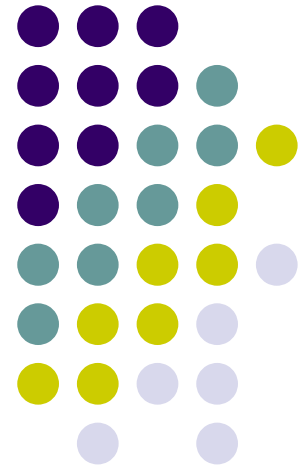


Chapter 17

Temperature



Outline for W13,D3

Temperature (Ch. 17)

Phases of matter

Zeroth law of thermodynamics

Temperature scales and conversions

Thermometers based on ...

Thermal expansion



Homework

Ch. 17 Read 17.1-17.4, 17.6-17.9

P. 3,4,8,10,11,20,30,33,34,35,37,43

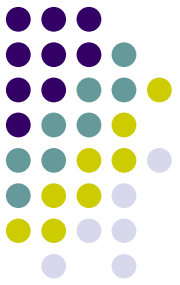
Ch. 18 Read 18.1 P. 1,6

Do for next Fri

Notes: Exam 2 scores and review on Monday.

Lab: thermal expansion

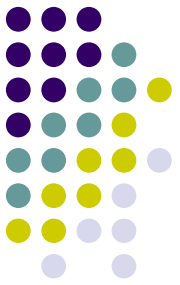
Course evaluations online soon



Temperature

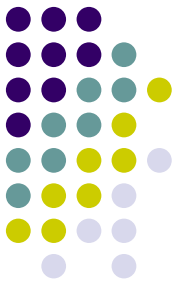
- 1) A measure of the internal energy (per mass) of an object.
 - 2) A measure of the average kinetic energy per particle stored in the random motions of the atoms and molecules in an object.
- Ex) $\langle 1/2mv^2 \rangle = 3/2 k_B T$ for monatomic ideal gases. (More on this in Ch. 18.)
 - How well can we judge temperatures through the sense of touch?

Temperature and phases of matter



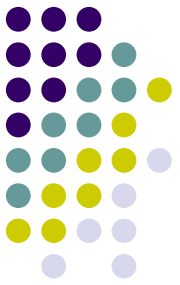
Visualize the 3 main phases of matter on molecular scales (about 10^{-9} m).

- 1) Solids
- 2) Liquids
- 3) Gases (or plasmas)



Thermal Contact

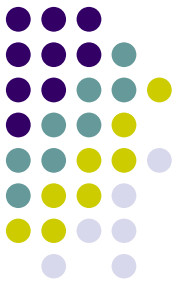
- Two objects are in **thermal contact** with each other if heat energy can be exchanged between them
 - The exchange, or transfer, of heat can happen through conduction, EM radiation, or convection. Conduction requires direct contact.
 - A net energy is exchanged when there is a temperature difference between the two.



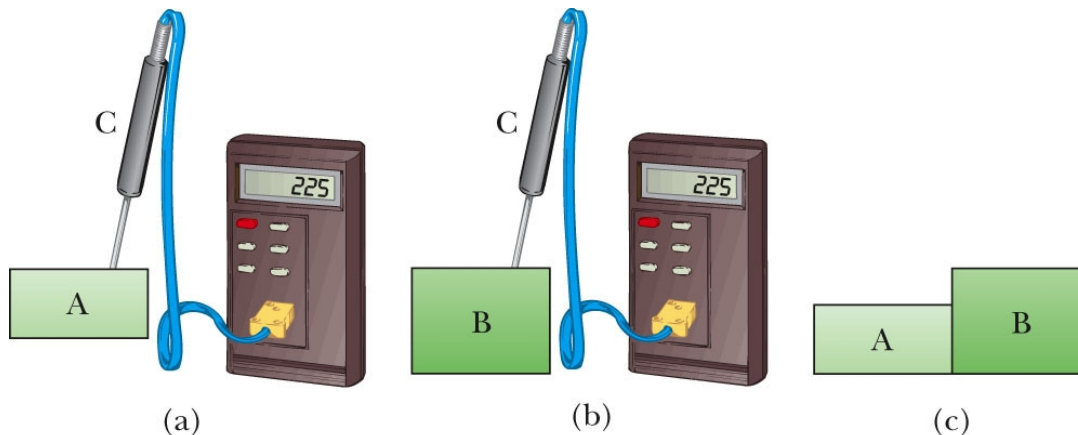
Thermal Equilibrium

- **Thermal equilibrium** is the situation in which no heat flows between two objects when they are placed in thermal contact
 - The “thermal contact” allows conduction and/or radiation.

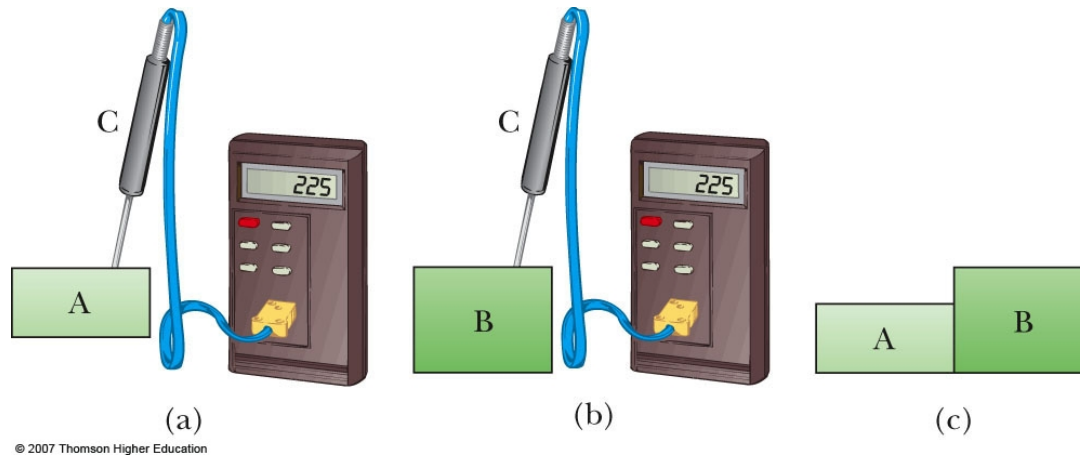
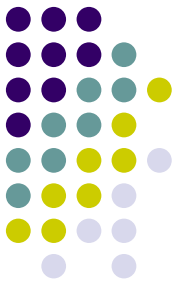
Zeroth Law of Thermodynamics



