Physics 111
Lecture 37 (Walker: 18.7)

Refrigerators & Heat Pumps
Final Review

December 14, 2009

- Review Session: Today, 3:10-4:00, TH231.
  (Limited seating.)
- Final exam, Wednesday Dec. 16, 10:45-1:15.

The Physics 111 Final Exam

- On Wednesday, Dec. 16, 10:45-1:15 we have the Final Exam, covering Chapters 1-11 and 13-18 of Walker. It will be similar in format to the midterms, with 60 pts of multiple choice questions and 140 pts of free-response questions. Closed book; calculators needed.
- Sections not covered: 8-5, 9-6 details, 9-8, 11-8, 11-9, 13-6, 14-3, 14-9, 15-9 surface tension, 17-3, 18-3, 18-4, 18-9, 18-10.
- All three equation sheets provided on the Final
- Suggestions: Work in symbols as long as possible; include units in answers.

Refrigerators, Air Conditioners, & Heat Pumps

While heat will flow spontaneously only from a higher temperature to a lower one, it can be made to flow the other way if work is done on the system. Refrigerators, air conditioners, and heat pumps all use work from motors to transfer heat from a cold region to a warmer region.

Refrigerators, Air Conditioners...

These appliances can be thought of as heat engines operating in reverse.

By adding energy as work, heat can be extracted from the cold reservoir and exhausted to the hot reservoir.

Note that $Q_H = Q_L + W$; more heat is exhausted to the kitchen than is removed from inside the refrigerator.
Refrigerators

Work Required by Refrigerator

Minimum amount of work $W$ needed to remove heat $Q_L$ set by entropy balance.

A reversible refrigerator has an output entropy $\Delta S_H = Q_H/T_H$ equal to the input entropy $\Delta S_L = Q_L/T_L$.

Thus $Q_H = Q_L(T_H/T_L)$. Also, $Q_H = Q_L + W$. Solving gives

$$W = Q_L[(T_H/T_L)-1]$$

The higher $T_H$ & the lower $T_L$, the more work required.

Refrigerators, Air Conditioners, & Heat Pumps

An air conditioner is essentially identical to a refrigerator; cold reservoir is the interior of house, hot reservoir is outdoors. Exhausting an air conditioner within the house will result in the house becoming warmer, just as keeping the refrigerator door open will result in the kitchen becoming warmer.

Refrigerators, Air Conditioners, & Heat Pumps

Finally, a heat pump is the same as an air conditioner, except with the reservoirs reversed. Heat is removed from the cold reservoir outside, and exhausted into the house, keeping it warm. Note that the work the pump does actually contributes to the desired result (a warmer house) in this case.
Entropy of Universe

- The total entropy of the universe is unchanged whenever a reversible process occurs.
- The total entropy of the universe increases whenever an irreversible process occurs.
  - Conversion of mechanical energy to heat by friction, viscosity, air drag
  - Heat flow across a temperature difference

Since all real processes are irreversible, the entropy of the universe continually increases. If entropy decreases in a system due to heat being taken out of it, an equal or greater increase in entropy occurs outside the system.

Summary of Chapter 14

A * next to an equation means it will not be tested on the final exam.

- A wave is a propagating disturbance.
- Transverse wave: disturbance is at right angles to propagation direction
- Longitudinal wave: disturbance is along propagation direction
- Wave speed: \( v = \lambda f \)
- Speed of a wave on a string: \( v = \sqrt{\frac{F}{m/L}} \)

Summary of Chapter 14

- If the end of a string is fixed, an incoming wave is inverted upon reflection.
- If the end is free to move transversely, the wave is not inverted upon reflection.
- A sound wave is a longitudinal wave of compressions and rarefactions in a material.
- High-pitched sounds have high frequencies; low-pitched sounds have low frequencies.
- Human hearing ranges from 20 Hz to 20,000 Hz.

