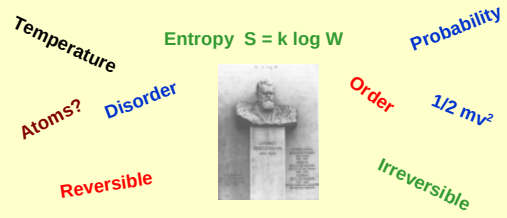
Lecture 7

The Second Law of Thermodynamics Entropy



"Of all the difficult concepts of classical physics, the most difficult is entropy"
Korean physics student's paper on the web

Announcements

- Today: Give out Homework 4
  Due MONDAY Sept. 29
- Wed., Sept. 24: Start Electricity and Magnetism
  Homework 3 due
- Mon., Sept 29: Review before Exam I
  Homework 4 due
- Wed., Oct. 1: Exam I
  Covers material through the Review
  Chapters 1 – 5, 7 of March; Ch. 11-2 of Lightman

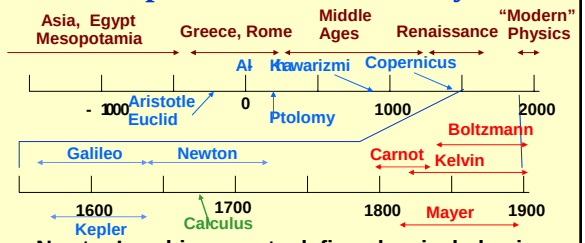
Introduction

- Last Time: Conservation Laws
  - The most useful conclusions without solving equations!
  - Conservation of momentum: Follows from Newton's third law. (Chapt. 2 in March)
  - Conservation of energy: The most important and useful law. (Chapt. 5 in March, Chapter 1 of Lightman)
  - MORE important than Newton's Equations! - still valid in modern physics even though Newton's laws are not !
  - Heat – internal energy – important in establishing the law as "The first law of thermodynamics"
- Today: The 2nd Law of Thermodynamics & Entropy
  - The second law states that entropy always increases!
  - What is entropy? (Chapt. 2 in Lightman)
  - Why is it so important in philospohical arguments? From the nature of time to evolution to ……

Time period – starting around 1700

- Newton's Laws show how to describe the motion of every object
  - Force of gravity obeys simple law
  - Electromagnetic forces not understood in 1700, but one its way to being described by simple laws
- Deterministic mechanical world view!
  - Entire universe is like a clock
  - In eternal motion – keeps ticking with every detail for all times determined by the state of the universe at one time
- Complete change from Pre-Copernican view
  - Mechanical and deterministic instead of spiritual and mystical

Development of Classical Physics



- Newton's achievements define classical physics
  - The fundamental underpinnnings of the inventions and changes of the industrial revolution
  - The deterministic world view of the "Modern History" starting around 1600
- But something is amiss - - - - - - - -

William Thomson (Lord Kelvin), 1824 - 1907

- Conceptual ideas that lead to the second law
- Defined "absolute zero of temperature" and what is now known as the Kelvin scale of temperature
- The key understanding of thermodynamics that tell us what we cannot do – maximum possible efficiency of engines, refrigerators, ….
- A gentleman that championed the work of others (unlike Newton)

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Ludwig Boltzmann, 1844 - 1906

- Boltzmannn developed statistical mechanics, which describes how atomic properties decide the perceptible properties of matter
- Boltzmann's equation, which expresses entropy in terms of probability
- Especially interested in the second law of thermodynamics
- At the center of philosophical debates:
  - Do atoms exist – even though no experiments could detect them directly at the time
- Committed suicide in 1906
- His equation was engraved on his headstone:

Ludwig Boltzmann, 1844 - 1906

- His equation is engraved on his tombstone:

$$S = k \log W$$

Entropy

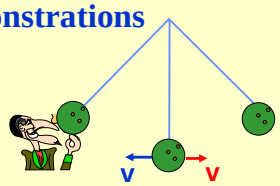
Number of configurations

Boltzmann's Constant

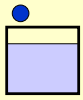
http://www.math.umbc.edu/~gobbert/Boltzmanntomb.html