- If objects A and B are separately in thermal equilibrium with a third object C, then A and B are in thermal equilibrium with each other
 - Let object C be the thermometer
 - Since they are in thermal equilibrium with each other, there is no energy exchanged among them

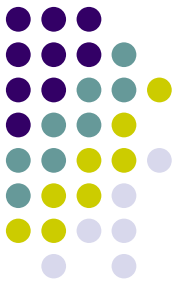


Zeroth Law of Thermodynamics, Example



- Object C (thermometer) is placed in contact with A until they achieve thermal equilibrium
 - The reading on C is recorded
- Object C is then placed in contact with object B until they achieve thermal equilibrium
 - The reading on C is recorded again
- If the two readings are the same, A and B are also in thermal equilibrium

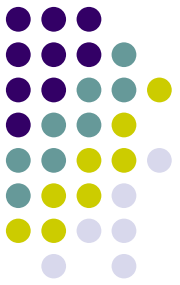
Temperature – more definitions



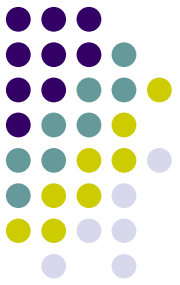
- **Temperature** can be thought of as the property that determines whether an object is in thermal equilibrium with other objects
- Two objects in thermal equilibrium with each other are at the same temperature.

Temperature Scales

Fahrenheit Scale

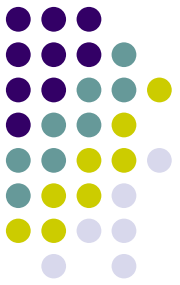


- A common scale in everyday use in the US
- Named for Daniel Fahrenheit
- Temperature of the ice point is 32°F
- Temperature of the steam point is 212°F
- There are 180 divisions (degrees) between the two reference points



Celsius Scale

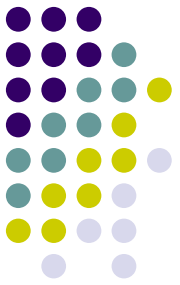
- The ice point of water is defined to be 0°C
- The steam point of water is defined to be 100°C
- The length of the column between these two points is divided into 100 increments, called degrees



Absolute Temperature Scale

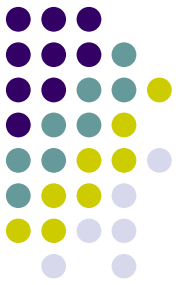
- Absolute zero is used as the basis of the absolute temperature scale, in Kelvin
- The size of the degree on the Kelvin scale is the same as the size of the degree on the Celsius scale
- To convert:
 - $T_C = T_K - 273.15$

Absolute Temperature Scale, 2



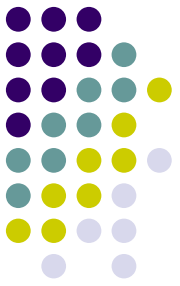
- The absolute temperature scale is now based on two new fixed points
 - Adopted by in 1954 by the International Committee on Weights and Measures
 - One point is absolute zero
 - The other point is the **triple point** of water
 - This is the combination of temperature and pressure where ice, water, and steam can all coexist

Absolute Temperature Scale, 3



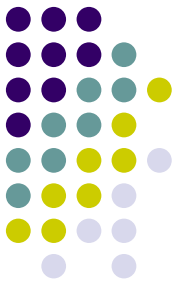
- The triple point of water occurs at 0.01°C and 4.58 mm of mercury
- This temperature was set to be 273.16 on the absolute temperature scale
 - This made the old absolute scale agree closely with the new one
 - The units of the absolute scale are **kelvins**

