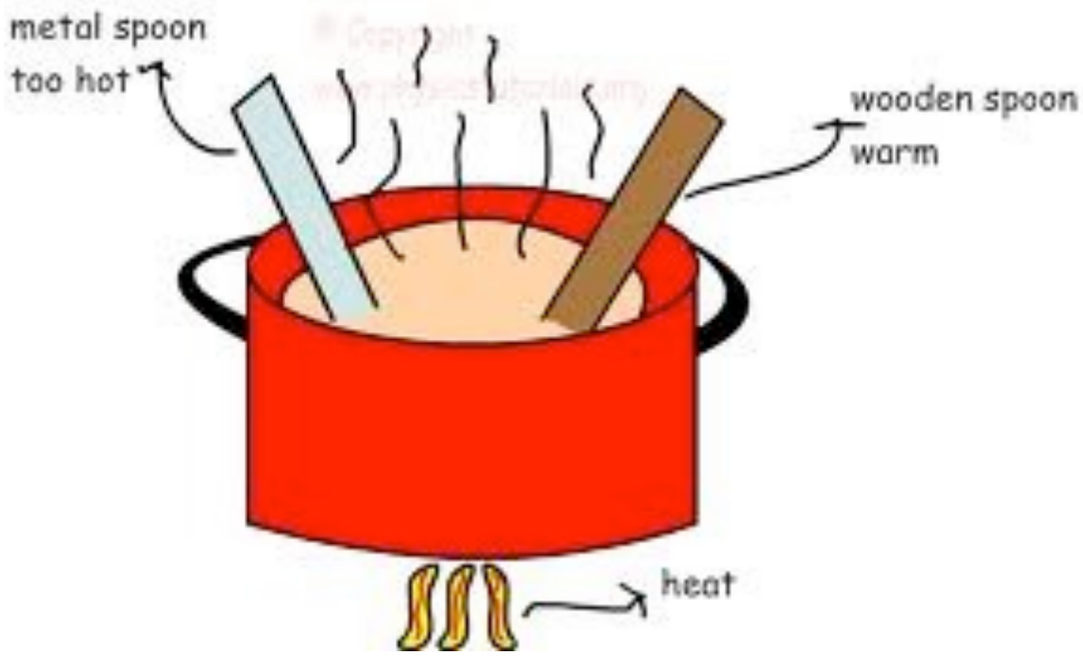
Temperature and Heat

Ken Intriligator's week 4 lectures, Oct 21, 2013



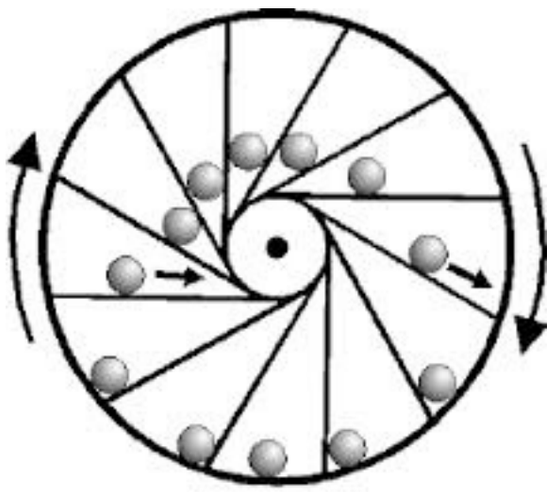
This week's subjects:

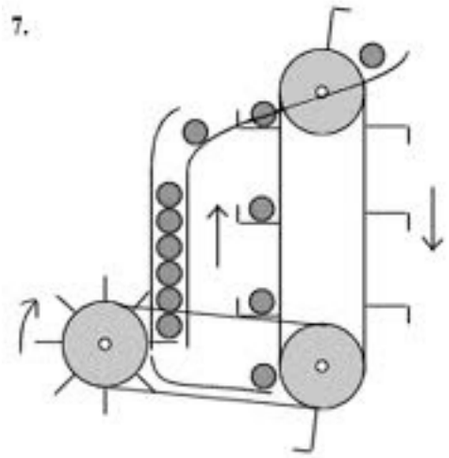
- Temperature and Heat chapter of text. All sections.
- Thermal properties of Matter chapter. Omit the section there on heat capacities (section 4). We will discuss that, and the First Law of Thermodynamics chapter, next week.

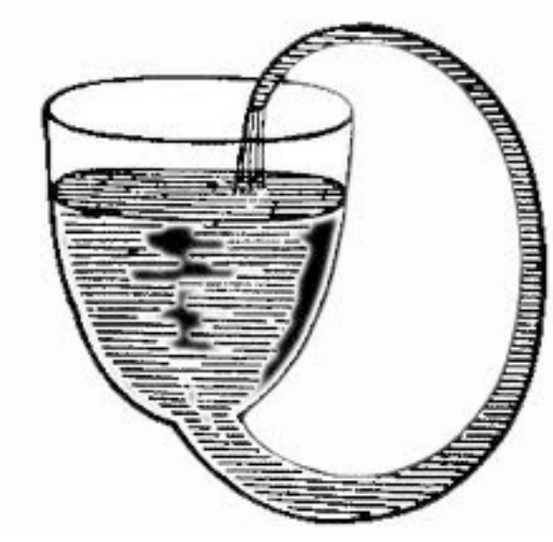
Thermodynamics

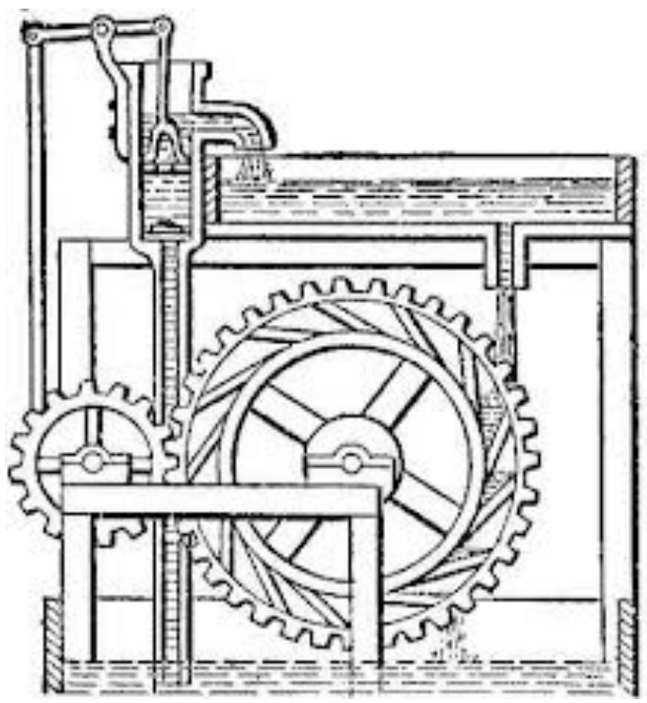
Beautiful subject (from a physicists perspective). The quality of a theory can be judged by its ratio of predictive output to number of inputs or assumptions. Thermodynamics is perhaps the best ever in this regard. It is an amazingly predictive theory, with a miraculous amount of understanding of Nature coming out of so few inputs. Developed mainly in the 1800s, out of practical desire to study, and improve the efficiency of heat engines. Showed e.g. that perpetual motion machines can't work. We'll explore the "Laws of Thermodynamics" over the next few weeks.

Perpetual motion? No!









Thousands of failed inventor's attempts. Would violate thermodynamic laws. Thermodynamics works!

Thermodyanamic laws

Zeroth: Can define notion of "temperature." This week's main topic.

First: Conservation of energy. Fundamental aspect of Nature. Next week's main topic.

