Thermodynamics

- A practical science initially concerned with economics, industry, real life problems.
- DYNAMICS -- Concerned with the concepts of energy *transfers* between a system and its environment and the resulting temperature variations
- Concerns itself with the physical and chemical transformations of matter in all of its forms: solid, liquid, and gas
- Concerns the processes that “violate” conservation of mechanical energy -- friction -- via the conversion between thermal and mechanical energy.

Physics 207, Lecture 25, Nov. 29

- Agenda: Chapter 19, Temperature
  - Heat
  - Thermal Expansion
  - Temperature and Zeroth Law of Thermodynamics
  - Temperature scales
  - Kinetic Theory of Gases (Ch. 22)

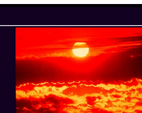
  Question: What has more internal energy, a 10 kg bar of glowing red hot iron (at ~800 C) or a 100 kg person (at 37 C)? Which can effect a larger heat transfer?

Assignments:
- Problem Set 9 due Tuesday, Dec. 5, 11:59 PM
- Monday, Chapter 20 (Heat & the First Law of Thermodynamics)

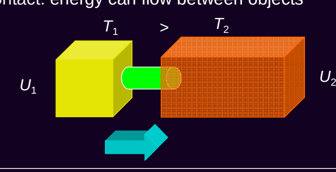
Temperature

- Temperature: A standardized measure of the motion of the individual atoms and molecules in a gas, liquid, or solid.
  - related to average kinetic energy of constituents
- High temperature: The constituents are moving around energetically
  - In a gas at high temperature the individual gas molecules are moving about independently at high speeds.
  - In a solid at high temperature the individual atoms of the solid are vibrating energetically in place.
- The converse is true for a "cold" object.
  - In a gas at low temperature the individual gas molecules are moving about sluggishly.
- There is an absolute zero temperature at which the classical motions of atoms and molecules practically stop. Quantum zero point energy cannot be removed (Planck’s constant is not zero.)

Heat

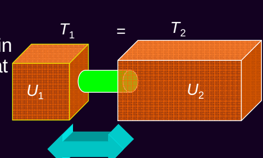


- Solids, liquids or gases have internal energy
  - Kinetic energy from random motion of molecules
    - → translation, rotation, vibration
  - At equilibrium, it is related to temperature
- Heat: Transfer of energy from one object to another as a result of their different temperatures
- Thermal contact: energy can flow between objects

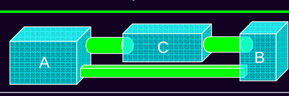


Zeroth Law of Thermodynamics

- Thermal equilibrium is established when objects in thermal contact cease heat transfer
  - They are said to be at the same temperature

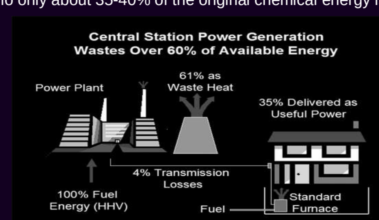


If objects A and B are separately in thermal equilibrium with a third object C, then objects A and B are in thermal equilibrium with each other.



What to do with heat and how do we assess it?

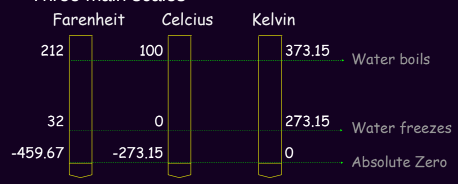
- Conversion of energy from one form to another often involves heat. Example: A power plant burns coal (chemical energy) and “heat” is used to produces steam (boiling water at high pressure) which turns a steam turbine generator. This provides point electricity which must be transferred to its use location. There is also waste heat. In a best case scenario only about 35-40% of the original chemical energy is utilized.



