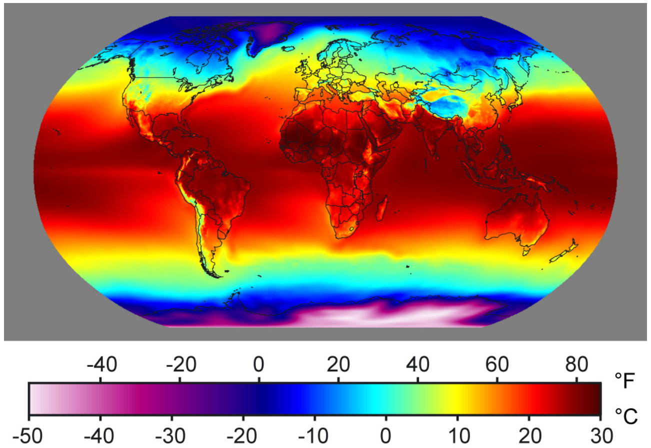
Today’s lecture

Thermal Physics

- Temperature
- Thermal Expansion
- Thermal Equilibrium
- The Ideal Gas Law



Annual Mean Temperature

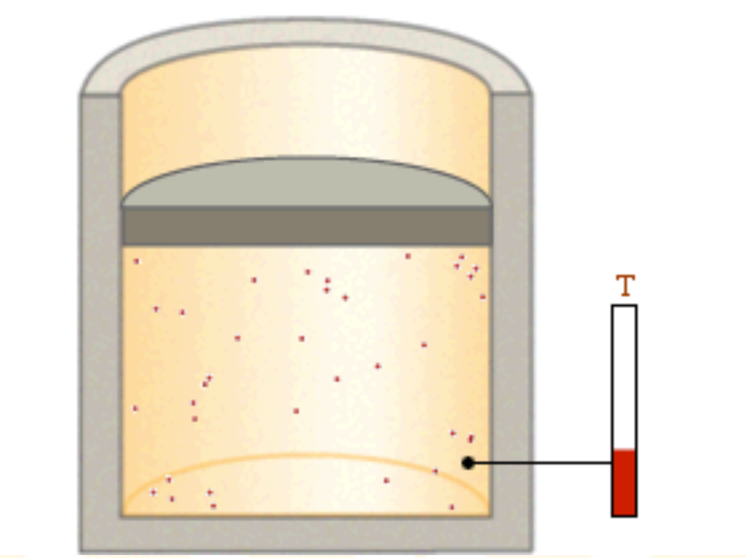
Temperature (gas)

The temperature, T, of a low density (*ideal*) gas is related to the average kinetic energy of each atom/molecule:

$$\boxed{\frac{1}{2}mv_{avg}^2 = \frac{3}{2}k_B T}$$

Here, v_{avg} is the average velocity and m is the mass of each atom/molecule.

$k_B = 1.38 \cdot 10^{-23}$ J/K is the Boltzmann constant.

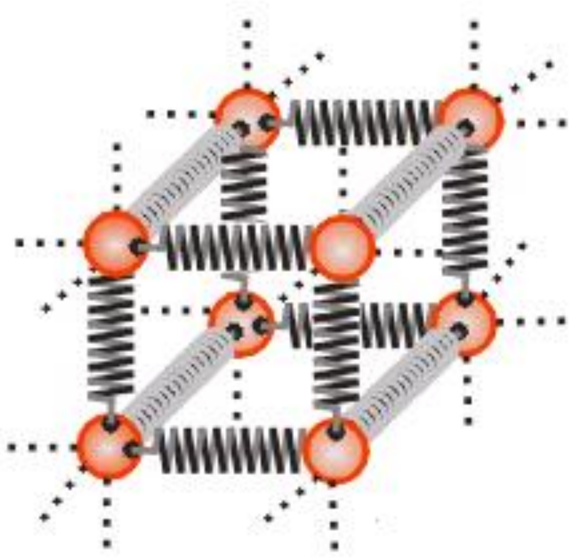


The higher the temperature the faster the atoms/molecules move.

If a gas is located in a container, the molecules (N molecules in a volume V) will collide with the walls more frequently and will transfer more momentum to the walls at higher temperature.

This is described by the ideal gas law: $\boxed{P = \frac{N}{V}k_B T}$

Temperature (solids + liquids)



In solids and liquids there are strong bonds between individual atoms and molecules.

Atoms/molecules cannot move freely.