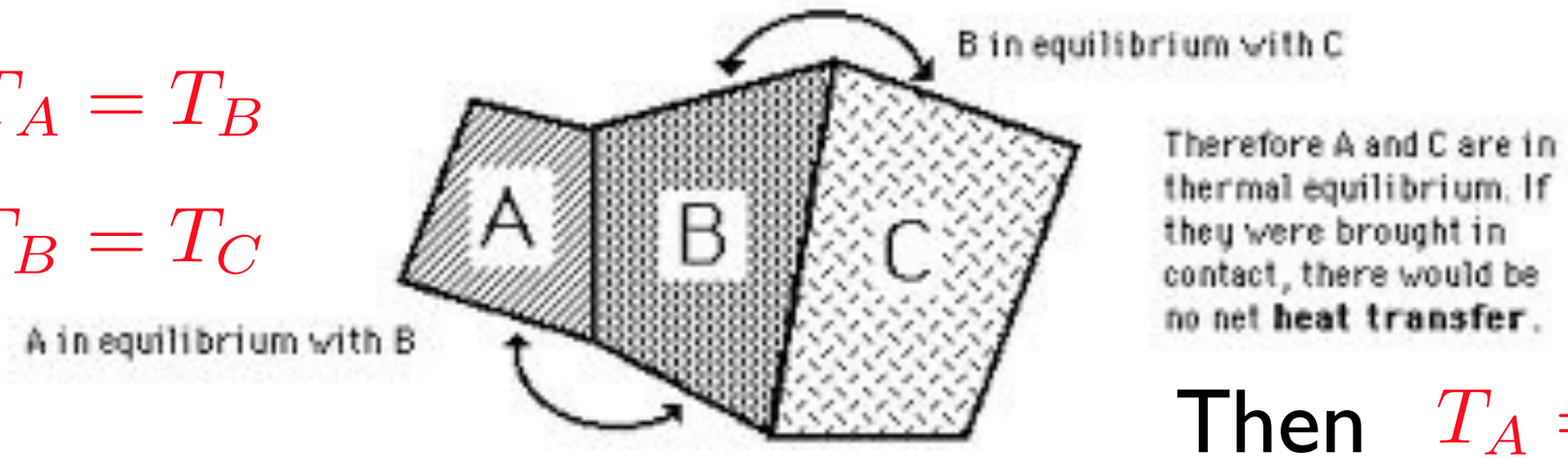
Second: Notion of entropy. Arrow of time. Later understood statistically, from micro-scopic atoms and molecules in matter Following week's main topic.

Zero-th law

Can assign a number, "temperature" to objects. If two objects have different temperatures, something happens when they are put in contact (heat transfer). They are temporarily out of equilibrium, and eventually reach equilibrium, where their temperatures are equal. If their temperatures are equal, they can be put in contact and remain in equilibrium.

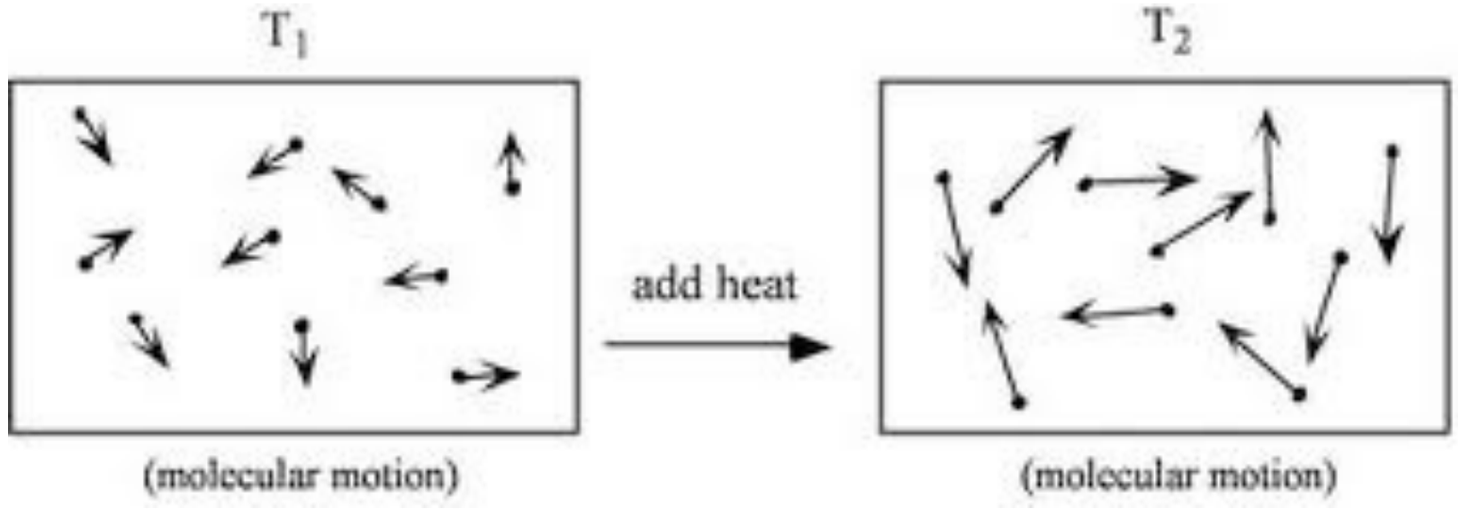
If $T_A = T_B$

and $T_B = T_C$



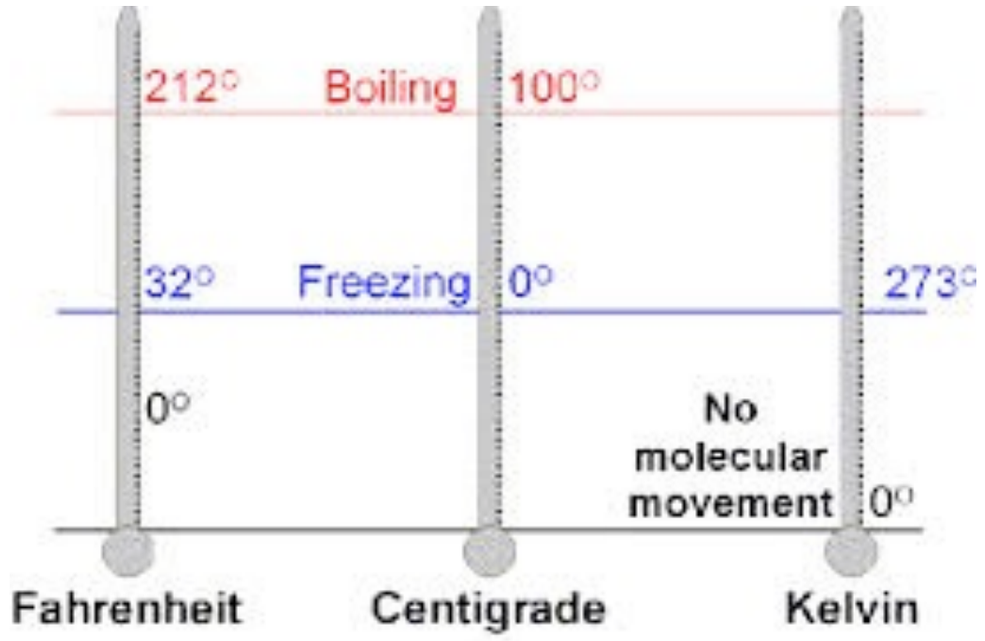
Then $T_A = T_C$

Micro picture (later)



"Temperature" characterizes the energy distribution of the constituents, e.g. molecules. Bigger "T" means they're moving around faster. There is a smallest T, called T=0 on the absolute scale, when everything is in the lowest energy state. If this classroom were at T=0, all air molecules would be in a pile on the floor.

Temperature scales



$$T_K \geq 0$$

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

British

Metric

$$T_C = T_K - 273$$

Kelvin or absolute scale, best choice for science.

Thermal expansion

How thermometers are built.

$$\frac{dL}{L} = \alpha dT$$

Fractional length change

Expansion coefficient, depends on material.

Temperature change

$$\frac{dV}{V} = \beta dT = 3\alpha dT$$

Fractional volume change

$$V \sim L^3$$

$$\beta_{quartz} = 0.12 \times 10^{-5}$$

$$\beta_{mercury} = 18 \times 10^{-5}$$

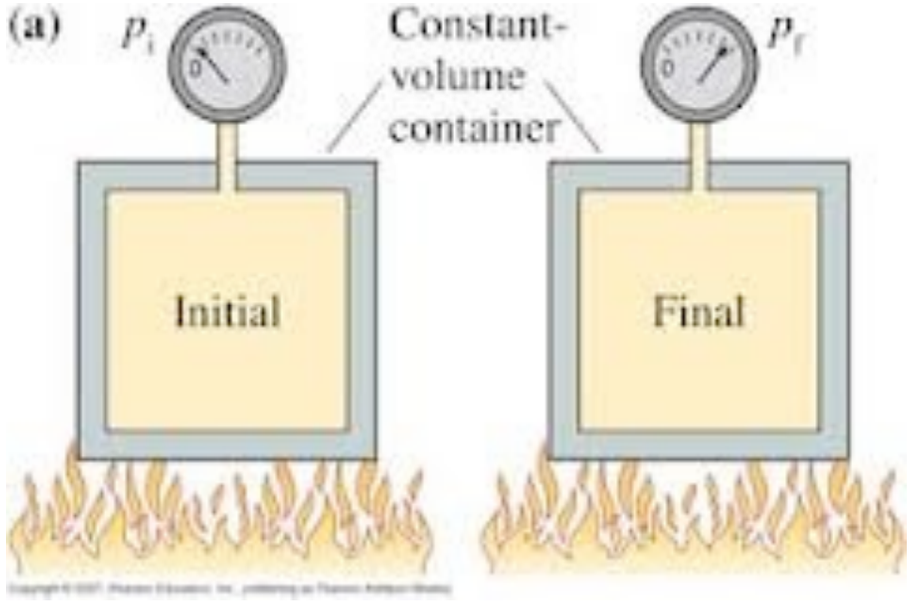
$$\beta_{ethanol} = 75 \times 10^{-5}$$

Ideal gas (low density)

$$PV \sim T$$

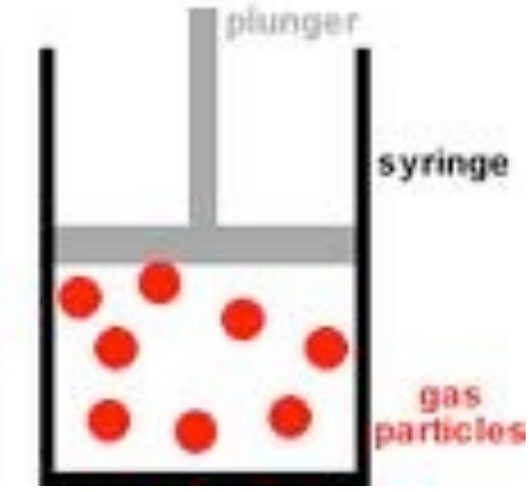
This is the absolute T (in K).