Demonstrations

- Pendulum



- Dye dropped into water



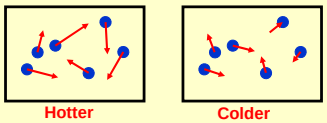
- Bridge collapsing

Statements fo the Second Law

- Many equivalent forms – Lightman p. 101
- In an ISOLATED system:
  - The system naturally evolves toward more probable configurations
  - The system evolves toward distributing its total energy equally among all its parts (conserving energy of course)
  - Heat flows from hotter to colder bodies
  - The system evolves toward decreasing order
  - The system evolves toward increasing entropy
  - The system's ability to covert work into heat is always diminishing
- Conclusions:
  - The universe is winding down – heading toward "thermal death"
  - The universe had a beginning
  - The direction of time is determined by this inevitable, irreversible tendency

Heat

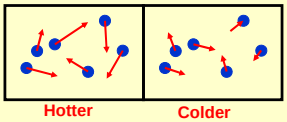
- Heat is a form of energy – internal energy of a material made up of atoms in motion (Atoms? More about them later)



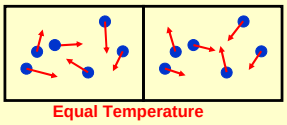
- Heat always flows from hotter to colder bodies
- Two bodies in isolation tend to come to the same temperature
- Observed for thousands of years – given precise definition with heat as a form of energy

Heat flow

- Heat always flows from hotter to colder bodies



- Much more PROBABLE to have the faster and slow molecules spread uniformly than the UNLIKELY situation of the fast ones on the left and slow ones on the right (like the dye in water)



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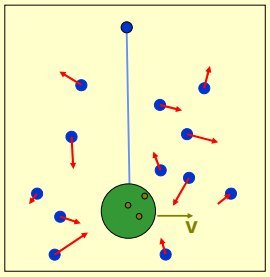
The Pendulum – in the air:



- Air molecules bouncing off the ball tend to transfer energy from the ball to the MANY molecules
- More PROBABLE for the energy to be distributed among many objects that concentrated in one

Probabilty

- Examples in Lightman, Ch. 2
  - Casting dice
- My example: Flipping a N coins

  Each can be head (+) or tail (-)
- One way to have all heads

  + + + + + + + + + + + +

  N ways to have one tail

  - + + + + + + + + + + +

  + - + + + + + + + + + +

  etc.

  N(N-1) way to have two tails

  - + + + + + + + + + + -

  + - + + + + + + + + + -

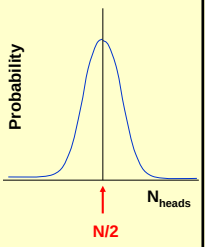
  etc.

  Most Probable – equal heads and tails

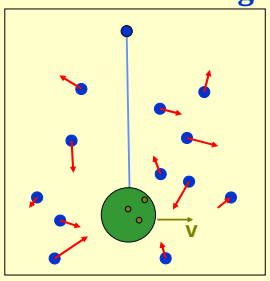
  + - + - - + + + - - + -

  + - + - + - + + - - + -

  etc.

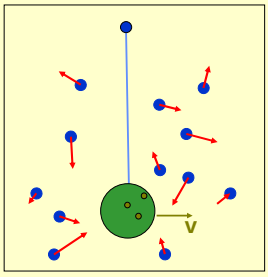


The Pendulum again



- Because there are MANY molecules ~ 10^{26} in the room
- It unimaginably more PROBABLE for the energy be lost from the pendulum to the air than not

The Pendulum continued



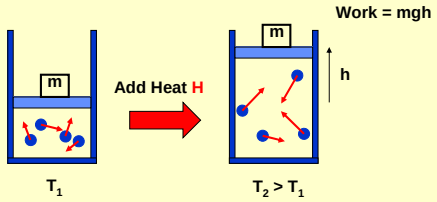
- Loss of energy from the pendulum to the air is a DECREASE in order of the pendulum-air system
- The swinging pendulum was a very special state that evolves toward more typical configurations

Conclusions - I

- Related to statements of 2nd law:
- In an ISOLATED system:
  - The system naturally evolves toward more probable configurations
  - The system evolves toward distributing its total energy equally among all its parts (conserving energy of course)
  - Heat flows from hotter to colder bodies
  - The system evolves toward decreasing order
  - The system evolves toward increasing entropy (defined to be a measure of disorder – more later)
- What about:
  - The system's ability to covert work into heat is always diminishing

How can we get work from heat?