The bonds can be represented by springs and Hooke’s law can be used to understand the situation qualitatively:

$$F_s = -kx \qquad PE_s = \frac{1}{2}kx^2$$

The higher the temperature the farer the atoms can move away from their equilibrium position and extend the springs.

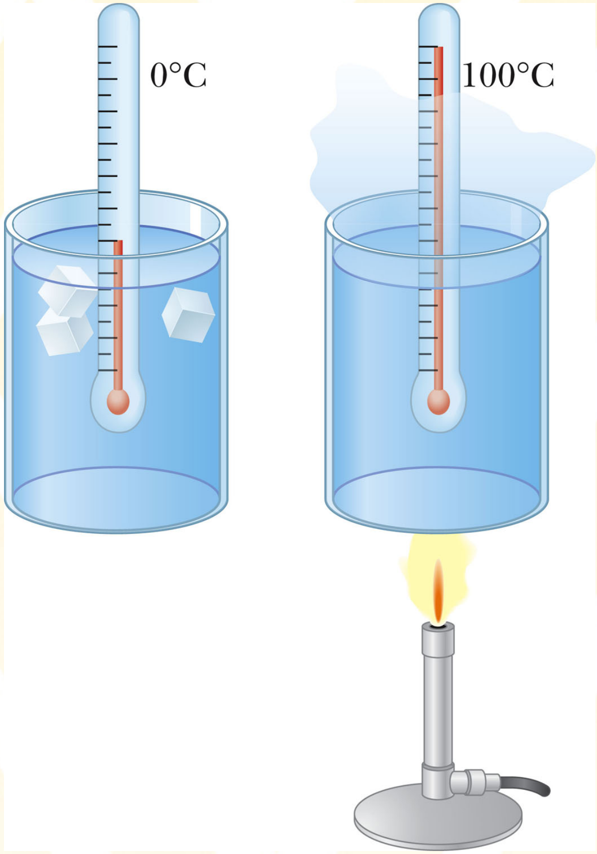
At high temperatures atoms “oscillate” around their equilibrium positions.

Temperature scales

The temperature of a material is measured by a thermometer. It can be measured on different scales:

1. The Celsius scale (used in most countries except US):

0°C: Freezing point of water at atmospheric pressure.
100°C: Boiling point of water at atmospheric pressure.



Clicker questions

The **temperature difference** between the inside and outside of a home on a cold winter day is 57.0°F.

1.) Express this difference on the Celsius scale.

A. 13.9 °C

B. 31.7 °C

C. 45.0 °C

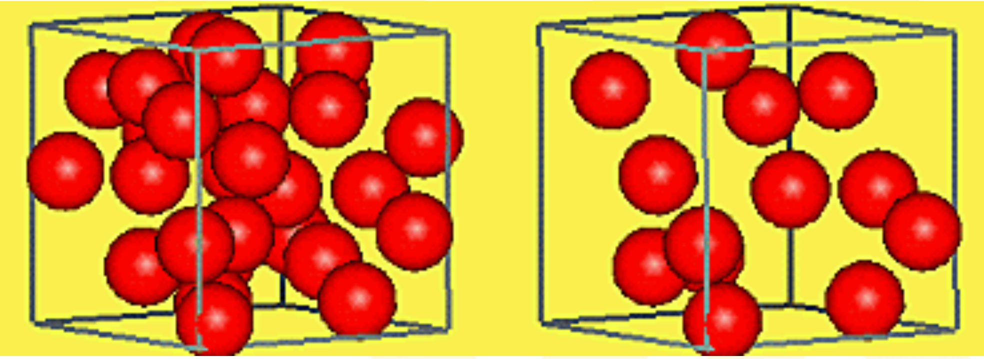
D. 134.6 °C

$$T[°C] = \frac{5}{9}(T[°F] - 32)$$

$$T[°C] = T[K] - 273.15$$

2.) What is the temperature difference in Kelvin?

