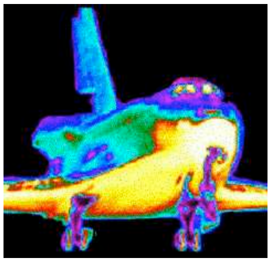
Physics 121, April 24.
Heat and the First Law of Thermodynamics.



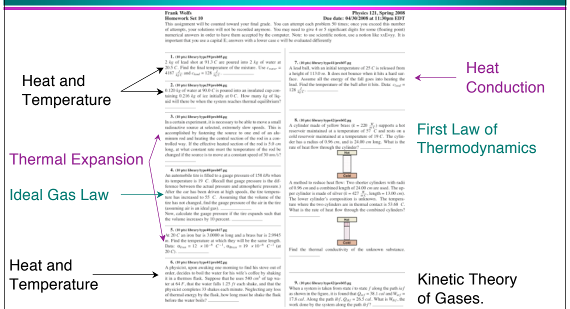
Physics 121.
April 24, 2008.

- 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.

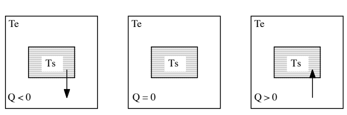


Physics 121.
Post-Test - Tuesday 4/29 at 8.45 am.

- 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.

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.



Heat.

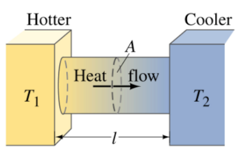
- We commonly use Q to indicate the amount of heat transferred.
- Since heat is a form of energy, its unit is the Joule.
- Another commonly used unit for heat is the calorie. One calorie is defined as the mount of heat required to raise the temperature of 1 g of water from 14.5°C to 15.5°C. 1 cal = 4.186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

- The rate of heat transfer (Q/t) via conduction depends on
  - The temperature difference ΔT
  - 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:

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

Thermal Conductivity (k)

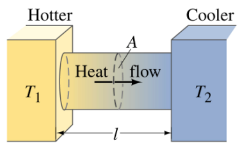
Transfer of heat. Conduction.

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

- 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:

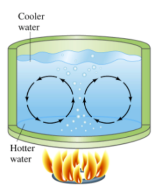
$$R = l/k$$

- R is called the R value of the insulator.



Transfer of heat. Convection.

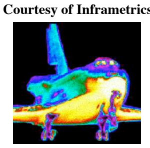
- Convection transfers heat by the mass movement of molecules from one location to another location.
- The driving force behind convection is thermal expansion, which results in a decrease in density with an increase in temperature.



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

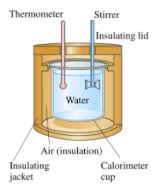
Heat and heat capacity.

- 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:

$$Q = c\,m\left(T_f - T_i\right)$$

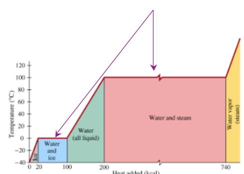


Latent heat.

- 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**:

$$Q = L\,m$$

Phase Change



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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

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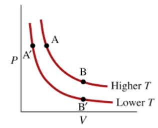
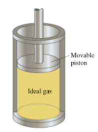
First law of thermodynamics. Isothermal processes.

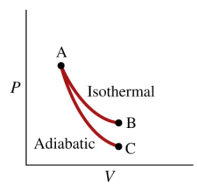
- An isothermal process is a process in which the temperature of the system is kept constant.
- This can be done by keeping the system in contact with a large heat reservoir and making all changes slowly.
- Since the temperature of the system is constant, the internal energy of the system is constant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





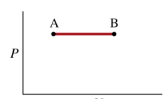
First law of thermodynamics. Adiabatic processes.

- 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).

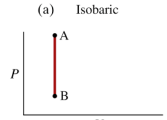


First law of thermodynamics. Isobaric and isochoric processes.

- Isobaric processes:
  - Processes in which the pressure is kept constant.
- Isochoric processes:
  - Processes in which the volume is kept constant.



(a) Isobaric



(b) Isochoric

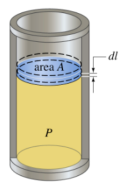
Work done during expansion/compression.

- 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:

$$dW = pAdl = pdV$$



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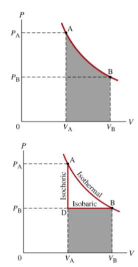
Work done during expansion/compression.

- 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)
  - $Q = nC_P\Delta T$ (Constant Pressure)

Here, C_V 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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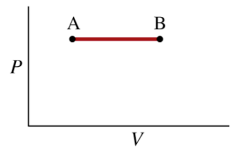
First law of thermodynamics. Molecular specific heat (p = const.).