Summary of Chapter 14

- Intensity of sound: (Unit: W/m²)
  \( I = \frac{P}{A} \)
- Intensity a distance \( r \) from a point source of sound:
  \( I = \frac{P}{4\pi r^2} \)

When the intensity of a sound increases by a factor of 10, it sounds twice as loud to us.

Intensity level*, measured in decibels:

\[ \beta = 10 \log \left( \frac{I}{I_0} \right) \]
### Summary of Chapter 14

- **Doppler effect**: change in frequency due to relative motion of sound source and receiver.
- **General case** (both source and receiver moving):
  \[ f' = \frac{1 \pm u_0/v}{1 \mp u_a/v} f \]
  
  Top signs used when source & observer approaching:
  - When two or more waves occupy the same location at the same time, their displacements add at each point.
  - If they add to give a larger amplitude, interference is constructive.
  - If they add to give a smaller amplitude, interference is destructive.

- **Standing waves on string; resonant frequencies**:
  \[ f_n = n f_1 = n (v/2L) \quad n = 1, 2, 3, \ldots \]
  \[ \lambda_n = \lambda_1/n = 2L/n \]

- **Standing waves in a half-closed column of air**:
  \[ f_n = n f_1 = n (v/4L) \quad n = 1, 3, 5, \ldots \]
  \[ \lambda_n = \lambda_1/n = 4L/n \]

- **Standing waves in a fully open column of air**:
  \[ f_n = n f_1 = n (v/2L) \]
  \[ \lambda_n = \lambda_1/n = 2L/n \]

### Summary of Chapter 14

- An interference pattern consists of constructive and destructive interference areas.
- Two sources are in phase if their crests are emitted at the same time. Two sources are out of phase if the crest of one is emitted at the same time as the trough of the other.
- Interference of waves arriving at a point from two sources (in phase) depends on path length difference \( \Delta L \):
  \- \( \Delta L \) an integral number of wavelengths -- constructive interference
  \- \( \Delta L \) an odd number of half-wavelengths -- destructive interference.

### Summary of Chapter 16

- **Heat** (Q) is the energy transferred between objects due to a temperature difference.
- Objects are in thermal contact if heat can flow between them.
- Objects that are in thermal contact without any flow of heat are in thermal equilibrium.
- Thermodynamics is the study of physical processes that involve heat.
- If objects A and B are both in thermal equilibrium with C, they are in thermal equilibrium with each other.
Summary of Chapter 16

• Temperature determines whether two objects will be in thermal equilibrium.

• Celsius scale: water freezes at 0° C, boils at 100° C

• Fahrenheit: water freezes at 32° F, boils at 212° F (nothing about Fahrenheit on final)

• The lowest attainable temperature is absolute zero. \( T = 0 \) K

• Kelvin scale: absolute zero is 0 K; water freezes at 273.15 K and boils at 373.15 K

Summary of Chapter 16

• Temperature scale conversions:

\[
T_F = \frac{9}{5} T_C + 32 \quad * \\
T_C = \frac{5}{9}(T_F - 32) \quad * \\
T = T_C + 273.15
\]

• Most substances expand when heated.

• Linear expansion: \( \Delta L = \alpha L_0 \Delta T \)

• Volume expansion: \( \Delta V = \beta V_0 \Delta T \)

• Water contracts when heated from 0° C to 4° C.

Summary of Chapter 16

• Heat is a form of energy; SI unit Joule (J)

• Heat capacity of an object:

(Unit: J/K or J/°C)

\[
C = \frac{Q}{\Delta T}
\]

• Specific heat is heat capacity per unit mass:

(Unit J/kg-K or J/kg-°C)

\[
c = \frac{C}{m}
\]

• Energy is conserved in heat flow.

Summary of Chapter 16

• Conduction: heat exchange from hotter part of material to cooler part, with no bulk motion of material.