- Temperature allows to discern the direction of energy transfer

Temperature scales

- Three main scales



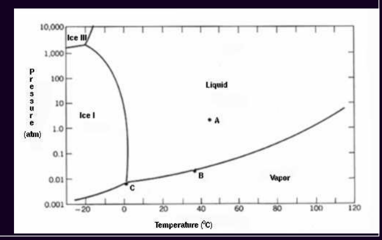
$$T_F = \frac{9}{5}T_C + 32^\circ F \qquad T_C = \frac{5}{9}(T_F - 32^\circ F)$$

$$T_C = T - 273.15K \qquad T = T_C + 273.15K$$

Modern Definition of Kelvin Scale

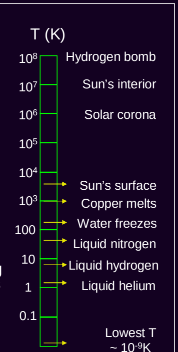
- The temperature of the triple point on the Kelvin scale is 273.16 K
- Therefore, the current definition of the Kelvin is defined as 1/273.16 of the temperature of the triple point of water

The triple point of water occurs at 0.01° C and 4.58 mm (0.06 atm) of Hg



Some interesting facts

- In 1724, Gabriel Fahrenheit made thermometers using mercury. The zero point of his scale is attained by mixing equal parts of water, ice, and salt. A second point was obtained when pure water froze (originally set at 30ºF), and a third (set at 96˚F) "when placing the thermometer in the mouth of a healthy man".
  - ❖ On that scale, water boiled at 212.
  - ❖ Later, Fahrenheit moved the freezing point of water to 32 (so that the scale had 180 increments).
- In 1745, Carolus Linnaeus of Upsula, Sweden, described a scale in which the freezing point of water was zero, and the boiling point 100, making it a centigrade (one hundred steps) scale. Anders Celsius (1701-1744) used the reverse scale in which 100 represented the freezing point and zero the boiling point of water, still, of course, with 100 degrees between the two defining points.

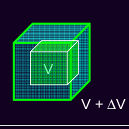


Thermometers: Devices to measure temperature

- Make use of physical properties that change with temperature
- Many physical properties can be used
  - ❖volume of a liquid
  - ❖length of a solid
  - ❖pressure of a gas held at constant volume
  - ❖volume of a gas held at constant pressure
  - ❖electric resistance of a conductor
  - ❖color of a very hot object

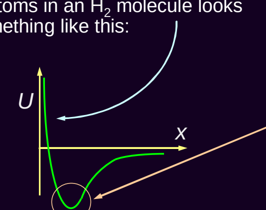
Thermal expansion

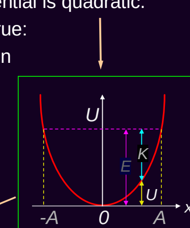
- In most liquids or solids, when temperature rises
  - ❖molecules have more kinetic energy
    - ➢they are moving faster, on the average
  - ❖consequently, things tend to expand (works for a gas)
- amount of expansion ΔL depends on…
  - ❖change in temperature ΔT
  - ❖original length L_0
  - ❖coefficient of thermal expansion
    - ➢ $L_0 + \Delta L = L_0 + \alpha L_0 \Delta T$
    - ➢ $\Delta L = \alpha L_0 \Delta T$ (linear expansion)
    - ➢ $\Delta V = \beta V_0 \Delta T$ (volume expansion)
    - ➢ $\alpha \cong 3\beta$



SHM and quadratic potentials

- SHM will occur whenever the potential is quadratic.
- For small oscillations this will be true:
- For example, the potential between H atoms in an H_2 molecule looks something like this:





- The well is not truly quadratic but anharmonic.

