Main points of today’s lecture:

Refrigerators:

coeff. of performance = \( \frac{Q_C}{W} \)

Reversible Refrigerator i.e. ideal or Carnot refrigerator

coeff. of performance = \( \frac{T_C}{T_h - T_C} \)

T is in Kelvin.

Entropy:

\( \Delta S = \frac{Q_{\text{reversible}}}{T} \)

Review:
Final Exam

- A common final exam time is scheduled for all sections of Physics 231
- Time: Wednesday December 14, from 8-10 pm.
- Location for section 002: BPS 1410 (our regular lecture room).
- This information can also be found on our course schedule page

- An alternate exam time will be scheduled for students who have conflicts with the regular time.
  - Two students have confirmed conflicts with me and will take the exam then.
  - You must contact me by email and obtain permission from me to take the exam at the alternate time. If you fail to do this, you will be barred from taking the alternate final exam.
  - RCPD students should arrange to take their final exam at Bessey.
- Alternate time: Tuesday December 13, from 1-3 pm
- Location: BPS 1410 (this room)
Heat pumps and refrigerators

• Heat engines can run in reverse
  – Send in energy
  – Energy is extracted from the cold reservoir
  – Energy is transferred to the hot reservoir

• This process means the heat engine is running as a heat pump
  – A refrigerator is a common type of heat pump
  – An air conditioner is another example of a heat pump
  – In the south, people often use heat pumps to heat homes

• A standard measure of the performance of a refrigerator is its “coefficient of performance”

  \[
  \text{coef. of performance} = \frac{Q_C}{W} \]

  heat removed per cycle

  work required to remove it
A Carnot refrigerator is a Carnot engine run in reverse

- A Carnot refrigerator maintains the food inside it at 276 K while the temperature of the kitchen is 298 K. The refrigerator removes $3.00 \times 10^4$ J of heat from the food. How much heat is delivered to the kitchen?

As a Carnot heat engine, we know that

$$e_{\text{carnot}} = 1 - \frac{Q_c}{Q_h} = 1 - \frac{T_c}{T_h} \Rightarrow \frac{Q_c}{Q_h} = \frac{T_c}{T_h}$$

The Carnot engine run in reverse takes mechanical energy $W$ to move $Q_c$ from the inside of the refrigerator and deposit $Q_h$ in the kitchen.

$$\frac{Q_c}{Q_h} = \frac{T_c}{T_h} \Rightarrow Q_h = Q_c \frac{T_h}{T_c} = 3 \times 10^4 \text{J} \frac{298}{276} = 3.23 \times 10^4 \text{J}$$

Note:

Carnot coefficient of performance $= \frac{Q_c}{W} = \frac{Q_h - Q_c}{T_h - T_c} = \frac{T_C}{T_h - T_C}$
Checking Understanding: Increasing Efficiency of a Heat Pump

Which of the following changes would allow your refrigerator to use less energy to run? (1) Increasing the temperature inside the refrigerator; (2) increasing the temperature of the kitchen; (3) decreasing the temperature inside the refrigerator; (4) decreasing the temperature of the kitchen.

A. All of the above
B. 1 and 4
C. 2 and 3

Assume the temperature dependence is similar to that of a Carnot refrigerator, where

$$\frac{Q_h}{Q_c} = \frac{T_h}{T_c}$$

Carnot Coefficient of performance $$= \frac{T_c}{T_h - T_c} = \frac{0.5}{3}$$

This is largest when $$T_h$$ and $$T_c$$ are closer to each other in temperature.
Heat pump example

- In warmer climates, it is now common to heat a room with a heat pump. It is essentially an air conditioner, which cools the outside air and deposits heat $Q_h = Q_c + W_{in}$ inside your room. If your heat pump has a coefficient of performance that is 80% that of a reversible heat pump, how much power would be required to supply 1 kW of heat power to your room when the inside temperature is 25°C and the outside is 15°C.

