#### Physics 121, April 24. Heat and the First Law of Thermodynamics.



Frank L. H. Wolfs

Physics 121. April 24, 2008.

- Course Information
- Topics to be discussed today:
  - Heat
  - First law of thermodynamics
  - Second law of thermodynamics
- Quiz

### Physics 121. April 24, 2008.

- Homework set # 10 is now available and is due on Wednesday evening, April 30, at 11.30 pm.
- Exam # 3 will be returned in workshop, starting today. Note: grading of the exams will not be completed until Sunday and exam grades will be distributed via email on Monday.
- On Monday I will also distribute information about the score you need to obtain on the final exam to get a C-, a B-, and an A- in this course.
- The final exam will be held on Thursday May 8 between 4 pm and 7 pm in Hubbell. The final exam will cover all the material discussed in the course; there will be NO particular focus on thermodynamics.

#### Physics 121. Homework Set 10.

#### Frank Wolfs Homework Set 10

1. (10 pts) library/type39/prob05.pg

2. (10 pts) library/type39/prob06.pg

3. (10 pts) library/type40/prob04.pg

4187  $\frac{J}{k_{P}C}$  and  $c_{lead} = 128 \frac{J}{k_{P}C}$ .

#### Physics 121, Spring 2008 Due date: 04/30/2008 at 11:30pm EDT

This assignment will be counted toward your final grade. You can attempt each problem 50 times; once you exceed this number of attempts, your solutions will not be recorded anymore. You may need to give 4 or 5 significant digits for some (floating point) numerical answers in order to have them accepted by the computer. Note: to use scientific notion, use a notion like xxE+yy. It is important that you use a capital E; answers with a lower case e will be evaluated differently

# Heat and Temperature

#### Thermal Expansion

#### **Ideal Gas Law**

#### 

long, at what constant rate must the temperature of the rod be changed if the source is to move at a constant speed of 30 *nm/s*? **4. (10 pts) library/type40/prob07.pg** An automobile tire is filled to a gauge pressure of 158 *kPa* when its temperature is 19 *C*. (Recall that gauge pressure is the difference between the actual pressure and atmospheric pressure.) After the car has been driven at high speeds, the tire temperature has increased to 55 *C*. Assuming that the volume of the tire has not changed, find the gauge pressure of the air in the tire (assuming air is an ideal gas).

2 kg of lead shot at 91.3 C are poured into 2 kg of water at

20.5 C. Find the final temperature of the mixture. Use  $c_{water} =$ 

0.120 kg of water at 90.0 C is poured into an insulated cup con-

taining 0.216 kg of ice initially at 0 C. How many kg of liq-

uid will there be when the system reaches thermal equilibrium?

In a certain experiment, it is necessary to be able to move a small

radioactive source at selected, extremely slow speeds. This is

accomplished by fastening the source to one end of an alu-

minum rod and heating the central section of the rod in a con-

trolled way. If the effective heated section of the rod is 5.0 cm

Now, calculate the gauge pressure if the tire expands such that the volume increases by 10 percent.

#### 5. (10 pts) library/type40/prob17.pg

At 20 *C* an iron bar is 3.0000 *m* long and a brass bar is 2.9945 *m*. Find the temperature at which they will be the same length. Data:  $\alpha_{Iron} = 12 \times 10^{-6} C^{-1}$ ,  $\alpha_{Brass} = 19 \times 10^{-6} C^{-1}$  (at 20 *C*).

#### 6. (10 pts) library/type41/prob02.pg

A physicist, upon awaking one morning to find his stove out of order, decides to boil the water for his wife's coffee by shaking it in a thermos flask. Suppose that he uses  $540 \text{ cm}^{-3}$  of tap water at 64 F, that the water falls 1.25 ft each shake, and that the physicist completes 33 shakes each minute. Neglecting any loss of thermal energy by the flask, how long must he shake the flask before the water boils?

#### 7. (10 pts) library/type41/prob07.pg

A lead ball, with an initial temperature of 25 *C* is released from a height of 113.0 *m*. It does not bounce when it hits a hard surface. Assume all the energy of the fall goes into heating the lead. Find the temperature of the ball after it hits. Data:  $c_{lead} = 128 \frac{J}{k_{\rm g}C}$ .