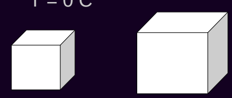
Lecture 25, ***Exercise 1***
Thermal expansion

- As you heat a block of aluminum from 0 ˚C to 100 ˚C, its density

(A) increases (B) decreases (C) stays the same

- Solution
  - Here β is positive
    Volume increases
    Density decreases

T = 0 C   T = 100 C



M, V_0 M, V_{100}

$\rho_0 = M / V_0$ $\rho_{100} = M / V_{100}$

$< \rho_0$

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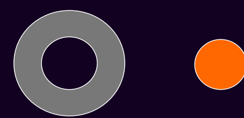
Lecture 25, ***Example 2***
Thermal expansion

- An aluminum plate (α=24×10^{-6}) has a circular hole cut in it. A copper ball (solid sphere, α=17×10^{-6}) has exactly the same diameter as the hole when both are at room temperature, and hence can just barely be pushed through it. If both the plate and the ball are now heated up to a few hundred degrees Celsius, how will the ball and the hole fit ?

(A) ball won't fit (B) fits more easily (C) same as before



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Lecture 25, ***Example 3***
Thermal expansion

A glass jar (α = 3x10^{-6} K^{-1}) has a metal lid (α = 16x10^{-6} K^{-1}) which is stuck. If you heat them by placing them in hot water, the lid will be

(A) Easier to open

(B) Harder to open

(C) Same

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Lecture 25, ***Exercise 4***
Thermal Expansion

- On a cold winter day with T = -10 ℃ , the Eiffel Tower is 300 m tall.
- How tall is it on a hot summer day when
  T = 40 ℃ ?
- The Eiffel Tower is made from steel with a thermal expansion coefficient
  α =11 x 10^{-6}/℃

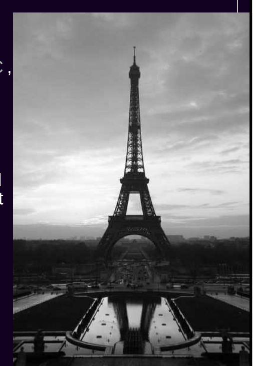
  Recall: $\Delta L/L = \alpha \, \Delta T$

(A) 300.001 m

(B) 300.16 m

(C) 316 m

(D) 420 m



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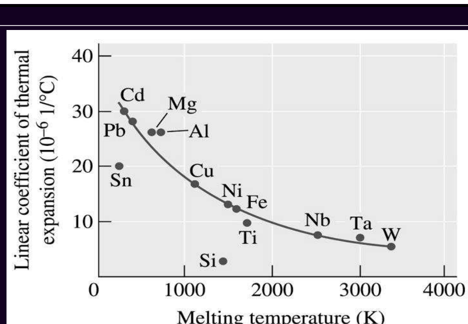

The relationship between the linear coefficient of thermal expansion and the melting temperature in metals at 25℃. High er melting point metals tend to expand to a lesser degree.

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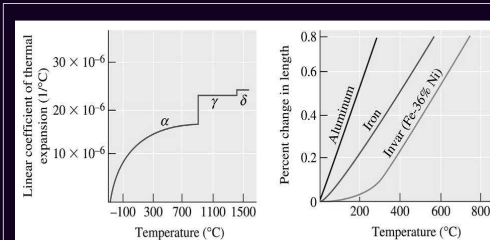

The linear coefficient of thermal expansion of iron changes abruptly at temperatures where an allotropic transformation occurs. (b) The expansion of Invar is very low due to the magnetic properties of the material at low temperatures.

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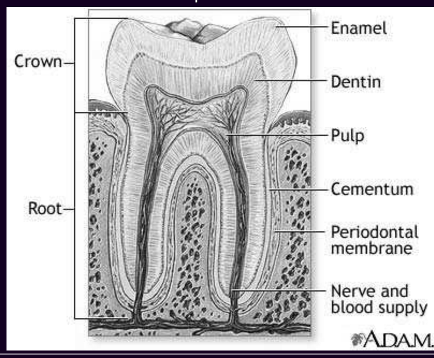
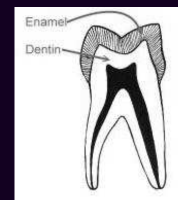
Thermal Expansion and Teeth