$$\text{Coeff. of Perf.} = \frac{Q_c}{W_{in}}$$

$$= 0.8 \frac{T_c}{T_h - T_c} = 0.8 \frac{273 + 15}{25 - 15} = 22.8$$

$$\Rightarrow Q_c = 22.8 W_{in}$$

$$Q_h = Q_c + W_{in} = 22.8 W_{in} + W_{in} = 23.8 W_{in}$$

$$Q_h = 1 kW \Delta t = 23.8 W_{in} = 23.8 P \Delta t$$

$$\Rightarrow 1 kW \Delta t = 23.8 P \Delta t$$

$$P = \frac{1 kW}{23.8} = 42 W$$
• Entropy can only be calculated from a reversible path, and must be done that way even if the system actually follows an irreversible path
  – To calculate the entropy for an irreversible process, model it as a reversible process
• When heat energy is absorbed, \( Q \) is positive and entropy increases
• When heat energy is expelled, \( Q \) is negative and entropy decreases
• In an adiabatic process \( Q=0 \) and entropy remains the same.
• \( S \propto \ln(\text{probability}) \).
• A disordered state with energy and matter spread out everywhere is more probable than having all of the energy stored in an organized way that can be used to do work.
Example

- The surface of the Sun is approximately at 5700 K, and the temperature of Earth’s surface is approximately 290 K. What entropy change occurs when 1000 J of energy is transferred by heat from the Sun to Earth?

The sun loses Q of heat and therefore decreases its entropy by the amount

\[ \Delta S_{\text{sun}} = \frac{-Q}{T_{\text{sun}}} \]

The earth gains Q of heat and therefore increases its entropy by the amount

\[ \Delta S_{\text{earth}} = \frac{Q}{T_{\text{earth}}} \]

The total entropy change is:

\[ \Delta S = \Delta S_{\text{sun}} + \Delta S_{\text{earth}} = Q \left( \frac{1}{T_{\text{earth}}} - \frac{1}{T_{\text{sun}}} \right) = 1000 \text{ J} \left( \frac{1}{290 \text{ K}} - \frac{1}{5700 \text{ K}} \right) = 3.27 \text{ J/K} \]

Note that the entropy change is always positive when you transfer Q from a hot object to a cold one. The total change in Entropy is never negative. Heat does not naturally flow from a cold object to a hot one.
Example

- What is the change in entropy of 1.00 kg of liquid water at 100°C as it changes to steam at 100°C?

\[
\Delta S = \frac{Q}{T} = \frac{L_{\text{vap}} m}{T} = \frac{(22.6 \times 10^5 \text{ J/kg})(1 \text{ kg})}{373 \text{ K}} = 6 \times 10^3 \text{ J/K}
\]
Entropy

Higher entropy states are more likely. Systems naturally evolve to states of higher entropy.
## Second Law of Thermodynamics

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Related Statement of the Second Law</th>
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<tbody>
<tr>
<td>Heat energy spontaneously flows from hot to cold.</td>
<td>When two systems at different temperatures interact, heat energy is transferred spontaneously from the hotter to the colder system, never from the colder to the hotter.</td>
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<tr>
<td>Entropy considerations limit the possible efficiency of a heat engine.</td>
<td>It is not possible to make a heat engine that converts thermal energy into an equivalent amount of work.</td>
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<tr>
<td>It takes energy to move heat from a cold object to a warm object.</td>
<td>It is not possible to make a heat pump that moves heat from a cold object to a hot object without an external energy input.</td>
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<td>The entropy of an isolated system will never spontaneously decrease.</td>
<td>The time direction in which the entropy of an isolated system increases is “the future.”</td>
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Example

• A power plant has been proposed that would make use of the temperature gradient in the ocean. The system is to operate between 20.0°C (surface-water temperature) and 5.00°C (water temperature at a depth of about 1 km). (1) What is the maximum efficiency of such a system? (2) If the useful power output of the plant is 75.0 MW, how much energy is absorbed per hour? (3) In view of your answer to (1), do you think such a system is worthwhile (considering that there is no charge for fuel)?