Absolute Temperature Scale, 4

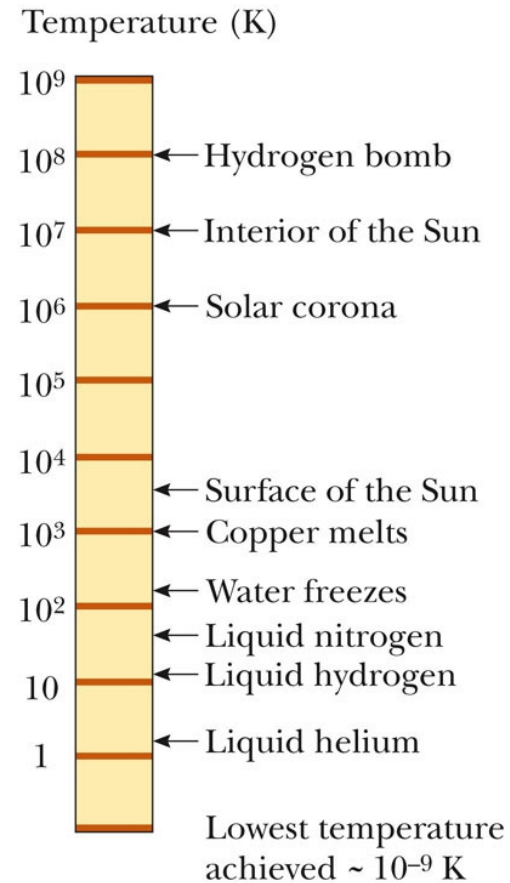


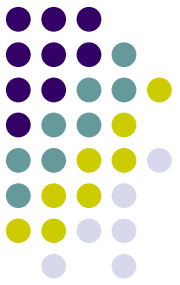
- The absolute scale is also called the Kelvin scale
 - Named for William Thomson, Lord Kelvin
- The triple point temperature is 273.16 K
 - No degree symbol is used with kelvins
- The kelvin is defined as $1/273.16$ of the difference between absolute zero and the temperature of the triple point of water

Some Examples of Absolute Temperatures



- The figure at right gives some absolute temperatures at which various physical processes occur
- The scale is logarithmic
- The temperature of absolute zero cannot be achieved
 - Experiments have come close

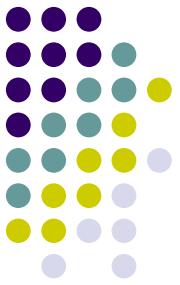




Comparison of Scales

- Celsius and Kelvin have the same size degrees, but different starting points
 - $T_C = T - 273.15$
- Celsius and Fahrenheit have different sized degrees and different starting points

$$T_F = \frac{9}{5} T_C + 32^\circ F$$

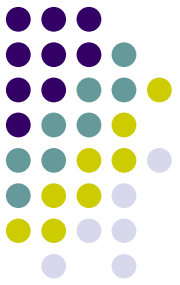


Comparison of Scales, cont

- To compare changes in temperature

$$\Delta T_{\text{C}} = \Delta T = \frac{5}{9} \Delta T_{\text{F}}$$

- Ice point temperatures
 - $0^{\circ}\text{C} = 273.15 \text{ K} = 32^{\circ} \text{ F}$
- Steam point temperatures
 - $100^{\circ}\text{C} = 373.15 \text{ K} = 212^{\circ} \text{ F}$



Outline for W14,D1

Temperature (Ch. 17)

Temperature scales and conversions

Thermometers based on physical effects of T change

Thermal expansion: linear, areal, volume

Electrical resistance, thermal radiation

Gas pressure $\sim T$

Homework

Ch. 17 Read 17.1-17.4, 17.6-17.9

P. 3,4,8,10,11,20,30,33,34,35,37,43

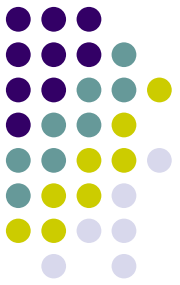
Ch. 18 Read 18.1 P. 1,6

Do for Fri

Notes: Exam 2 means = 71%, 67%

Lab: thermal expansion

Course evaluations online soon



Outline for W14,D2

Temperature (Ch. 17)

Temperature scales and conversions

Thermometers based on physical effects of T change

Thermal expansion: linear, areal, volume

Electrical resistance, thermal radiation

Gas pressure $\sim T$

Homework

Ch. 17 Read 17.1-17.4, 17.6-17.9

P. 3,4,8,10,11,20,30,33,34,35,37,43

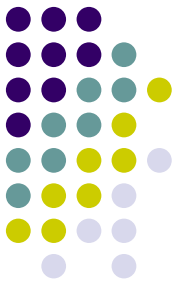
Ch. 18 Read 18.1 P. 1,6

Do for Fri

Notes: Exam 2 means = 71%, 67%

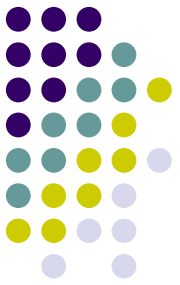
See “NEW STUFF” for thermodynamics and final.

Course evaluations online!



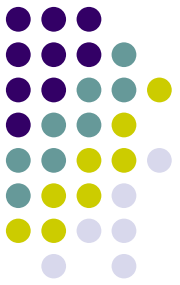
Thermometers

- A **thermometer** is a device that is used to measure the temperature of a system
- Thermometers are based on the principle that some physical property of a system changes as the system's temperature changes.
- The physical property needs to change continuously, so we don't use phase changes to make thermometers.



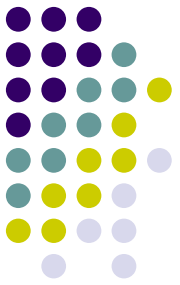
Thermometers, cont

- These properties include:
 - The dimensions of a solid
 - The volume of a liquid
 - The electrical properties of conductors
 - The pressure of a gas at a constant volume
 - The color (glow) of an object
- A temperature scale can be established on the basis of any of these physical properties



Thermal Expansion

- Thermal expansion is the increase in the size of an object with an increase in its temperature
- Thermal expansion is a consequence of the change in the average separation between the atoms in an object