Example problem: Ideal gas law

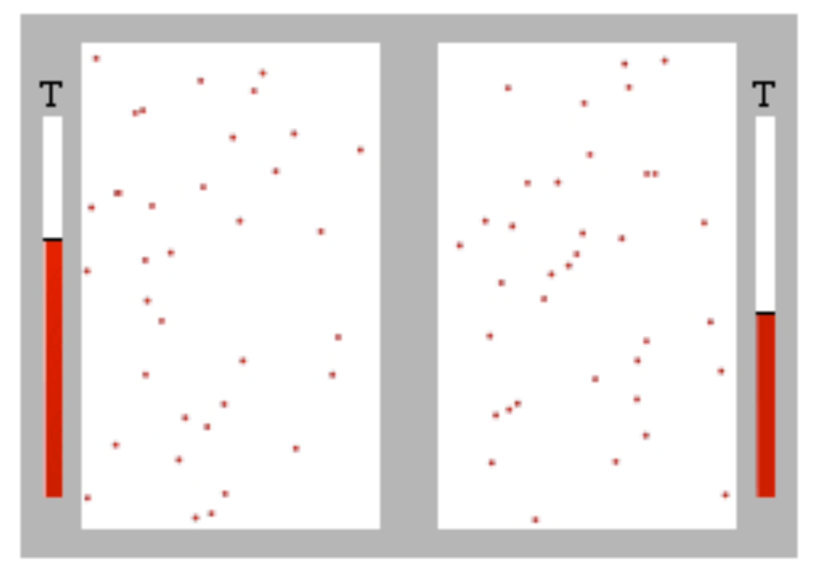


The density of Helium gas at 0 °C is $\rho_0 = 0.179\ \mathrm{kg/m^3}$. The temperature is then raised to 105 °C, but the pressure is kept constant. Calculate the new density, ρ_f, of the gas.

$$\boxed{P = \frac{N}{V} k_B T}$$

Thermal Equilibrium

When two objects of different temperatures are brought in (thermal) contact with each other, they exchange (thermal) energy, i.e. heat, until both objects have the same temperature.



Two objects in thermal equilibrium with each other are at the same temperature.

No energy will be exchanged, if they are in thermal equilibrium.

Nature tends towards equilibrium! - This concept is transferable to many areas outside physics:

Economy: If wealth is distributed too unequally in a society, there will be rebellions to restore economic equilibrium.

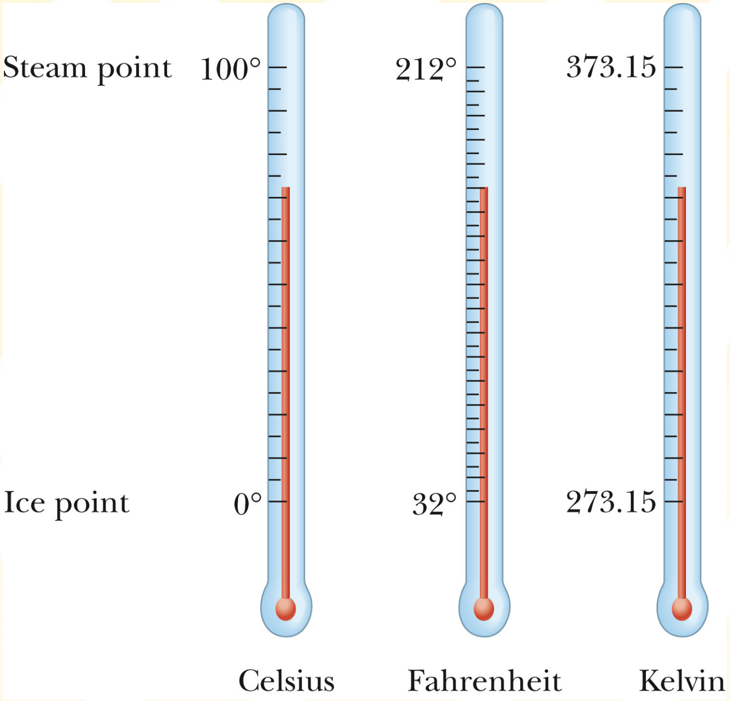
How does a thermometer work?

Classical thermometers consist of a vertical tube partially filled with a liquid (usually mercury or ethanol) and a scale.

If it is brought in contact with a hotter/cooler material, energy will be exchanged until thermal equilibrium is reached.

If the object is hotter than the thermometer, the thermometer will heat up.

This will cause a thermal expansion of the liquid in the tube, which will rise higher marking a higher temperature on the scale.