$$\frac{P_1 V_1}{P_2 V_2} = \frac{T_1}{T_2}$$



initial temperature = T_i

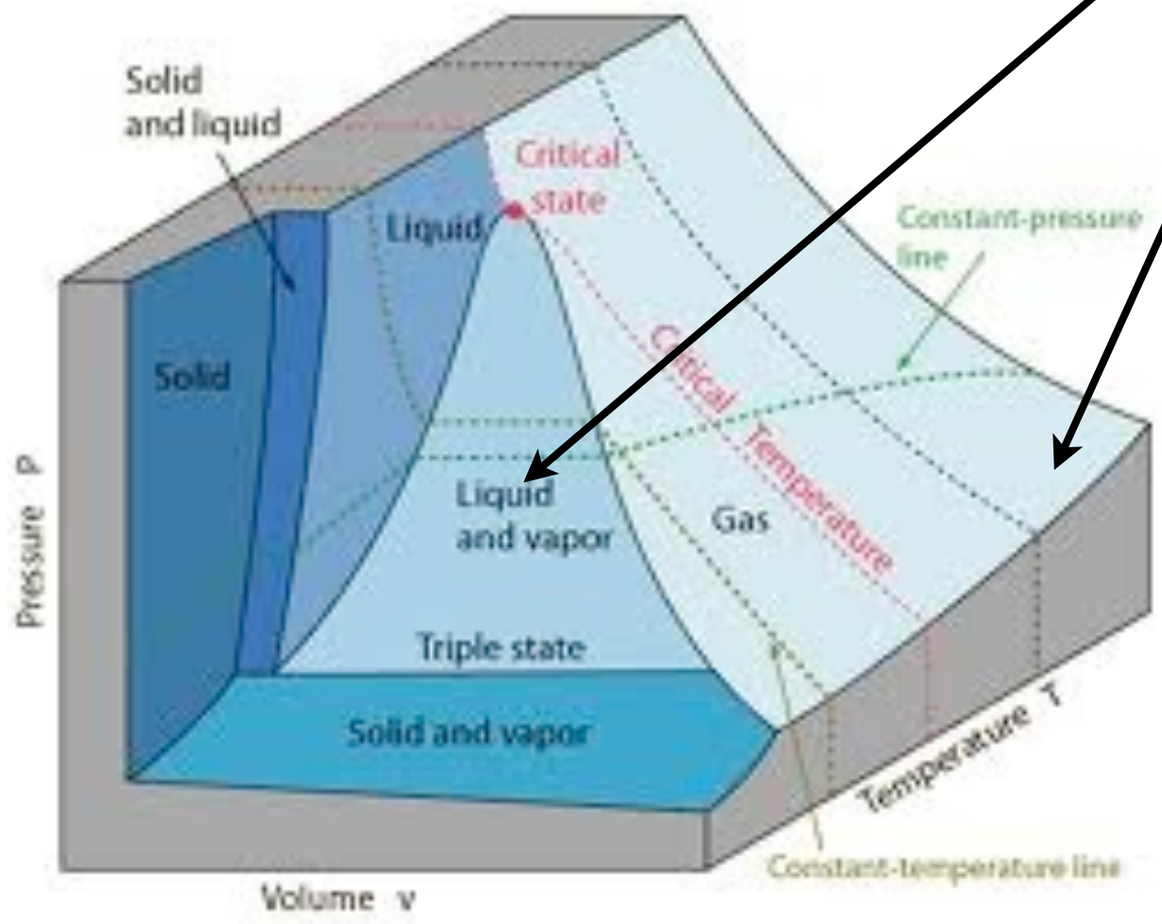
initial volume = V_i



We'll write the ideal gas eqn. more precisely in a few slides. Note we get zero pressure for zero T. That's because molecules then just sit on the bottom of the container. T and p is related to them bouncing around.

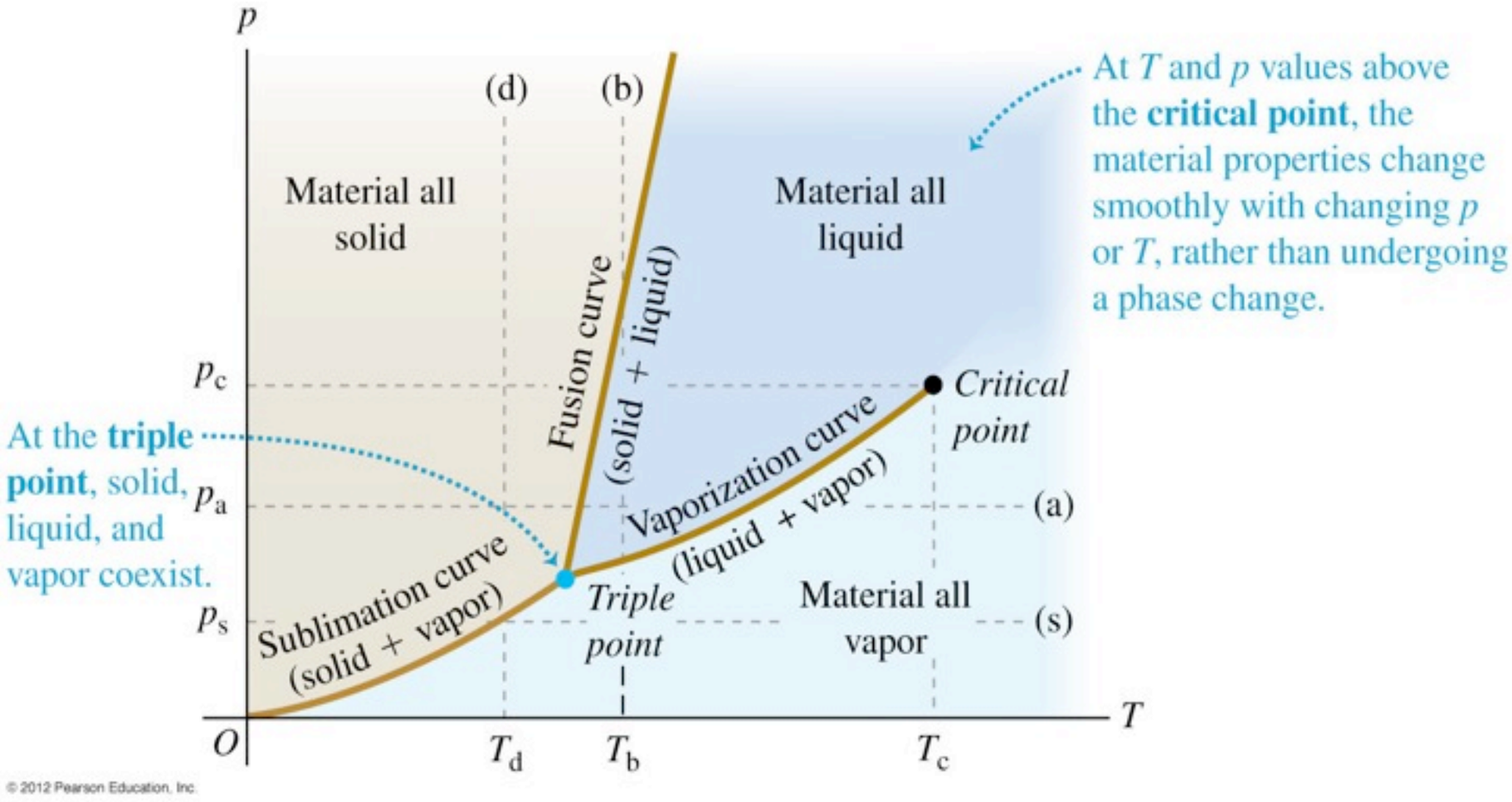
State variables: p, V, T

The gross (macroscopic) state of a system is specified by state variables, particularly p, V, T. In equilibrium, the state is on a 2d surface in the 3d space of (p, V, T), i.e. some f(p, V, T)=0.



equilibrium states surface.