#### 8. (10 pts) library/type42/prob02.pg

A cylinder made of yellow brass  $(k = 220 \frac{W}{mC})$  supports a hot reservoir maintained at a temperature of 57 *C* and rests on a cold reservoir maintained at a temperature of 19 *C*. The cylinder has a radius of 0.96 *cm*, and is 24.00 *cm* long. What is the rate of heat flow through the cylinder?



A method to reduce heat flow: Two shorter cylinders with radii of 0.96 cm and a combined length of 24.00 cm are used. The upper cylinder is made of silver ( $k = 427 \frac{W}{mC}$ , length = 13.00 cm). The lower cylinder's composition is unknown. The temperature where the two cylinders are in thermal contact is 53.68 C. What is the rate of heat flow through the combined cylinders?

# Hot

Find the thermal conductivity of the unknown substance.

#### 9. (10 pts) library/type42/prob03.pg

When a system is taken from state *i* to state *f* along the path *iaf* as shown in the figure, it is found that  $Q_{iaf} = 38.1 cal$  and  $W_{iaf} = 17.8 cal$ . Along the path *ibf*,  $Q_{ibf} = 26.5 cal$ . What is  $W_{ibf}$ , the work done by the system along the path *ibf*?



# First Law of Thermodynamics

# Kinetic Theory of Gases.

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### Physics 121. Post-Test - Tuesday 4/29 at 8.45 am.

- The post-test is scheduled for Tuesday morning, 8.45 am in Hoyt (**not** Hubbell).
- The post-test, in comparison to your pre-test, will provide me with important information about your progress in Physics 121. It is a required component of the course.
- Although this test does not count towards your final grade, I will use it to confirm my final grade assignment (especially in border-line cases).
- You will receive an email from me showing a comparison between your pre-test and your post-test, indicating how much you have learned.

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#### Heat and thermal equilibrium.

- When two objects are brought in thermal contact they can achieve thermal equilibrium via the exchange of heat.
- The exchange of heat will continue until the two objects have the same temperature.
- Energy can also be exchanged if work is done.



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#### Heat.

- We commonly use Q to indicate the amount of heat transferred.
- Since heat is a form of energy, its unit is the Joule.
- Another commonly used unit for heat is the calorie. One calorie is defined as the mount of heat required to raise the temperature of 1 g of water from 14.5°C to 15.5°C. 1 cal = 4.186 J.

#### Transfer of heat.

- Heat can be transferred in a number of different ways:
  - **Conduction**: transfer of heat via molecular collisions. Usually the dominant mechanism for heat transfer in metals.
  - **Convection**: transfer of heat of mass movement of molecules. Usually the dominant mechanism of heat transfer in liquids and gases.
  - Radiation: transfer of heat using electromagnetic radiation (e.g. light).
- We will now briefly discuss each of these mechanisms in more detail.

### Transfer of heat. Conduction.

Hotter

- The rate of heat transfer (Q/t) via conduction depends on
  - The temperature difference  $\Delta T$
  - The cross section area A
  - The length of the conductor *l*
  - The properties of the material
- The following expression for *Q*/*t* was found experimentally:

$$H = \frac{Q}{t} = \underset{\uparrow}{k} A \frac{T_{H} - T_{C}}{L}$$
  
Thermal Conductivity

 $T_1$  Heat flow  $T_2$ 

Cooler

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### Transfer of heat. Conduction.

$$H = \frac{Q}{t} = k A \frac{T_H - T_C}{L}$$

- Large values of k (200 400 J/(s m °C) occur for good heat conductors.
- Poor conductors have small values of *k* (0.01 1 J/(s m °C).
- Instead of the thermal conductivity, we often specify the thermal resistance *R* for insulators:

Hotter Cooler  

$$T_1$$
 Heat flow  $T_2$ 

$$R = l/k$$

• *R* is called the *R* value of the insulator.

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### Transfer of heat. Convection.

- Convection transfers heat by the mass movement of molecules from one location to another location.
- The driving force behind convection is thermal expansion, which results in a decrease in density with an increase in temperature.