• Heat \( Q \) conducted through length \( L \) of material of cross-section area \( A \) and thermal conductivity \( k \) in time \( t \) if temperature difference is \( \Delta T \):

\[
Q = kA \left( \frac{\Delta T}{L} \right) t
\]

• Convection: heat exchange due to the bulk motion of an unevenly heated fluid.

• Radiation: heat exchange due to electromagnetic radiation.
Summary of Chapter 16

- Radiated power as a function of temperature:
  \[ P = e \sigma A T^4 \]
- Stefan-Boltzmann constant:
  \[ \sigma = 5.67 \times 10^{-8} \text{ W/(m}^2\cdot\text{K}^4) \]
- Net radiated power with surroundings at temperature \( T_s \):
  \[ P_{\text{net}} = e \sigma A (T^4 - T_s^4) \]

Summary of Chapter 17

- An ideal gas is one in which interactions between molecules are ignored.
- Equation of state for an ideal gas:
  \[ PV = NkT \]
- Boltzmann’s constant:
  \[ k = 1.38 \times 10^{-23} \text{ J/K} \]
- Universal gas constant:
  \[ R = 8.31 \text{ J/(mol} \cdot \text{K}) \]
- Equation of state again:
  \[ PV = nRT \]
- Number of molecules in a mole is Avogadro’s number:
  \[ N_A = 6.022 \times 10^{23} \]
Summary of Chapter 17
• Most common phases of matter: solid, liquid, gas
• When phases are in equilibrium, the number of molecules in each is constant
• Evaporation occurs when molecules in liquid move fast enough to escape into gas phase
• Latent heat: amount of heat required to transform mass m from one phase to another
  \[ Q = mL \]
• Latent heat of fusion \( L_F \): melting or freezing

Summary of Chapter 17
• Latent heat of vaporization \( L_V \): vaporizing or condensing
• Latent heat of sublimation: sublimation or condensation directly between gas and solid phases
• When heat is exchanged within a system isolated from its surroundings, the energy of the system is conserved. Heat lost from one part of system is gained by another part.

Summary of Chapter 18
• When two objects have the same temperature, they are in thermal equilibrium.
• The First Law of Thermodynamics is a statement of energy conservation that includes heat.
  \[ \Delta U = Q_{in} - W_{by} \]
• The internal energy (U) of a system depends on its temperature, pressure, volume, and phase.
• Internal kinetic energy of a material is proportional to its (Kelvin) temperature.
• Internal potential energy depends on the phase, volume, and pressure.

Summary of Chapter 18
• Entropy (S) is a measure of disorder. Units: J/K
• Change of entropy during a reversible heat exchange:
  \[ \Delta S = \frac{Q_{in}}{T} \]
• Second Law of Thermodynamics: \( \Delta S_{universe} \geq 0 \)
  • Total entropy of the universe increases when an irreversible process occurs; total entropy is unchanged after an ideal reversible process.
  • Heat flows spontaneously from a hot object to a cold one, but not the reverse.
  • A given amount of heat cannot be changed entirely to work.
• Natural processes tend to increase entropy of universe.
Summary of Chapter 18

• A heat engine converts heat into work.
• Efficiency of a heat engine:

\[ e = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h} \]

Summary of Chapter 18

• A reversible engine has the maximum possible efficiency,

\[ e_{\text{max}} = 1 - \frac{T_c}{T_h} \]

• The maximum possible work:

\[ W_{\text{max}} = e_{\text{max}} Q_h = \left(1 - \frac{T_c}{T_h}\right) Q_h \]

• Refrigerators, air conditioners, and heat pumps use work to transfer heat from a cold region to a hot region. Heat exhausted to the hot region is always more than heat removed from cold region.

End of Lecture 37

• Final exam: Wednesday, Dec. 16, 10:45-1:15.
• Review Session: Today, 3:10-4:00, TH231.
• Homework 18a (last one !) due at 11:00 p.m. tonight.