Typical phase diagram



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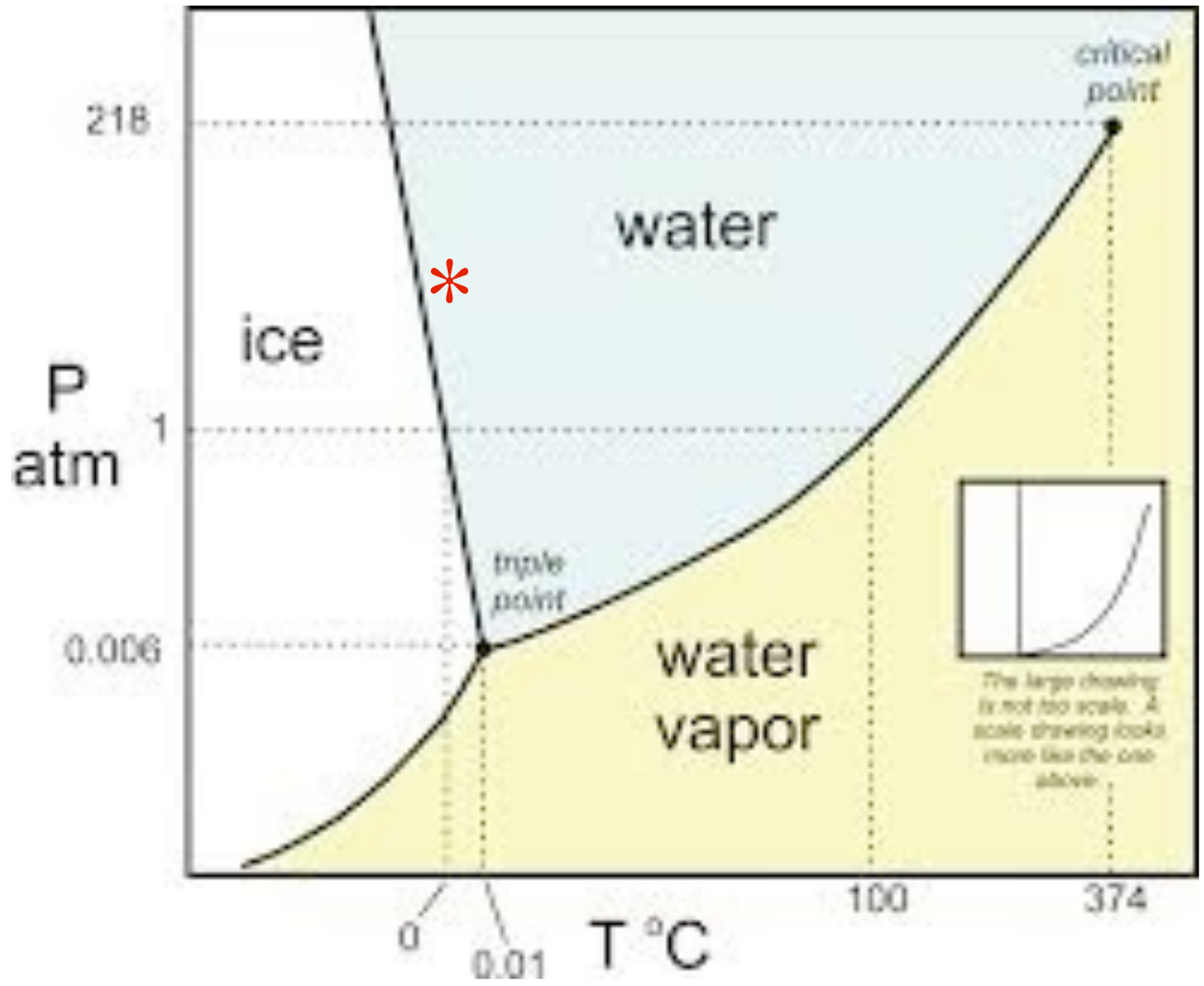
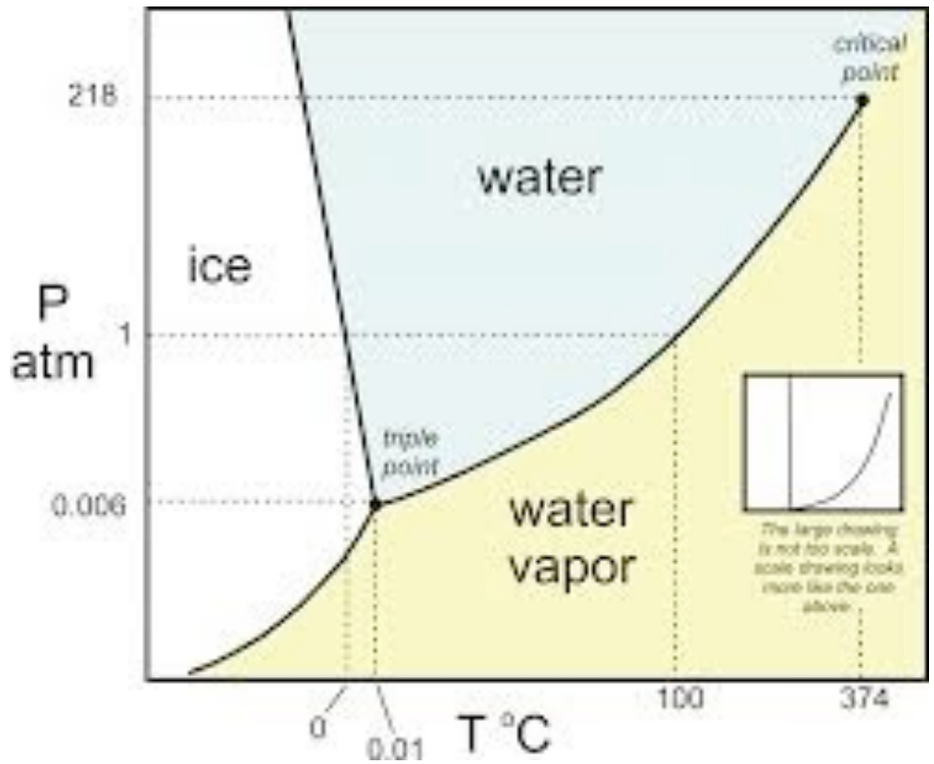
Water's phases



*The slope of this phase line is unusual. Relatedly, most liquids contract when frozen, but water expands. This is why ice floats, and why skiing works: the pressure of the skis melts the snow beneath, lubricating the ski-snow interface.

Water's triple point

Aside, cont.: If the temperature and the pressure are adjusted just right, ice, liquid, and steam can exist in equilibrium.