## Transfer of heat. Radiation.

- Conduction and convection require a medium to transfer heat.
- If the medium is absent, heat can still be transferred, but only via radiation.
- Good example of transfer of heat via radiation:
  - The sunlight that heats up the earth.
  - Infra-red radiation allowing us to see in the dark.

#### **Courtesy of Inframetrics**





Courtesy of Meditherm Department of Physics and Astronomy, University of Rochester

#### Heat and heat capacity.

• When heat is added to an object, its temperature will increase:

$$Q = C \left( T_{f} - T_{i} \right)$$

- The coefficient C is the heat capacity of the object. It depends on the type and the amount of material used.
- In order to remove the dependence on the amount of material, we prefer to use the heat capacity per unit mass c:

$$Q = c m \left( T_{f} - T_{i} \right)$$



#### Latent heat.

- When heat is added to a solid or a liquid, the temperature of the sample does not necessarily rise.
- During a phase change (melting, boiling) heat is added to the sample without an increase in temperature.
- The amount of heat transferred per mass unit during a phase change is called the **heat of transformation L**:



$$Q = Lm$$

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#### First law of thermodynamics.

- Consider a closed system:
  - Closed system
    - No change in mass
    - Change in energy allowed (exchange with environment)
  - Isolated system:
    - Closed system that does not allow an exchange of energy
- The internal energy of the system can change and will be equal to the heat added tot he system minus the work done by the system:  $\Delta U = Q W$
- Note: keep track of the signs:
  - Heat: Q > 0 means heat added, Q < 0 means heat lost
  - Work: W > 0 mean work done by the system, W < 0 means work done on the system

### First law of thermodynamics. Isothermal processes.

- An isothermal process is a process in which the temperature of the system is kept constant.
- This can be done by keeping the system in contact with a large heat reservoir and making all changes slowly.
- Since the temperature of the system is constant, the internal energy of the system is constant ( $\Delta U = 0$  J).
- The first law of thermodynamics thus tells us that Q = W.



### First law of thermodynamics. Adiabatic processes.

- An adiabatic process is a process in which there is no flow of heat (the system is an isolated system).
- Adiabatic processes can also occur in non-isolated systems, if the change in state is carried out rapidly. A rapid change in the state of the system does not allow sufficient time for heat flow.
- The expansion of gases differs greatly depending on the process that is followed (see Figure).



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### First law of thermodynamics. Isobaric and isochoric processes.



#### Work done during expansion/compression.

- Consider an ideal gas at pressure *p*.
- The gas exerts a force F on a moveable piston, and F = pA.
- If the piston moves a distance *dl*, the gas will do work:

$$dW = Fdl$$

• The work done can be expressed in terms of the pressure and volume of the gas:





#### Work done during expansion/compression.

- The work done during the expansion of a gas is equal to the area under the *pV* curve.
- Since the shape of the *pV* curve depends on the nature of the expansion, so does the work done:
  - Isothermal:  $W = nRT \ln(V_B / V_A)$
  - Isochoric: W = 0
  - Isobaric:  $W = p_B (V_B V_A)$



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### First law of thermodynamics. Molecular specific heat.

- When we add heat to a system, its temperature will increase.
- For solids and liquids, the increase in temperature is proportional to the heat added, and the constant of proportionality is called the specific heat of the solid or liquid.
- When we add heat to a gas, the increase in temperature will depend on the other parameters of the system. For example, keeping the volume constant will results in a temperature rise that is different from the rise we see when we keep the pressure constant (the heat capacities will differ):
  - $Q = nC_V \Delta T$  (Constant Volume) •  $Q = nC_V \Delta T$  (Constant Pressure)

•  $Q = nC_P \Delta T$  (Constant Pressure) Here,  $C_V$  and  $C_P$  are the molecular specific heats for constant

Note that  $C_P$  and  $C_P$  are the molecular specific heats for constant volume and constant pressure. And n is the number of moles of gas.

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#### First law of thermodynamics. Molecular specific heat (p = const.).