Linear Thermal Expansion

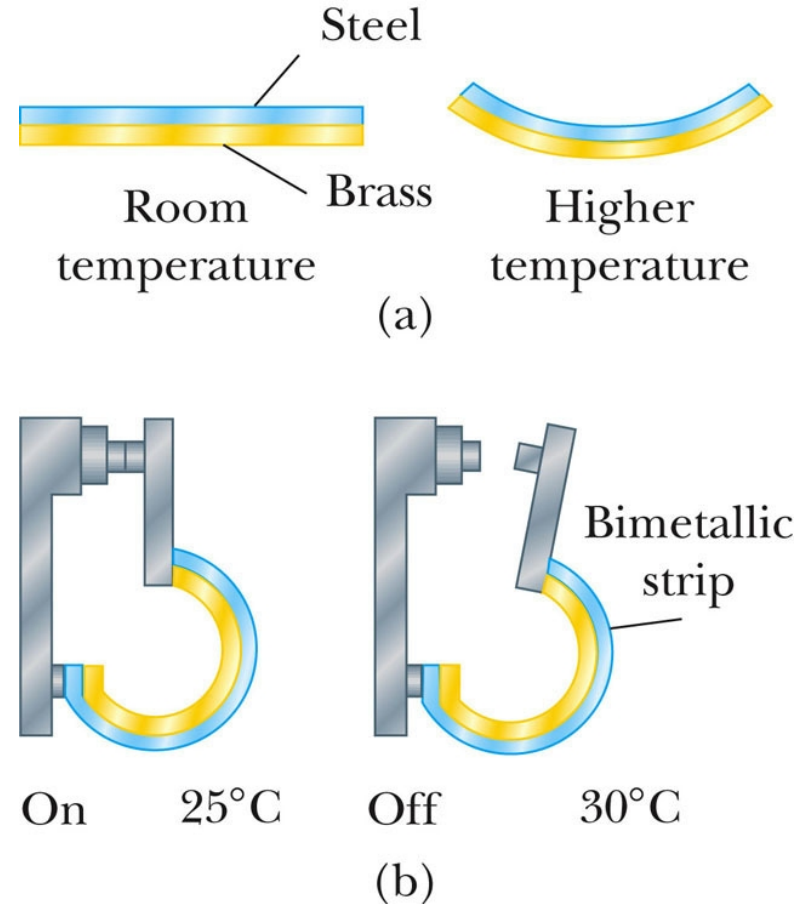
- Assume an object has an initial length L
- That length increases by ΔL as the temperature changes by ΔT
- The formula is $\Delta L = \alpha L_i \Delta T$
- We define the **coefficient of linear expansion** as

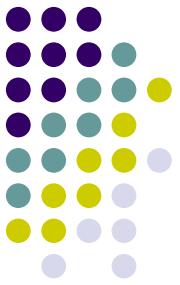
$$\alpha = \frac{\Delta L / L_i}{\Delta T}$$

- This fractional change in length per change in temperature is a property of the *material*.

Bimetallic Strip

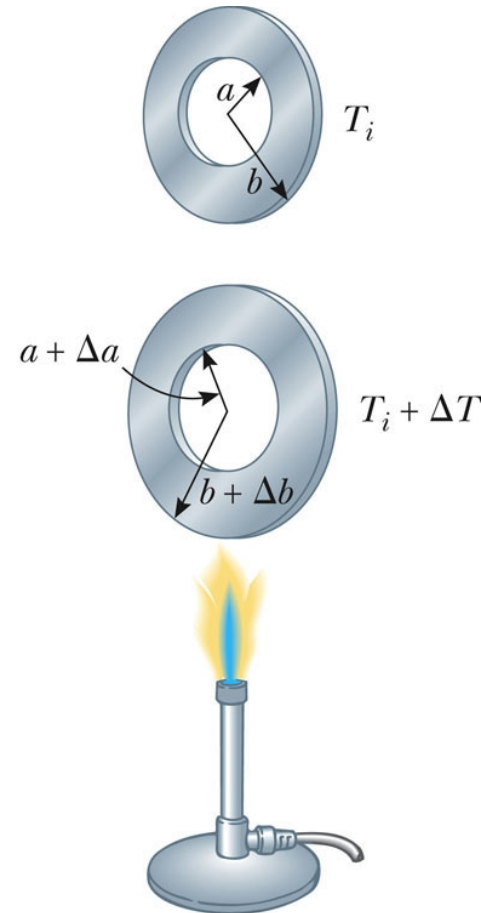
- Each substance has its own characteristic coefficient of expansion
- This can be made use of in the device shown, called a bimetallic strip
- DEMO
- It can be used in a thermostat

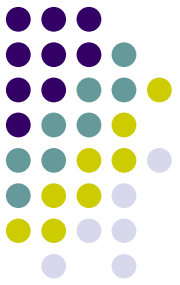




Thermal Expansion, example

- As the washer shown at right is heated, all the dimensions will increase
- A cavity in a piece of material expands in the same way as if the cavity were filled with the material
- The expansion is exaggerated in this figure





Linear Expansion, cont

- The formula can also be written in terms of the initial and final conditions of the object:
 - $L_f - L_i = \alpha L_i (T_f - T_i)$ or ...
 - $L_f = L_i (1 + \alpha \Delta T)$
- The coefficient of linear thermal expansion, α , has units of $(^{\circ}\text{C})^{-1}$
- Here is a table of thermal expansion coefficients ...