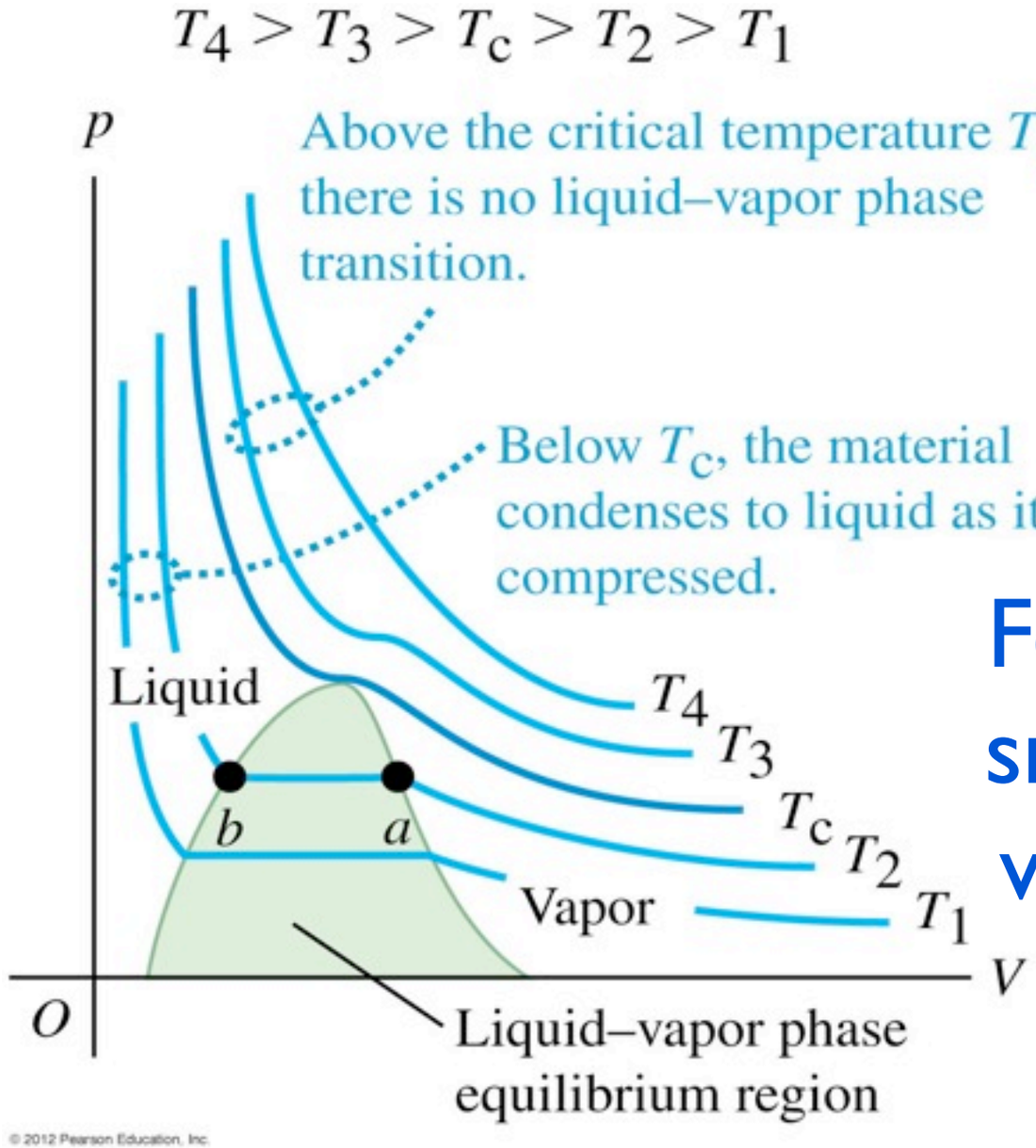


$T_{triple} \equiv 273.16K.$ $p_{triple} \equiv 610Pa$

Uniquely defines our T conventions.

E.g. could have a phone call with aliens, explaining our various conventions and names of things, and could thus explain to them what call temperature and e.g. the temperature of our planet. Physics is more than human conventions - it applies everywhere in the Universe.

Plot p, V for various T



For low densities (big V, small p, all gasses have a very simple p, V, T eqn...

Ideal Gas eqn.

$$pV = Nk_BT$$

Example of a (p,V,T) equilibrium surface. For any

N here is the number of gas molecules in the container of volume V. k is Boltzmann's constant.

Units: pV has the same units as energy. So does kT.

The book uses instead n and R (sigh...).

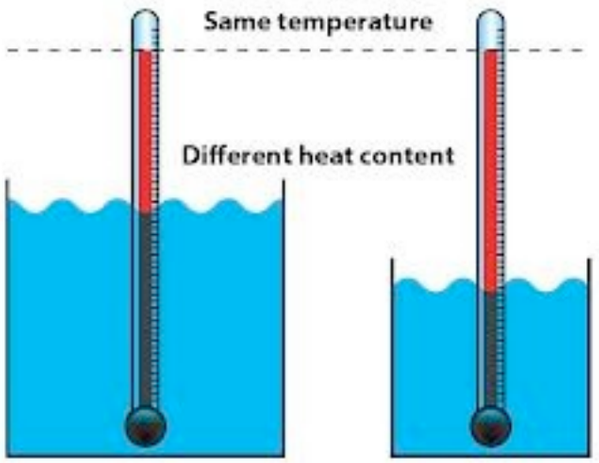
$$n \equiv N/N_A \qquad R \equiv kN_A \qquad N_A = 6.02 \times 10^{23}$$

$$Nk_B = nR \qquad R \approx 8.31 J/molK$$

Ideal gas eqn. applies whenever densities are low, i.e. when gas molecules don't interact with each other.

Heat (called Q)

It's basically energy (moving molecules). Units of energy, i.e. Joules. Bigger systems have more heat.

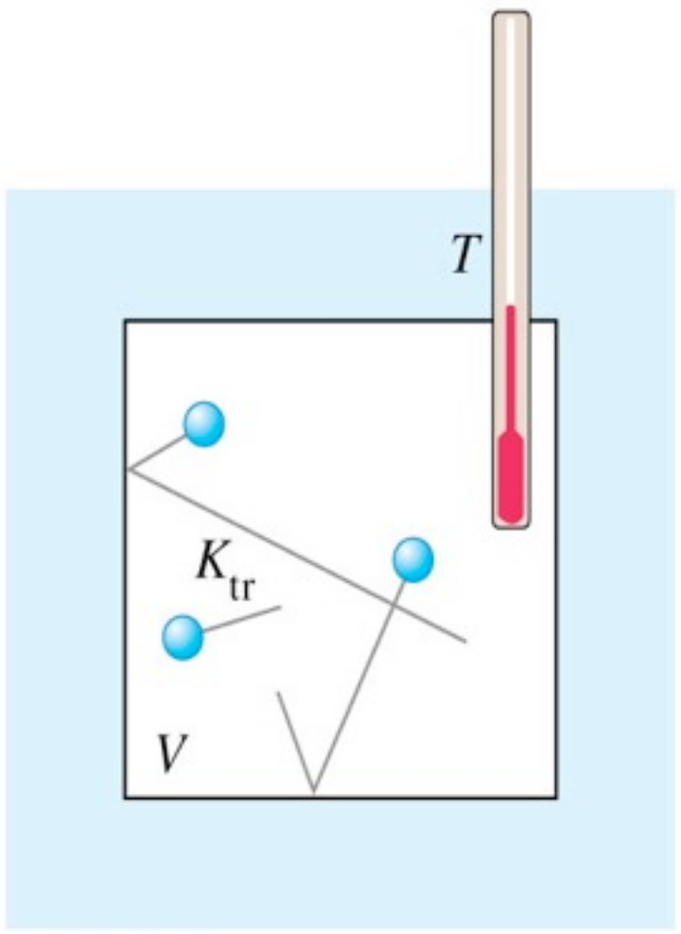


Heat, Q, is "extensive," i.e. it is proportional to size of the system. Temperature is "intensive," doesn't depend on size. Two systems of same T, brought in contact, still have same T, but the heat (internal energy) adds.

The actual Q value of a system isn't of much use. What's useful is the change in the heat, Delta Q. It's energy transferred from one system to another.

Heat's effect

(a)



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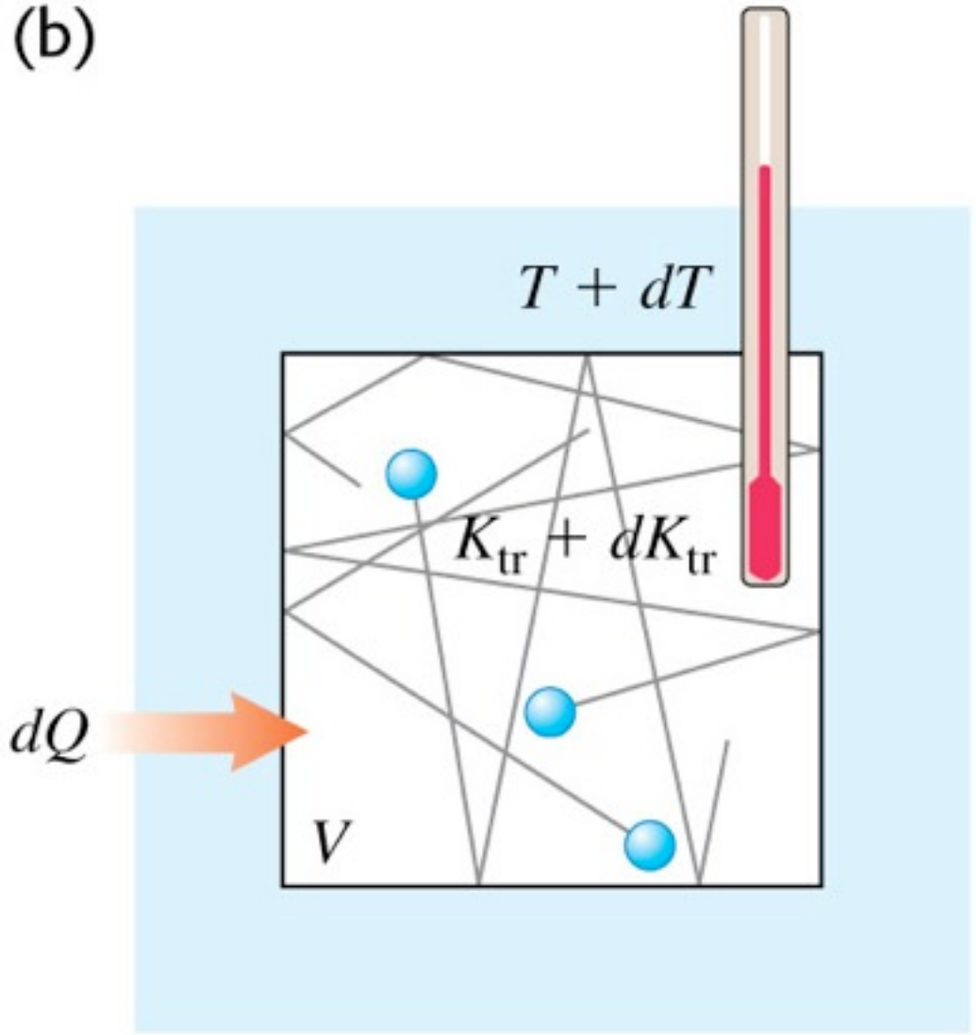
(b)