• Answers for 1 and 2:
  – a) 0.025, 3.2x10^6 J
  – b) 0.51, 5.3x10^{12} J
  – c) 0.25, 3.2x10^7 J
  – d) 0.51, 5.3x10^{13} J

  \[ e_{\text{max}} = e_{\text{carnot}} = 1 - \frac{T_c}{T_h} = 1 - \frac{278}{293} = 0.051 \]

  \[ e = \frac{W}{Q_h} \Rightarrow Q_h = \frac{W}{e} = \frac{(75\text{MW})(3600\text{s})}{0.051} = 5.3\times10^{12}\text{ J} \]

  c) What is the energy required to pump the water?
Keahole sits at a point where underwater land slopes sharply down into the sea, it was a place where warm water can be piped from the surface of the sea and cold water can be piped from depths of about a half-mile.

A process called ocean thermal energy conversion, or OTEC, used the temperature difference between hot and cold sea water to produce 50 KW of electricity at Keahole in 1993. The process worked but it was uneconomical.

KAILUA, HAWAI'I — Koyo USA Corp., a company selling deep-sea water from Keahole Hawai'i, is expanding its plant and has applied to sell the water in the United States.

The company is producing more than 200,000 bottles a day and says it can't keep up with demand in Japan, where it sells 1.5 liter bottles of its MaHaLo brand for $4 to $6 each.
A rocket, undertook uniform acceleration from rest, experiences a displacement of 850 m in 3.7 s. What is its acceleration? (in m/s^2)

1. A 52.78  B 70.20  C 93.37
   D 124.18  E 165.16  F 219.66
   G 292.15  H 388.55

A rocket, starting from rest, undergoes a uniform acceleration of 52 m/s^2 for distance of 900 m. What is its final velocity?

\[ v^2 - v_0^2 = 2a\Delta x \]
\[ v_0 = 0. \]
\[ v = \sqrt{2a\Delta x} \]
\[ v = \sqrt{2 \cdot 52 \cdot 900} \text{ m/s} \]
\[ v = 305 \text{ m/s} \]
Exam 1 problem 3

• Concepts/equations:
  
  \[ g = 9.8 \text{ m/s}^2 \text{ downwards} \]

  \[ v_y = v_{y0} - gt \]

  \[ \Delta y \equiv y - y_0 = \frac{1}{2} (v_y + v_{y0})t \]

  \[ \Delta y = v_{y0}t - \frac{1}{2} gt^2 \]

  \[ v_y^2 - v_{y0}^2 = -2g\Delta y \]

  \[ v_x = v_{x0} \]

  \[ \Delta x = v_{x0}t \]

• Examples of alternate formulations

  – Give drop distance and ask for speed.

  – Give drop distance and ask for horizontal displacement

\[ 4 \text{ pt} \]

A pitcher throws a ball horizontally with a speed of 41 m/s to a catcher 17.7 m away. When the ball is caught its height has decreased by: \( \text{(in m)} \)

\[ \Delta = 0.3 \text{ m} \]

A pitcher throws a ball horizontally to a catcher 17.7 m away. When the ball is caught, its height has decreased by 0.3 m. What is the initial speed of the ball?

\[ g = 9.8 \text{ m/s}^2 \text{ downwards} \]

\[ \Delta y = -\frac{1}{2} gt^2 = -0.3 \text{ m} \]

\[ t = \sqrt{\frac{2\Delta y}{g}} = 0.25 \text{ s} \]

\[ \Delta x = v_{x0}t \]

\[ v_{x0} = \frac{\Delta x}{t} = \frac{17.7 \text{ m}}{0.25 \text{ s}} = 71.5 \text{ m/s} \]