Some Coefficients

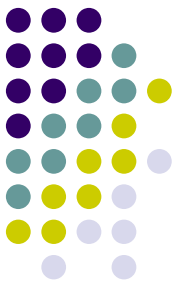
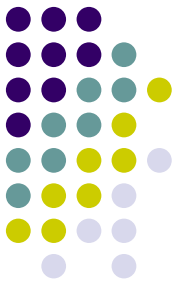


TABLE 19.1

Average Expansion Coefficients for Some Materials Near Room Temperature

Material	Average Linear Expansion Coefficient (α) ($^{\circ}\text{C}$) ⁻¹	Material	Average Volume Expansion Coefficient (β) ($^{\circ}\text{C}$) ⁻¹
Aluminum	24×10^{-6}	Alcohol, ethyl	1.12×10^{-4}
Brass and bronze	19×10^{-6}	Benzene	1.24×10^{-4}
Copper	17×10^{-6}	Acetone	1.5×10^{-4}
Glass (ordinary)	9×10^{-6}	Glycerin	4.85×10^{-4}
Glass (Pyrex)	3.2×10^{-6}	Mercury	1.82×10^{-4}
Lead	29×10^{-6}	Turpentine	9.0×10^{-4}
Steel	11×10^{-6}	Gasoline	9.6×10^{-4}
Invar (Ni-Fe alloy)	0.9×10^{-6}	Air ^a at 0°C	3.67×10^{-3}
Concrete	12×10^{-6}	Helium ^a	3.665×10^{-3}

^a Gases do not have a specific value for the volume expansion coefficient because the amount of expansion depends on the type of process through which the gas is taken. The values given here assume the gas undergoes an expansion at constant pressure.



Outline for W14,D3

Thermometers based on physical effects of T change

Thermal expansion: linear, areal, volume

Electrical resistance, thermal radiation

Gas pressure $\sim T$ (Constant-V gas thermometer)

Pressure: gauge vs absolute

Ideal gas law

Homework

Ch. 17 Read 17.1-17.4, 17.6-17.9

P. 3,4,8,10,11,20,30,33,34,35,37,43

Ch. 18 Read 18.1 P. 1,6

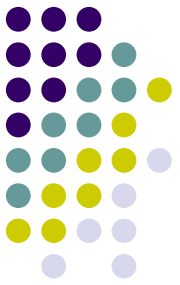
Do for Fri

Ch. 19 P. 1,6,8,9,20,21,32,33,35,36,40,49 Do for next Fri

Notes:

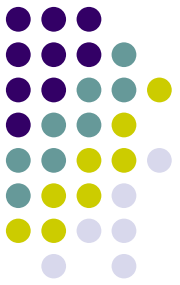
See “NEW STUFF” for thermodynamics and final.

Course evaluations online!



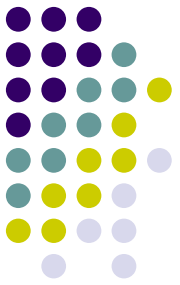
Area Expansion

- The change in area is proportional to the original area and to the change in temperature:
 - $\Delta A = 2\alpha A_i \Delta T$
 - Shouldn't there be an α^2 in this equation?



Volume Expansion

- The change in volume is proportional to the original volume and to the change in temperature
- $\Delta V = \beta V_i \Delta T$
 - β is the coefficient of volume expansion
 - For a solid, $\beta = 3\alpha$
 - This assumes the material is isotropic, the same in all directions
 - For a liquid or gas, β is given in the table



Thermometer, Liquid in Glass

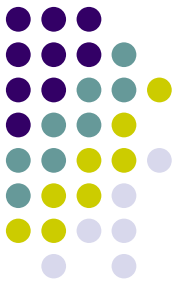
- A common type of thermometer is a liquid-in-glass
- The material in the capillary tube expands as it is heated
- The liquid is usually mercury or alcohol



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Electrical properties that depend on T.



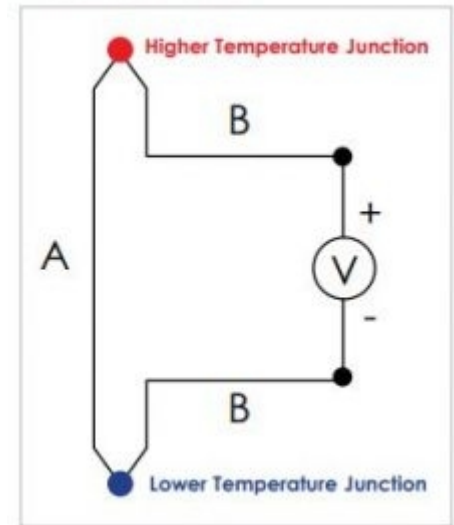
Resistance increases with temperature for typical metal conductors (Iron, silver, copper, etc) and semiconductors. This can form the basis of a thermometer or *thermistor*. Here's the temperature dependence of resistivity, ρ :

$$\rho_T = \rho_0 [1 + \epsilon(T - T_0)]$$

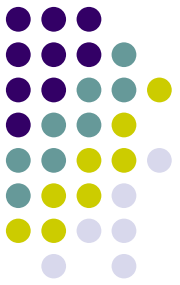
The Seebeck Effect and Thermocouple Thermometers

A thermocouple is formed by the junction of two dissimilar metals (e.g., Fe for A, and Cu for B). They are self-powered because the thermocouple creates a small thermoelectric voltage known as the Seebeck Effect. This voltage is proportional to the difference in the temperature between the hot end and the cold end of the thermocouple. As a result, the instrument requires a known temperature at one end of the thermocouple to calculate the temperature at the other end.