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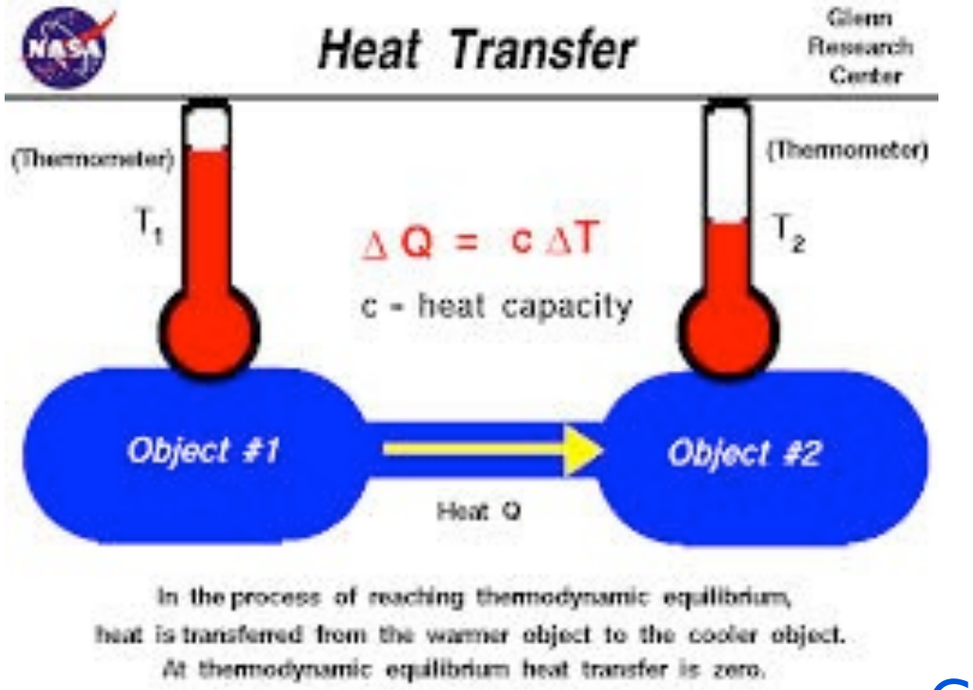
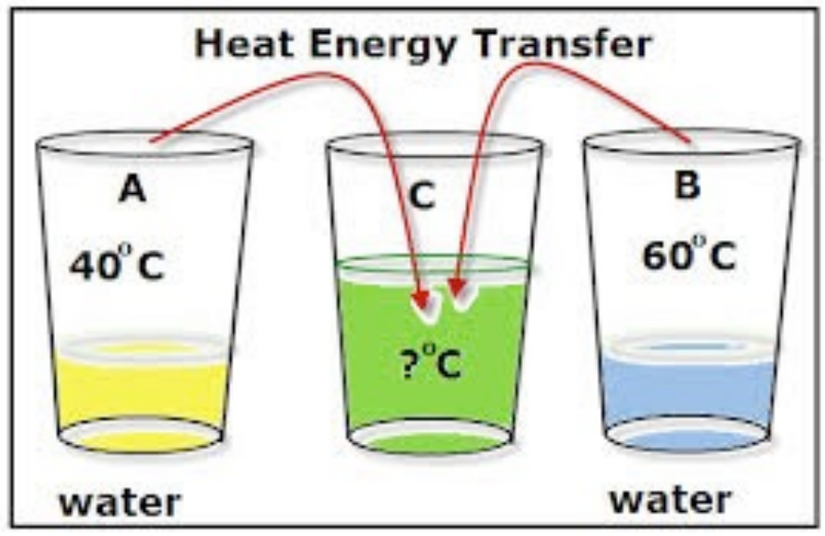
Heat transfer



In the process of reaching thermodynamic equilibrium, heat is transferred from the warmer object to the cooler object. At thermodynamic equilibrium heat transfer is zero.



Can be + or -, cooling is negative heating.

Heat transfer

$$dQ = mcdT$$

mass

Specific heat, c, e.g.

Temperature change

$$c_{water} \approx 4190 J/kgK$$

Heat of phase changes

Without phase change: $dQ = mcdT$

At a phase change: $dQ \neq 0,\ dT = 0$

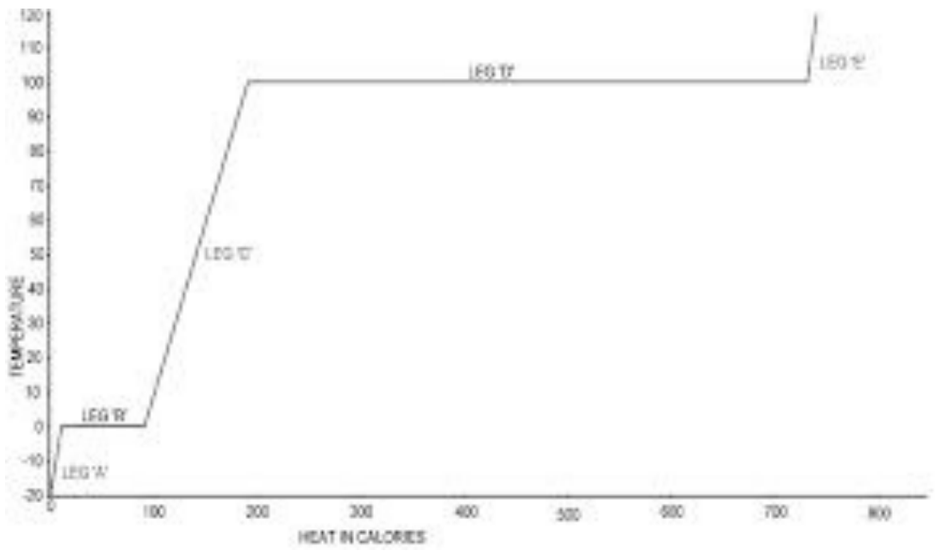
E.g. boiling water: phase change from liquid to gas. T=100C the whole time, as the pot of water boils away.

Solid to liquid: "(latent) heat of fusion."

Liquid to gas: "heat of vaporization

$$L_f^{water} = 3.34 \times 10^5 J/kg$$

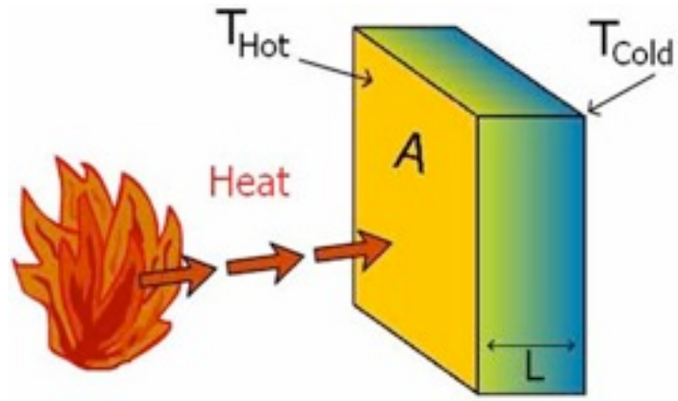
$$L_v^{water} = 2.256 \times 10^6 J/kg$$



Heat conduction current

$$H = \frac{dQ}{dt} = -kA\frac{dT}{dx} \xrightarrow[\text{uniform case}]{} \frac{Q}{t} = k\frac{A}{L}(T_H - T_C)$$

Since heat always flows in direction of decreasing T (next week: 2nd law).

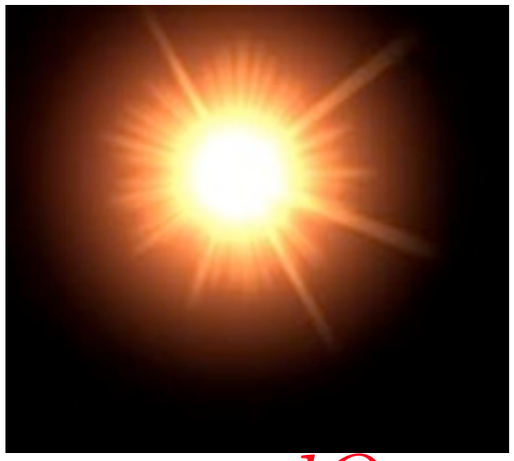


A = area of interface.

