature is a measure of the average kinetic energy of molecules – higher T more motion. This is called the Kinetic Theory of Gasses

• Actually, each molecule in a gas has a range of kinetic energies. Boltzmann Distribution

• Illustration: [http://celiah.usc.edu/collide/1/](http://celiah.usc.edu/collide/1/)

• Average kinetic energy of a gas molecule

\[
KE = \frac{1}{2}mv^2 \quad KE_{\text{average}} = \frac{3}{2}k_B T \quad k_B = 1.38 \times 10^{-23} \frac{J}{K}
\]
The distribution depends on temperature

$N_2$ molecules
Boltzmann Distribution – Different masses

All molecules have the same average kinetic energy.

Larger mass means less velocity.

Distribution of Noble gas speeds at 25 C.
Energy in air

What is the energy content in 22.4 l of air at room temperature?
DATA: $T_{\text{room}} = 300$ K

To make this simple, let's assume air is all $N_2$.

22.4 l is one mole or $6.022\times10^{23}$ atoms

\[
\text{Energy} = N \cdot \frac{3}{2} k_B T = 6.022 \times 10^{23} \cdot \frac{3}{2} \cdot 1.38 \times 10^{-23} \cdot 300
\]

\[
\text{Energy} = 3739. \, J
\]
Energy Flow Diagrams

We can represent the conservation of energy by a diagram:

Book sliding across the table

\[ \text{ChemE} \rightarrow \text{ThermE (body)} \rightarrow \text{KinE} \rightarrow \text{ThermE (table and book)} \]

A book falls off table and hits the floor

\[ \text{GravE} \rightarrow \text{KinE} \rightarrow \text{ThermE (air)} \rightarrow \text{ThermE (impact)} \]

\[ \text{chemE (food)} = \text{heat} + \frac{1}{2} \text{mv}^2 \]

\[ mgh = \text{heat} + \frac{1}{2} \text{mv}^2 \]

- 1 Calorie = 4184 Joule
- 1 Calorie = energy to raise the temp. of 1 kg of water by 1 degree Celsius
Energy Flow Diagram

Engine

Heat engine

Work output

ThermE input

ThermE exhaust

Hot Gas

Cold Gas

Refrigerator

Picture

Higher T

Lower T
What happens if you put a cold object in contact with a warm object?

The cold object warms up while the warm object cools off.
Second Law of Thermodynamics

Thermal energy ALWAYS flows from Hot to Cold, and NOT the other way around.

This is one way of stating the second law of thermodynamics:

*Thermal energy flows spontaneously from higher to lower temperature, but not from lower to higher temperature.*
Any device that turns thermal energy into work is called a heat engine.

One feature of a heat engine is that not all of the thermal energy is used to do work.

Just as with the hot exhaust coming out of a car’s tailpipe, some thermal energy is always exhausted.
Heat Engine Energy Flow

- Nature simply does NOT allow us to convert ALL the input thermal energy into work

\[
\text{efficiency} = \frac{\text{(work output)}}{\text{(thermal energy input)}}
\]
This leads to another way to state the second law of thermodynamics:

*Any cyclic process that uses thermal energy to do work must also have a thermal energy exhaust.*

*In other words, heat engines are always less than 100% efficient at using thermal energy to do work.*
Heat Engine used to produce work

**Maximum Efficiency**

\[
\text{efficiency} = \frac{T_{\text{hot}} - T_{\text{cold}}}{T_{\text{hot}}}
\]

- \(T\) must be measured in Kelvin.

In reality, efficiencies are even smaller due to friction etc.
Water is boiled and the steam used to turn a turbine which turns a generator.

The steam is cooled back to water and the cycle repeats.
The plant has an overall efficiency of 40%.

Example: Power Plant
Some Example Efficiencies

Note: previous formula is without friction or other losses.

**Table 7.1**

Heat engine efficiencies. Typical input and exhaust temperatures, best possible efficiencies, and actual efficiencies.