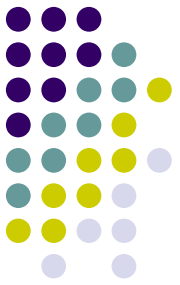
The Seebeck Effect



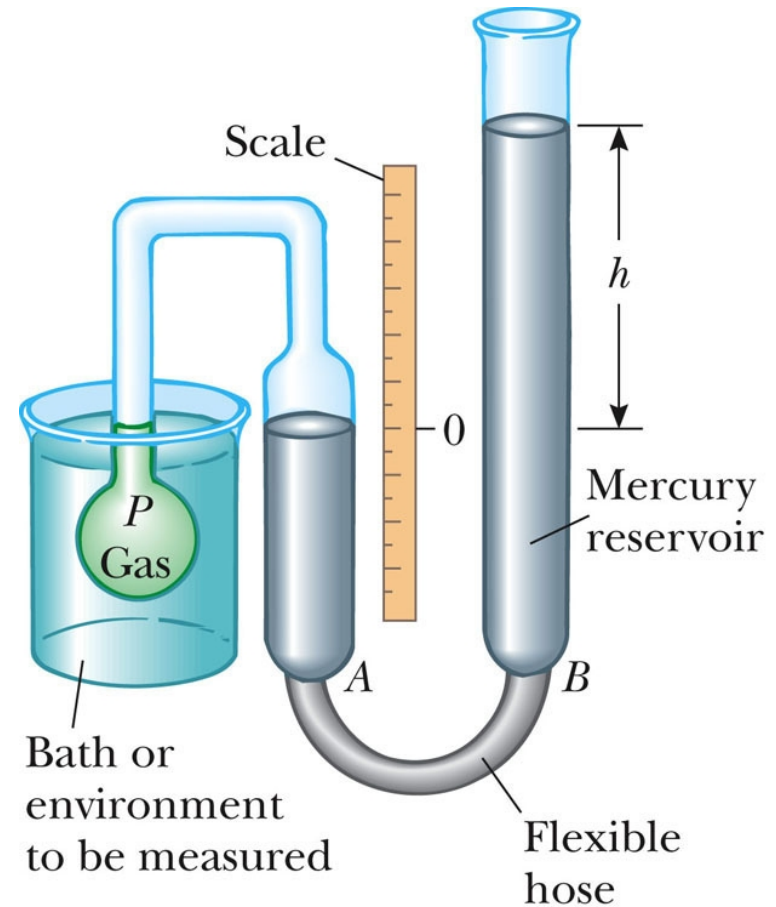
Thermal Radiation



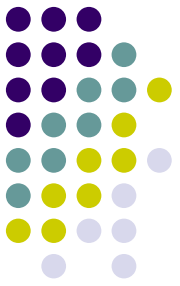
Gas Pressure increases with T: The Constant-Volume Gas Thermometer



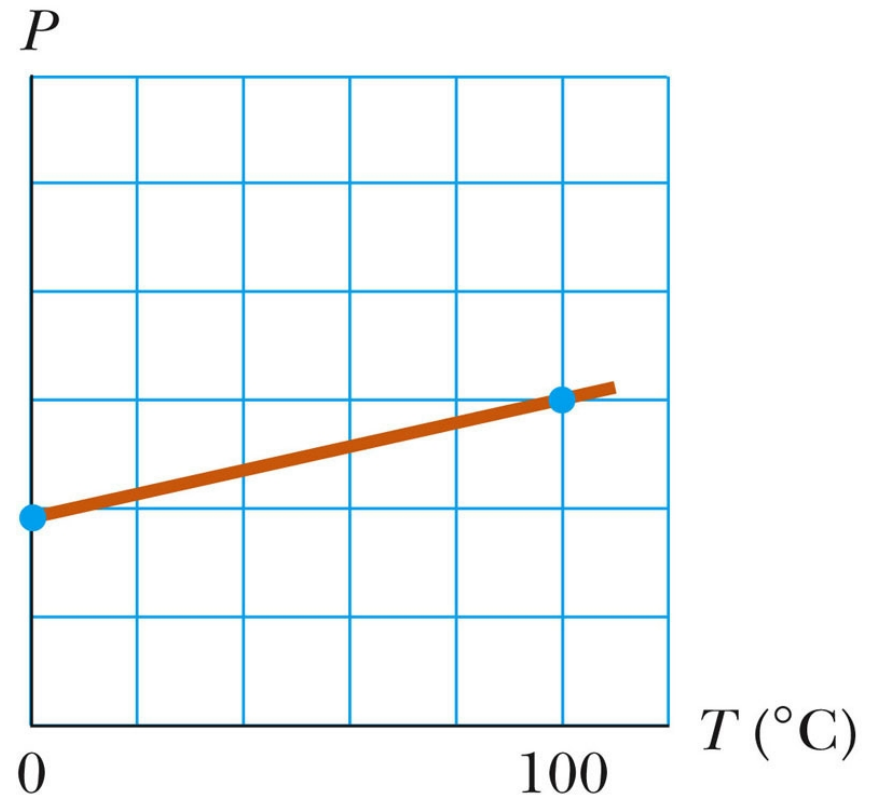
- The physical change exploited is the variation of pressure of a fixed volume gas as its temperature changes
- The volume of the gas is kept constant by raising or lowering the reservoir B to keep the mercury level at A constant