Clicker question

The illustration shows a thermometer that uses a column of liquid (usually mercury or ethanol) to measure air temperature. In thermal equilibrium, this thermometer measures the temperature of

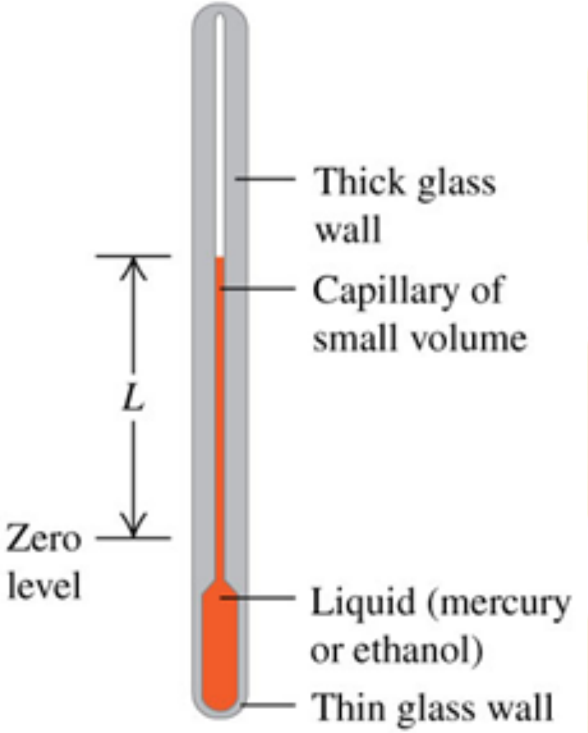
A. the column of liquid.

B. the glass that encloses the liquid.

C. the air outside the thermometer.

D. both A. and B.

E. all of A., B., and C.



Three types of thermal expansion

1. Length expansion (thermometer):

$$\boxed{\Delta L = \alpha L_0 \Delta T}$$

L_0 is the object's initial length, α is the material specific coefficient of linear expansion.

2. Area expansion (ring):

$$\boxed{\Delta A = \gamma A_0 \Delta T}$$

with $\gamma = 2\alpha$.

3. Volume expansion:

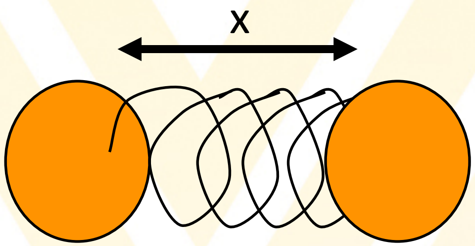
$$\boxed{\Delta V = \beta V_0 \Delta T}$$

with $\beta = 3\alpha$.

Without these joints to separate sections of roadway on bridges, the surface would buckle due to thermal expansion on very hot days or crack due to contraction on very cold days.

What is the reason for thermal expansion?

When an object is heated up, its molecules move faster. They oscillate around an equilibrium position with larger amplitude at higher temperatures.



Thus, the volume of the object increases.

Thermal expansion must be taken into account in manufacturing applications.

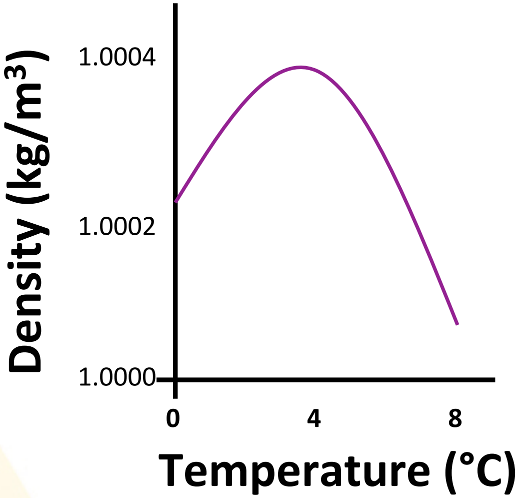
Example: In a car engine, all parts must not expand more than a well defined limit. Otherwise the engine would be destroyed at high temperatures.

Example problem

The New River Gorge bridge in West Virginia is 518 m long and made of steel ($\alpha = 11 \cdot 10^{-6}$ °C^{-1}).

How much will its length change between temperature extremes of -20 °C and 35 °C?

Water: A rare and important exception



The density of water does not decrease monotonically as a function of temperature.

Thus, water will not always expand, if the temperature is increased.

The density of water is maximum at 4°C, i.e. ice is less dense compared to water!

As heavy material sinks in a liquid, the water temperature at the bottom of a lake is closest to 4°C and lakes freeze at the surface!

This allows marine life to survive at low temperatures. Imagine lakes would freeze from the bottom up: All fish would be pushed to the surface out of the water. Life on earth would not be possible under these conditions.