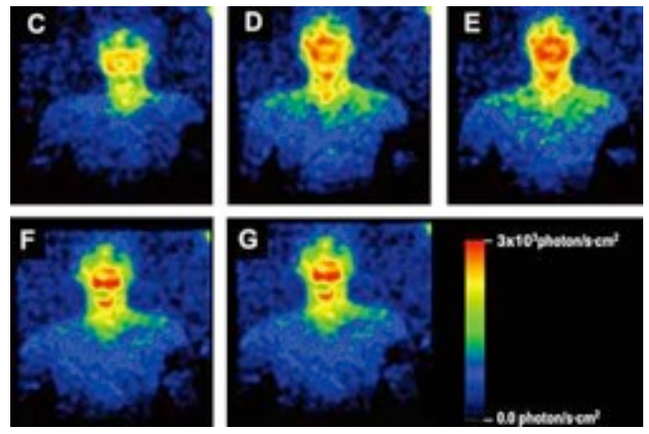
k = "thermal conductivity"

$$k_{copper} = 385 W/mK$$

$$k_{wood} \approx 0.8 W/mK$$



Radiation



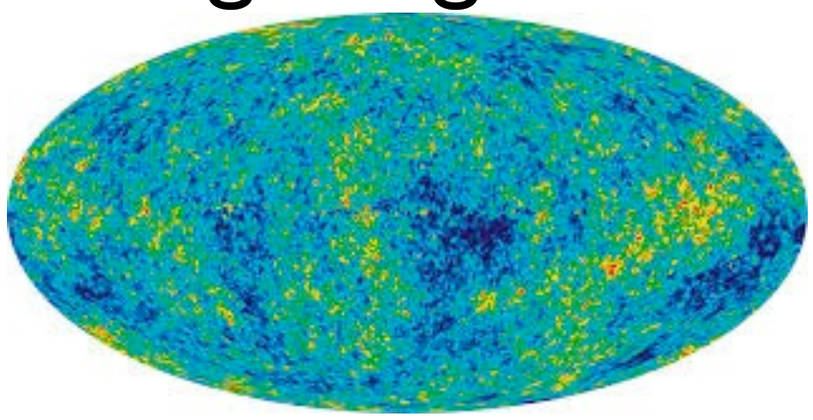
$$H = \frac{dQ}{dt} = Ae\sigma T^4$$

$$\sigma \approx 5.67 \times 10^{-8} Jm^{-2}s^{-1}K^{-4}$$

"Stefan-Boltzmann constant (= a combination of Planck's and Boltzmann's constants).

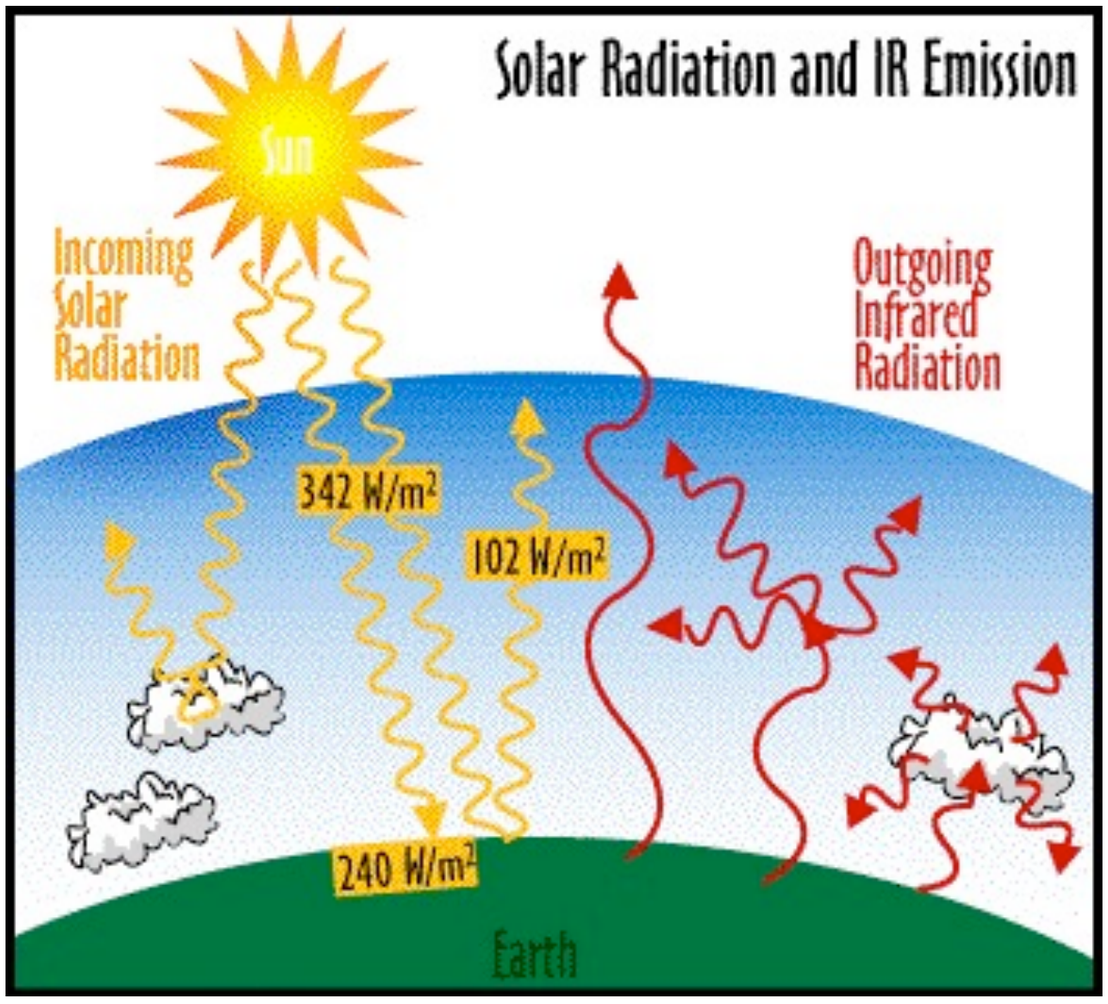
$$0 \leq e \leq 1 \qquad e_{white} < e_{black}$$

E.g. universe radiates like this, at a T of about 3K. Cosmic microwave background radiation, afterglow from big bang, it was discovered in 1964.



Recently mapped, slightly differing T over our universe.