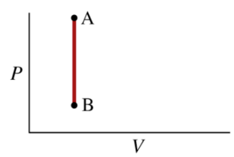
- Consider what happens when we add Q_p to the system while keeping its pressure constant.
- The work done by the gas will be $p\Delta V$.
- Using the ideal gas law, we can rewrite the work done by the gas as $p(nR\Delta T/p) = nR\Delta T$.
- The change in the internal energy of the gas is thus equal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



(a) Isobaric

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 $C_V = (3/2)R$.



(b) Isochoric

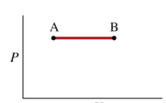
First law of thermodynamics. Molecular specific heat.

- Compare the two previous results:

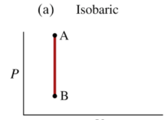
  $\Delta U = nC_p\Delta T - nR\Delta T$

  $\Delta U = nC_V\Delta T$

- If in both cases the temperature changes by the same amount ΔT the change in the internal energy ΔU will also be the same.
- We thus conclude that $C_p - R = C_V$ or $C_p - C_V = R$.



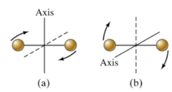
(a) Isobaric

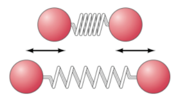


(b) Isochoric

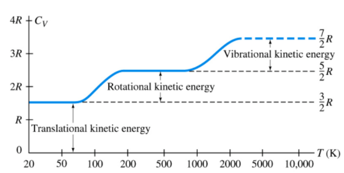
First law of thermodynamics. The internal energy.

- 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.



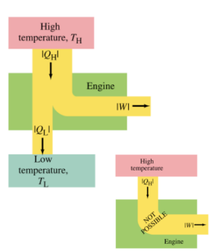


First law of thermodynamics. Using C_V to measure the degrees of freedom.



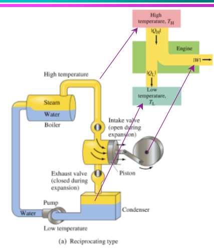
Second law of thermodynamics.

- 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.



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: $W_{in} = nRT_{in}(1\text{-}V_{in}/V_{out})$
  - To remove the steam, the piston has to do work on the steam: $W_{out} = nRT_{out}(1\text{-}V_{out}/V_{in})$
  - 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.

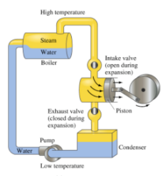


Second law of thermodynamics. Heat engines.

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

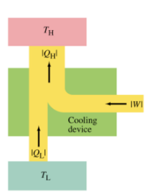
Efficiency = $|W| / |Q_H|$

- 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.

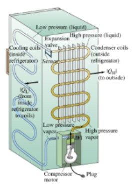


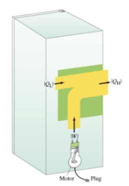
Second law of thermodynamics. Heat pumps.

- 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).



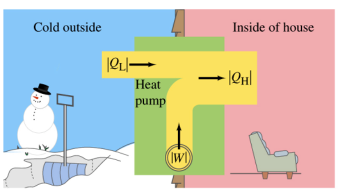
Second law of thermodynamics. Heat pumps.





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

Second law of thermodynamics. Heat pumps.

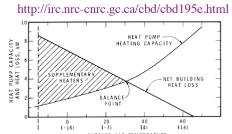


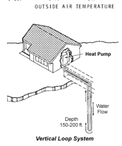
Note: You usually pay for the work done but not for the heat extracted from the outside. You can thus get more energy than what you pay for!

Second law of thermodynamics. Heat pumps.

- 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://irc.nrc-cnrc.gc.ca/cbd/cbd195e.html

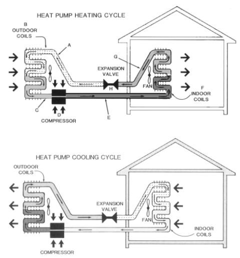




http://www.bchydro.com/powersmart/elibrary/elibrary685.html

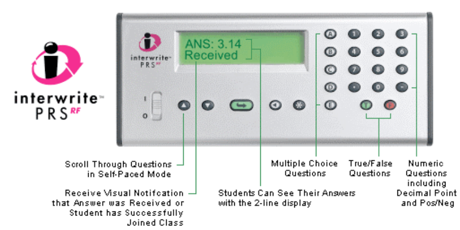
Second law of thermodynamics. Heat pumps.

- 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.

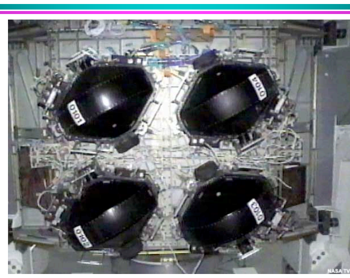


Physics 121. Quiz lecture 25.

- 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.