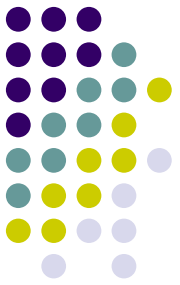
Constant-Volume Gas Thermometer, DEMO



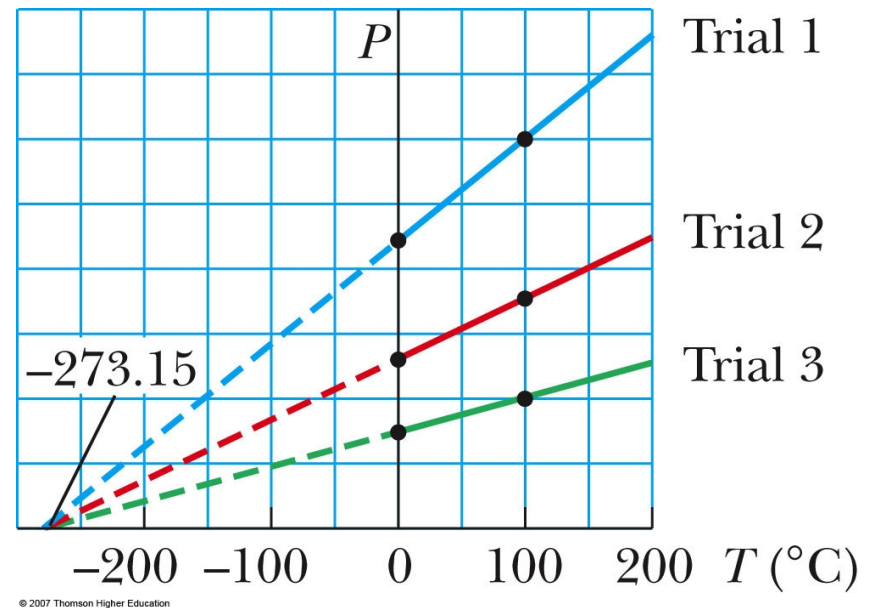
- To find the temperature of a substance, the gas flask is placed in thermal contact with the substance
- The pressure is found on the graph
- The temperature is read from the graph

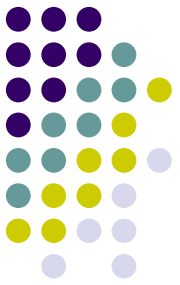


Absolute Zero



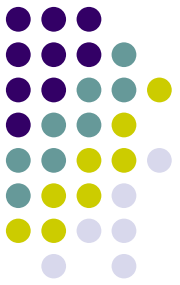
- The thermometer readings are virtually independent of the gas used
- If the lines for various gases are extended, the pressure is always zero when the temperature is -273.15°C
- This temperature is called **absolute zero**





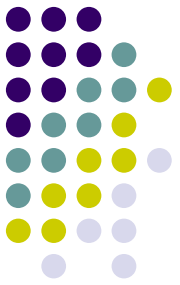
An Ideal Gas

- For gases, the interatomic forces within the gas are very weak
 - We can imagine these forces to be nonexistent
- Note that there is no equilibrium separation for the atoms
 - Thus, no “standard” volume at a given temperature



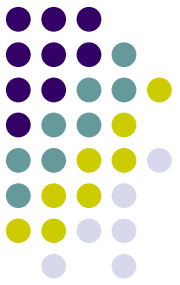
Ideal Gas, cont

- For a gas, the volume is entirely determined by the container holding the gas
- Equations involving gases will contain the volume, V , as a variable
 - This is instead of focusing on ΔV



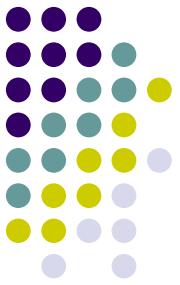
Gas: Equation of State

- It is useful to know how the volume, pressure and temperature of the gas of mass m are related
- An equation that interrelates these quantities is called an *equation of state*
 - If the gas is maintained at a low pressure, the equation of state becomes the **Ideal Gas Law**:
$$PV = nRT$$
 - This type of a low density gas is commonly referred to as an ideal gas



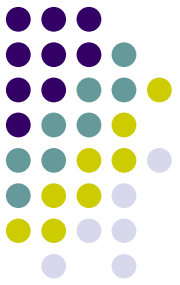
Ideal Gas Model

- The ideal gas model can be used to make predictions about the behavior of gases
 - If the gases are at low pressures, this model adequately describes the behavior of real gases



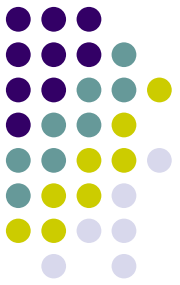
The Mole

- The amount of gas in a given volume is conveniently expressed in terms of the number of moles
- One **mole** of any substance is that amount of the substance that contains **Avogadro's number** of constituent particles
 - Avogadro's number $N_A = 6.022 \times 10^{23}$
 - The constituent particles can be atoms or molecules



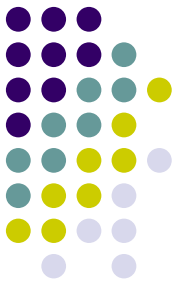
Moles, cont

- The number of moles can be determined from the mass of the gas: $n = m / M$
 - M is the molar mass of the substance
 - M can be obtained from the periodic table
 - M is the atomic mass expressed in grams/mole
 - Example: He has mass of 4.00 u so $M = 4.00$ g/mol or .004 kg/mol.
 - m is the mass of the sample
 - n is the number of moles
 - Example: How much mass does 3 mol of N_2 have?
 - Sol: $m=nM$. N_2 has mass of 28.0 u so $M = 28.0$ g/mol.
Thus, $m=3(28g) = 84$ g.



Gas Laws (derived from $PV=nRT$)

- When a gas is kept at a constant temperature, its pressure is inversely proportional to its volume (Boyle's law)
- When a gas is kept at a constant pressure, its volume is directly proportional to its temperature (Charles and Gay-Lussac's law)
- When the volume of the gas is kept constant, the pressure is directly proportional to the temperature (Gay-Lussac's law)



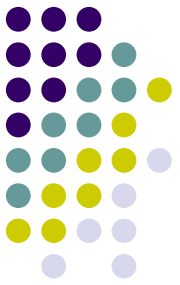
Ideal Gas Law

- The equation of state for an ideal gas combines and summarizes the other gas laws

$$PV = nRT$$

- This is known as the **ideal gas law**
- R is a constant, called the Universal Gas Constant
 - $R = 8.314 \text{ J/mol}\cdot\text{K} = 0.08214 \text{ L} \cdot \text{atm/mol}\cdot\text{K}$
- From this, you can determine that 1 mole of any gas at atmospheric pressure and at 0°C is 22.4 L.