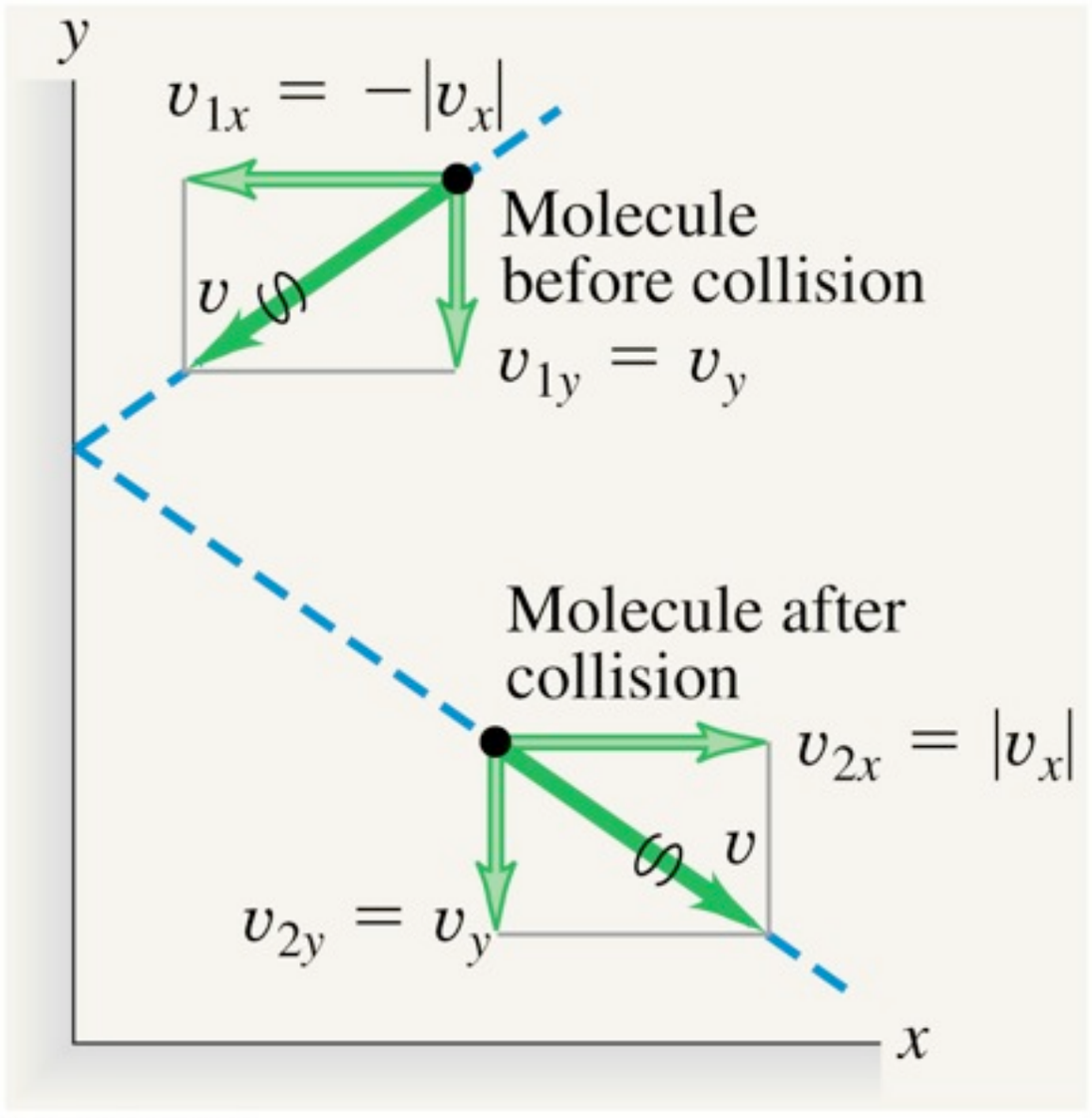
Climate science



Thermo & Stat Mech

- Thermodynamics came first, before knowing about atoms and molecules.
- At a microscopic level, thermodynamic results can be derived as a consequence of probabilities involving huge numbers (like Avagadro's) of molecules: "Statistical Mechanics." We'll only briefly see it here.
- Ideal gas law and energy equipartition.

Pressure from molecule's bouncing



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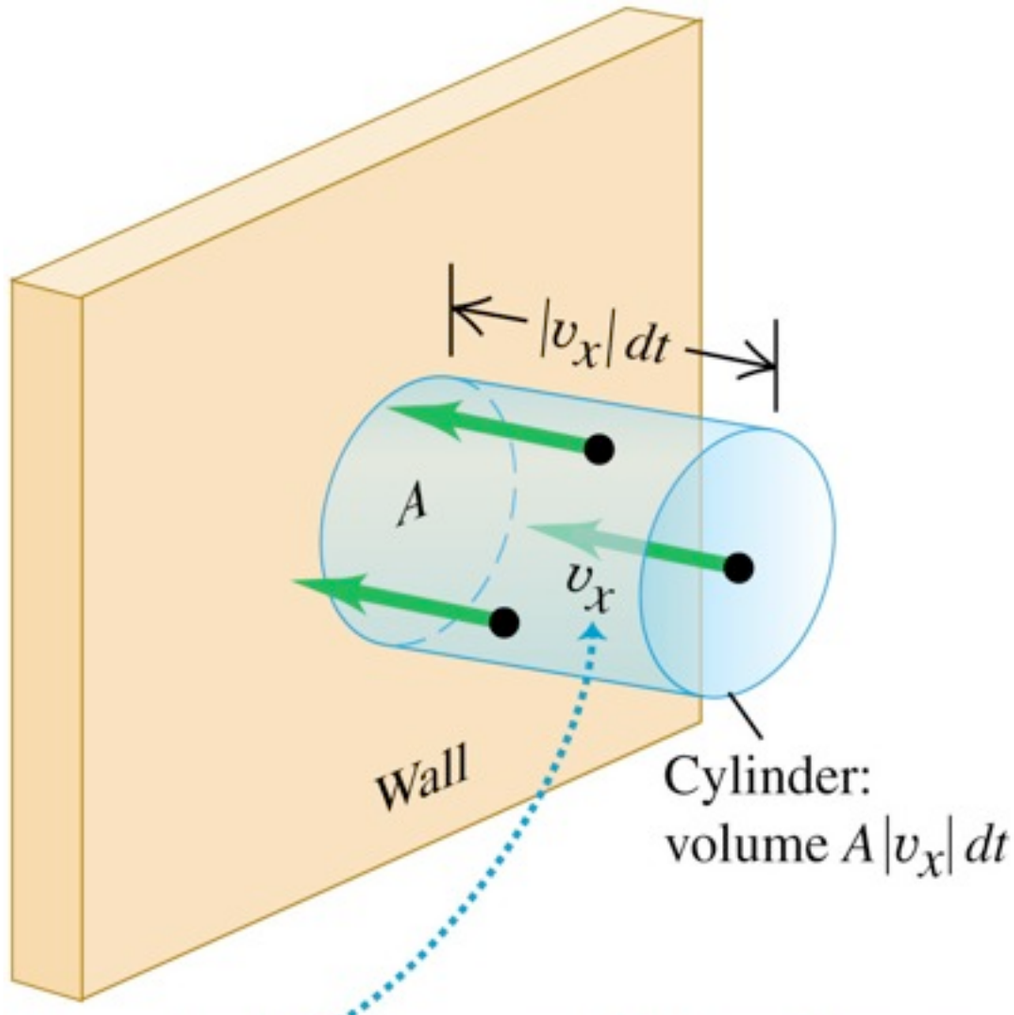

All molecules are assumed to have the same magnitude $|v_x|$ of x-velocity.

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Pressure & collisions

container wall

Gas molecules in here, bouncing off the walls.

$$p = \frac{F_\perp}{A} = \frac{dp_\perp}{Adt} = \frac{1}{2}\frac{N}{V}(Av_\perp dt)(2mv_\perp)\frac{1}{Adt} = \frac{N}{V}mv_\perp^2$$

So $pV = \frac{1}{3}Nm\overline{v^2}$ since $\overline{v_x^2} = \overline{v_y^2} = \overline{v_z^2} = \frac{1}{3}\overline{v^2}$

So an ideal gas has $\overline{E} = N\frac{1}{2}m\overline{v^2} = \frac{3}{2}NkT$

Each molecule has average kinetic energy $\boxed{\frac{3}{2}kT}$

$$v_{rms} \equiv \sqrt{\overline{v^2}} \qquad v_{rms} = \sqrt{\frac{3kT}{m}}$$

Equipartition

$$\frac{1}{2}m\overline{v_x^2} = \frac{1}{2}m\overline{v_y^2} = \frac{1}{2}m\overline{v_z^2} = \frac{1}{2}m\frac{\overline{v^2}}{3} = \frac{1}{2}kT$$

There are three translational degrees of freedom, and each has average energy $= \frac{1}{2}kT$. As we'll discuss more next week, this is a general result. Each "energy degree of freedom" has average value of $= \frac{1}{2}kT$.

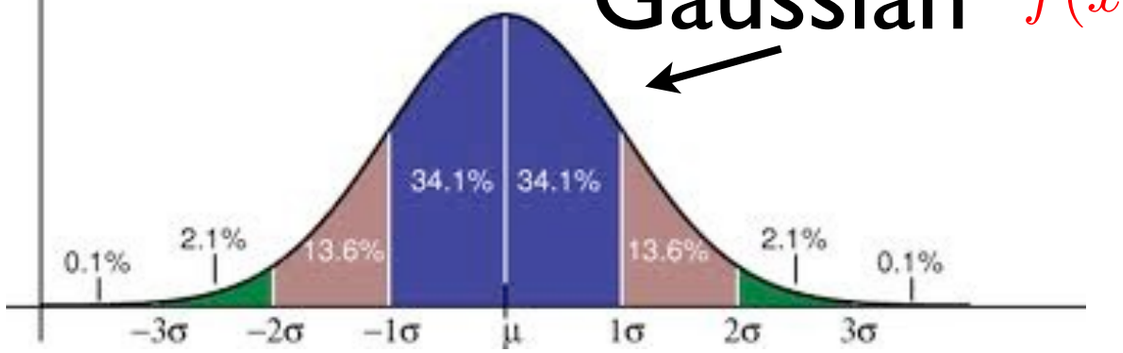
Molecules containing more than one atom also can have vibrational and rotational energy. Each gets an average value of $= \frac{1}{2}kT$

Maxwell-Boltzmann

Whenever you have a large uncorrelated sample, you get a "Gaussian probability distribution," fully specified by the "mean" and the "standard deviation."

plot number in sample

"Gaussian" $f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\bar{x})^2/2\sigma^2}$



vs. anything

The (x, y, z) components of molecule's velocity probability distribution behaves like this, with

$\overline{v_x} = \overline{v_y} = \overline{v_z} = 0$ and $\overline{v_x^2} = \overline{v_y^2} = \overline{v_z^2} = \sigma^2 = \frac{kT}{m}$

Zero mean

Standard deviation width given by T/m. Hotter T means higher RMS v.