- Consider what happens when we add  $Q_p$  to the system while keeping its pressure constant.
- The work done by the gas will be  $p\Delta V$ .
- Using the ideal gas law, we can rewrite the work done by the gas as  $p(nR\Delta T/p) = nR\Delta T$ .
- The change in the internal energy of the gas is thus equal to  $\Delta U = Q_p - nR\Delta T = nC_p\Delta T - nR\Delta T$



#### First law of thermodynamics. Molecular specific heat (V = const.).

- Consider what happens when we add  $Q_V$  to the system while keeping its pressure constant.
- The work done by the gas will be  $p\Delta V = 0$  J.
- The change in the internal energy of the gas is thus equal to  $\Delta U = Q_V = nC_V \Delta T$



• Note: we also know that  $U(\Delta T) = (3/2)nR\Delta T$  and we can thus conclude that  $C_V = (3/2)R$ .

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### First law of thermodynamics. Molecular specific heat.

- Compare the two previous results:
  - $\Delta U = nC_P \Delta T nR\Delta T$
  - $\Delta U = nC_V \Delta T$
- If in both cases the temperature changes by the same amount  $\Delta T$ the change in the internal energy  $\Delta U$  will also be the same.
- We thus conclude that  $C_P - R = C_V \text{ or } C_P - C_V = R.$



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## First law of thermodynamics. The internal energy.

- Up to now we have assumed that the internal energy *U* of a gas is equal to (3/2)kT.
- This is correct for a monatomic gas, but is not correct for diatomic or triatomic gases.
- It turns out that each degree of freedom carried an internal energy of (1/2)kT.
- Predictions for a diatomic molecule:
  - Linear motion: 3 degrees of freedom.
  - Rotational motion: 2 degrees of freedom.
  - Vibrational motion: 2 degrees of freedom.
- The number of degrees of freedom excited depend on the temperature.



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#### First law of thermodynamics. Using $C_V$ to measure the degrees of freedom.



#### Second law of thermodynamics.

- There are several different forms of the second law of thermodynamics:
  - It is not possible to completely change heat into work with no other change taking place.
  - Heat flows naturally from a hot object to a cold object; heat will not flow spontaneously from a cold object to a hot object.
- Many naturally processes do not violate conservation of energy when executed in reverse, but would violate the second law.



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#### Second law of thermodynamics. Heat engines.

- Most engines rely on a temperature difference to operate.
- Let's understand why:
  - The steam pushes the piston to the right and does work on the piston:  $W_{in} = nRT_{in}(1-V_{in}/V_{out})$
  - To remove the steam, the piston has to do work on the steam:  $W_{out} = nRT_{out}(1-V_{out}/V_{in})$
  - If  $T_{in} = T_{out}$ :  $W_{in} + W_{out} = 0$  (no net work is done).
  - In order to do work  $T_{in} > T_{out}$  and we must thus cool the steam before compression starts.



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#### Second law of thermodynamics. Heat engines.

• The efficiency of an engine is defined as the ratio of the heat extracted from the hot reservoir and the work done:

Efficiency =  $|W| / |Q_H|$ 

- Because of the second law, no engine can have a 100% efficiency!
- Note: the cost of operation does not only depend on the cost of maintaining the high temperature reservoir, but may also include the cost of maintaining the cold temperature reservoir.



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- In many cases (heat engines), the conversion of flow of heat to work is the primary purpose of the engine (e.g. the car engine).
- In many other applications (heat pumps), work is converted to a flow of heat (e.g. air conditioning).





# Note: you can not cool your house by opening the door of your refrigerator!

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 $|Q_{\rm H}|$ 

👡 Plug



Note: You usually pay for the work done but not for the heat extracted from the outside. You can thus get more energy than what you pay for!

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- Heat pumps:
  - The heat capacity increases with increasing outside temperature.
  - Additional heaters may be required in colder climates.
  - The heat capacity can also be increased by changing the source of heat from the air to the ground.



http://www.bchydro.com/powersmart/elibrary/elibrary685.html Department of Physics and Astronomy, University of Rochester

- Heat pumps:
  - Heaters in the winter: take heat from the outside to the inside.
  - Air conditioners in the summer: take heat from the inside to the outside.



#### Physics 121. Quiz lecture 25.

#### • The quiz today will have 3 questions!



#### Done for today! On Tuesday: The second law and entropy.



The four gyroscopes of the international space station.

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