- Simple example: (Lightman – p. 52-53)



- Part of H goes into work, part into heating the gas
- See Homework problem
- Physics error in Lightman! Extra credit to analyze the error in his example.

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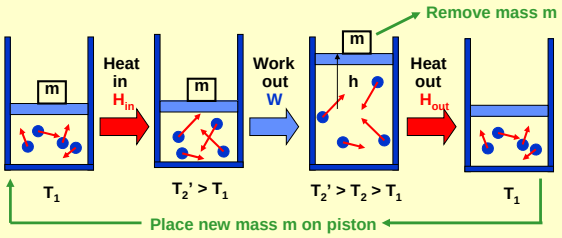
Heat engine

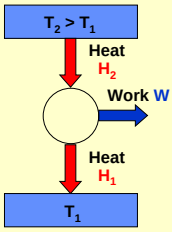
- Example - steam engine – see Lightman – p. 92



- Engine cycles back to starting configuration
- Work is done and heat is transferred through the engine
- Heat input is at a higher temperature than output

Heat Engine - Schematic

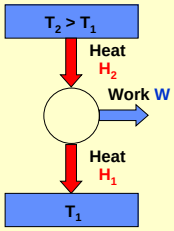
- Universal diagram – Lightman, p 93



- 1st Law: $W = H_2 - H_1$
- Efficiency defined to be $e = W/H_2$
- Engines can be run forward (work output) or backward (work input - like a refrigerator)

Reversible Heat Engine

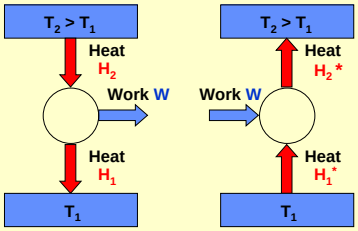
- An ideal engine that works perfectly – no losses



- Since there are no losses, use 1st Law: $W = H_2 - H_1$
- Efficiency $e = W/H_2 = 1 - H_1/H_2$
- Clausius showed $H_1/T_1 = H_2/T_2 \rightarrow$ $e = 1 - T_1/T_2$

Maximum Efficiency of a Heat Engine

- Suppose there were a more efficient engine:



- If there were a more efficient engine, it could be run in reverse (right side) to have a net transfer of heat from the colder body to the hotter body!
- Maximum possible efficiency: $e = 1 - T_1/T_2$

Conclusions - II

- Related to statements of 2nd law:
- In an ISOLATED system:
  - The system's ability to covert work into heat is always diminishing
- As temperature becomes more uniform, one cannot extract work – useful energy!
- Maximum possible efficiency = $e = 1 - T_1/T_2$

Can order be created

- In a system that is NOT ISOLATED, order can increase
- There can be input of energy at a high temperature and output at a low temperature
- What about the earth?
- What is the external source of energy to the earth?
  - A guess about it temperature?
- Since the earth does not get hotter, energy must be leaving the earth at the same rate.
  - To where is the energy going?
  - A guess about it temperature?
  - Maximum efficiency of earthlings?

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Entropy

- Entropy – usually termed S - is a well-defined measure of disorder
  - Can be defined in terms of the number of configurations for any system – for example, the flipped pennies
  - Defined by Boltzmann for systems of atoms
- Larger entropy means more disorder
- The statement that disorder tends to increase is the same as the statement that entropy increases
- Entropy provides a quantitative measure of the increase in disorder
  - NOT done here

Summary

- The 2nd law explains basic phenomena
  - The tendency for mechanical energy to be lost to heat
  - The direction of time – irreversible
  - Maximum efficiency of heat engines – NO exceptions!
- The 2nd law is one of the most disturbing laws of physics
  - The universe must wind down
  - "Thermal death"
  - Conversely, it cannot have existed forever it is present form – there must have been a beginning
- Explained by probabilities and the motions of extremely large numbers of atoms in an ordinary piece of matter ~ 10^{21} – 10^{26}
  - Boltzmann
  - Leads up to many ideas in modern physics- later

Next Time

- Electric and magnetic forces
  - Known since ancient China and Greece and …
  - Coulomb
  - Ben Franklin
  - …….
- Read
  - March, Ch. 6