Thermal Expansion and Teeth

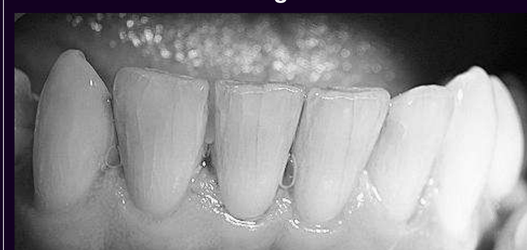
Coefficients of linear expansion:

Enamel: 11.4 x 10^{-6} °C
Dentin: 8.3 x 10^{-6} °C



If you quickly switch from eating/drinking something hot to something cold, the brittle enamel will contract more than the dentin, and develop small cracks called **crazes**.

Crazing:



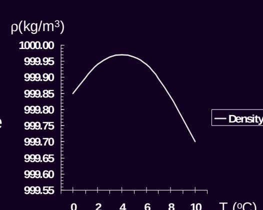
Thermal expansion matching is important in choosing materials for fillings.

Applications of Thermal Expansion – Bimetallic Strip

- Thermostats
  - Use a *bimetallic strip*
  - Two metals expand differently
    - Since they have different coefficients of expansion

Special system: Water

- Most liquids increase in volume with increasing T
  - water is special
  - density increases from 0 to 4 °C !
  - ice is less dense than liquid water at 4 °C: hence it floats
  - water at the bottom of a pond is the denser, i.e. at 4 °C



Water has its maximum density at 4 degrees.

- Reason: Alignment of water molecules

Lecture 25, *Exercise 5*

- Not being a great athlete, and having lots of money to spend, Gill Bates decides to keep the lake in his back yard at the exact temperature which will maximize the buoyant force on him when he swims. Which of the following would be the best choice?

(A) 0 °C (B) 4 °C (D) 32 °C (D) 100 °C (E) 212 °C

Ideal gas: Macroscopic description

- Consider a gas in a container of volume V, at pressure P, and at temperature T
- Equation of state
  - Links these quantities
  - Generally very complicated: but not for ideal gas
- Equation of state for an ideal gas
  - Collection of atoms/molecules moving randomly
  - No long-range forces
  - Their size (volume) is negligible

$PV = nRT$ R is called the universal gas constant

In SI units, R =8.315 J / mol·K   n = m/M : number of moles

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Boltzmann's constant

- Number of moles: n = m/M   m=mass, M=mass of one mole
  - One mole contains N_A=6.022 X 10^{23} particles : Avogadro's number = number of carbon atoms in 12 g of carbon
- In terms of the total number of particles N

$PV = nRT = (N/N_A)\,RT$

$$PV = N\,k_B\,T$$

$k_B = R/N_A = 1.38$ X 10^{-23} J/K

k_B is called the Boltzmann's constant

- P, V, and T are the thermodynamics variables

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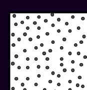
The Ideal Gas Law

$$pV = nRT$$



What is the volume of 1 mol of gas at STP ?
T = 0 ℃ = 273 K
p = 1 atm = 1.01 x 10^5 Pa

$$\frac{V}{n} = \frac{RT}{P} = \frac{8.31\ J/(mol \cdot K)\,273\ K}{1.01\ x10^5\ Pa} = 0.0224\ m^3 = 22.4\ \ell$$

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Example

- A spray can containing a propellant gas at twice atmospheric pressure (202 kPa) and having a volume of 125.00 cm^3 is at 22°C. It is then tossed into an open fire. When the temperature of the gas in the can reaches 195°C, what is the pressure inside the can?

Assume any change in the volume of the can is negligible.

Steps
1. Convert to Kelvin
2. Use P/T = nR/V = constant
3. Solve for final pressure

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Lecture 25, Recap

- Agenda: Chapter 19, Temperature
  - Heat
  - Thermal Expansion
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