<table>
<thead>
<tr>
<th>Engine type</th>
<th>$T_{in}$ (°C)</th>
<th>$T_{ex}$ (°C)</th>
<th>Best possible</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline automobile/truck</td>
<td>400</td>
<td>25</td>
<td>55</td>
<td>10–15</td>
</tr>
<tr>
<td>Diesel auto/truck/locomotive</td>
<td>500</td>
<td>25</td>
<td>60</td>
<td>15–20</td>
</tr>
<tr>
<td>Steam locomotive</td>
<td>180</td>
<td>100</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Steam–electric power plants</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fossil fuel</td>
<td>550</td>
<td>40</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>Nuclear powered</td>
<td>350</td>
<td>40</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>Solar powered</td>
<td>225</td>
<td>40</td>
<td>40</td>
<td>30</td>
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<tr>
<td>Ocean-thermal</td>
<td>25</td>
<td>5</td>
<td>7</td>
<td>???</td>
</tr>
</tbody>
</table>

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Entropy

• Entropy is a measure of the number of ways a system can be arranged. We usually use the symbol S.
• Purists would say Entropy is not a measure of disorder! But this is an OK definition for this course.
• The unit is J/K  (joules/Kelvin)
• Formula: $S = k \ln(W)$, where $k=1.38\times10^{-23}$ J/K and $W$ is the number of possible states of a system.
• Alternative formula: $S = \text{heat/temperature}$
The Second Law of Thermodynamics

• Statement: No device can transform a given amount of heat completely into work.
• Modern way to say this: The entropy of an isolated system never decreases.
• Natural process tend to move toward a state of greater disorder.
• Consequence: Time appears to have a direction!
The Three Laws of Thermodynamics

Thermodynamics is the study of the inter-relation between heat, work and energy of a system.

The British scientist and author C.P. Snow had an excellent way of stating the three laws:

• 1st Law: Energy is conserved. You cannot win (that is, you cannot get something for nothing, because matter and energy are conserved).

• 2nd Law: You cannot break even (you cannot return to the same energy state, because there is always an increase in disorder; entropy always increases).

• 3rd Law: You cannot get out of the game (because absolute zero is unattainable).
Two examples

What is the entropy of a deck of cards that has one pair? Data: there are 1,098,240 ways to order such a deck.

\[ S = 1.38 \times 10^{-23} \text{ J/K} \quad \ln(1,098,240) = 1.92 \times 10^{-22} \text{ J/K} \]

How much is the entropy of a glass of water increased if 1.0 J of heat is added when the water is at 295 K. Assume the temperature rise of the water is small.

\[ S = \frac{1.0 \text{ J}}{295 \text{ K}} = 3.39 \times 10^{-3} \text{ J/K} \]
### Coin Tosses

- Suppose we have 10 coins: HHHHHHHHHHH

\[ S = k \ln(1) = 0 \]

<table>
<thead>
<tr>
<th>Heads</th>
<th>Number of ways</th>
<th>Entropy (J/K) $\times 10^{-23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>10</td>
<td>3.18</td>
</tr>
<tr>
<td>8</td>
<td>45</td>
<td>5.25</td>
</tr>
<tr>
<td>7</td>
<td>120</td>
<td>6.61</td>
</tr>
<tr>
<td>6</td>
<td>210</td>
<td>7.38</td>
</tr>
<tr>
<td>5</td>
<td>252</td>
<td>7.63</td>
</tr>
<tr>
<td>4</td>
<td>210</td>
<td>7.38</td>
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<td>3</td>
<td>120</td>
<td>6.61</td>
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<td>2</td>
<td>45</td>
<td>5.25</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>3.18</td>
</tr>
</tbody>
</table>
Why does time always move in one direction?

• The Universe was created with very low entropy. Much too low for its size. It is like the Universe started with all heads.

• Hence, everything in the Universe moves toward reaching the correct amount of entropy. It is very improbable to go the other way. In this case very means so improbably that it never happens.

• Time has a direction because going back in time would imply the entropy could be decreased. That is very improbable.

• The Universe tends toward increasing entropy.