$$\text{Show: } V = nRT/P = (1\text{mol})(0.08214)(273\text{K})/(1\text{atm}) \\ = 22.4 \text{ L}$$



Ideal Gas Law, cont

- The ideal gas law is often expressed in terms of the total number of molecules, N , present in the sample
- $PV = nRT = (N/N_A) RT = Nk_B T$
 - k_B is Boltzmann's constant
 - $k_B = 1.38 \times 10^{-23} \text{ J/K}$
- It is common to call P , V , and T the **thermodynamic variables** of an ideal gas

Outline for W15,D1

Ideal gas law – Examples

Kinetic Theory

Pressure

$$P = \frac{1}{3} \frac{Nm \overline{v^2}}{V}$$

Translational Kinetic Energy

$$\overline{K} = \frac{1}{2} m \overline{v^2} = \frac{3}{2} kT$$

Examples

1st Law of Thermodynamics: $\Delta E_{\text{int}} = Q - W$



Homework

Ch. 17 Read 17.1-17.4, 17.6-17.9

P. 3,4,8,10,11,20,30,33,34,35,37,43

Ch. 18 Read 18.1 P. 1,6

Do for last Fri

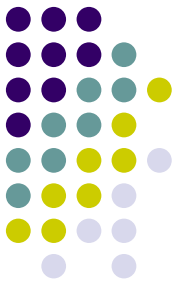
Ch. 19 P. 1,6,8,9,20,21,32,33,35,36,40,49 Do for this Fri

Notes:

See “NEW STUFF” for exam-like problems on Ch 17,18.

Course evaluations online.

Ideal Gas Law - Examples



Ex) P. 34. In an internal combustion engine, air at atmospheric pressure and temperature of about 20°C is compressed in the cylinder by a piston to 1/9 of its original volume. Estimate the temperature of the compressed air, assuming the pressure reaches 40 atm.

$$\text{Soln: } P_i V_i / T_i = P_f V_f / T_f \rightarrow T_f = (P_f V_f / P_i V_i) T_i = (40 * 1/9) T_i$$

$$\text{Use } T_i = 273 + 20 = 293 \text{ K. } T_f = (40/9) * 293 = 1302 \text{ K}$$

Ideal Gas Law - Examples



Ex) P. 37. Calculate the density of nitrogen at STP using the ideal gas law.

Soln: Need to know “nitrogen” means N_2 and that N_2 has molar mass of $M=28$ g/mol or .028 kg/mol.

Density, $\rho = m/V$

STP $\rightarrow T=273$ K, $P=101,000$ Pa

$PV = nRT$

Take $n=1$ mol, then $m=.028$ kg. Just need V ...

$V = nRT/P = 1(8.314)(273)/101000 = .02246$ m³ (true for all gases).

So $\rho = m/V = .028/.02246 = 1.25$ kg/m³

Ideal Gas Law - Examples



Ex) P. 43. A sealed metal container contains a gas at 30 C and absolute pressure of 1.0 atm. To what temperature must the gas be heated for the pressure to double to 2.0 atmospheres? (Ignore the expansion of the container.)

Soln: V fixed \rightarrow Gay-Lussac Law, $P \propto T$.

Convert $T_i = 30 + 273 = 303$ K.

Use ratios.

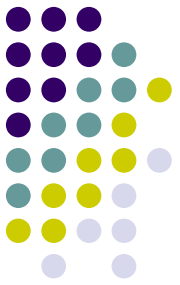
$$P_i/P_f = T_i/T_f$$

$$1/2 = 303/T_f$$

$$T_f = 303/0.5 = 606 \text{ K}$$

$$T_f = 606 - 273 = 333^\circ\text{C}$$

Kinetic Theory (Ch. 18)



See textbook's derivation of this expression for pressure:

$$P = \frac{1}{3} \frac{Nm \overline{v^2}}{V}$$

N = number of molecules in container

m = mass of the gas molecules

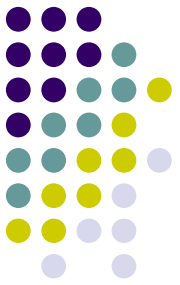
$\overline{v^2}$ = mean speed squared. Note, the v is called v_{RMS}

V = volume of container

If all of the molecules have the same mass, then the average translational kinetic energy is given by

$$\overline{\text{KE}_{\text{trans}}} = \overline{K} = \left\langle \frac{1}{2} m v^2 \right\rangle = \frac{1}{2} m \overline{v^2} = \frac{3}{2} kT$$

Kinetic Theory (Ch. 18)



Ex) Express the pressure in terms of the average translational kinetic energy.

$$P = \frac{1}{3} \frac{Nm \overline{v^2}}{V}$$
$$P = \frac{2}{3} \frac{N \left(\frac{1}{2}\right) m \overline{v^2}}{V}$$
$$P = \frac{2}{3} N \frac{\overline{K}}{V}$$

P. 18.1) Calculate the rms speed of He atoms near the surface of the Sun at a temperature of about 6000 K.

$$\frac{1}{2} m \overline{v^2} = \frac{3}{2} kT \quad v_{\text{RMS}} = (3 kT/m)^{1/2}$$

Need $M_{\text{He}} = 4 \text{ u}$, and $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$

$$v_{\text{RMS}} = [(3 \cdot 1.38 \times 10^{-23} \cdot 6000) / (6.64 \times 10^{-27})]^{1/2} = 6100 \text{ m/s}$$