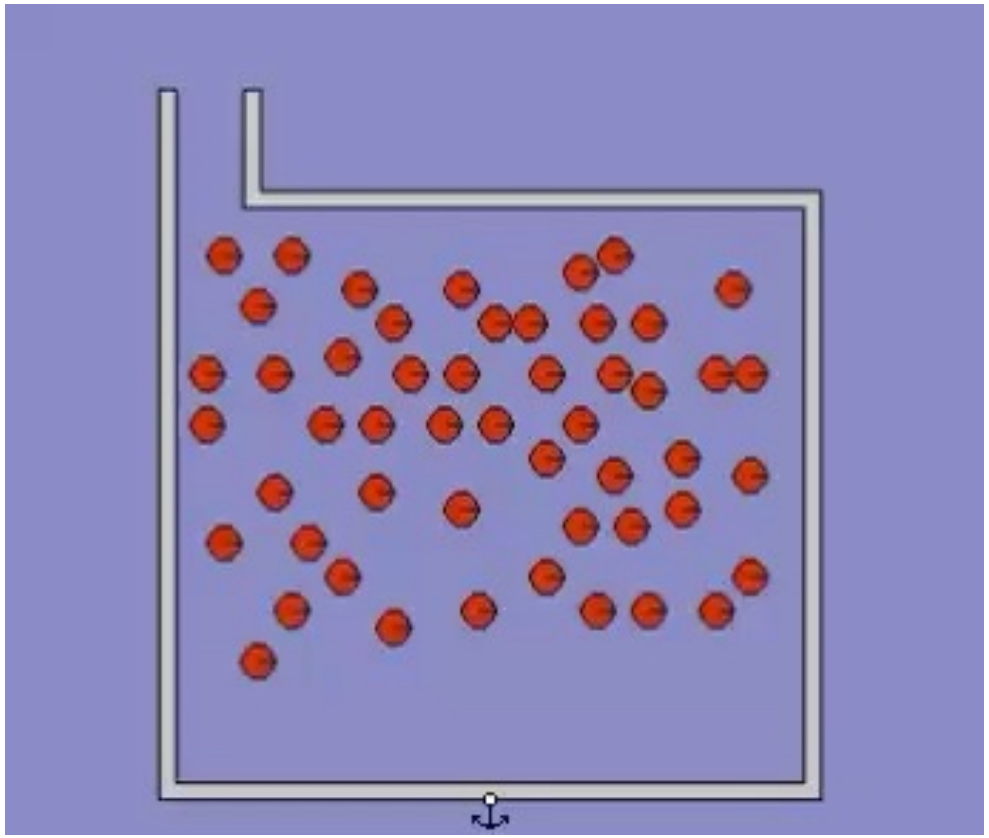
Physics 121.
First law of thermodynamics.



http://eml.ou.edu/Physics/module/thermal/ketcher/Idg4.avi

Physics 121.
Lecture 24.

- Course Information
- Topics to be discussed today:
  - The ideal gas law (review).
  - The real equation of state.
  - The first law of thermodynamics.

Physics 121.
Lecture 24.

- Homework set # 10 is due on Saturday morning, May 2, at 8.30 am.
- Set # 10 is optional. Your final homework grade will be determined after removing your lowest homework grade.
- There will be no office hours and workshops on Tuesday, Wednesday, Thursday, and Friday. The only exception are my office hours on Thursday. You can pick up the written components of HW 5 and HW 7 or ask questions.
- You will receive your grade on exam # 3 on Monday May 4 (via email).
- You can pick up Exam # 3 in the POA on Monday May 4, time TBD.
- The final exam will be on Friday May 8 at 7.15 pm in Hubble.

Quiz.

- Let us practice what we have learned.

The molecular point of view of a gas.

- Obtained using the molecular point of view:

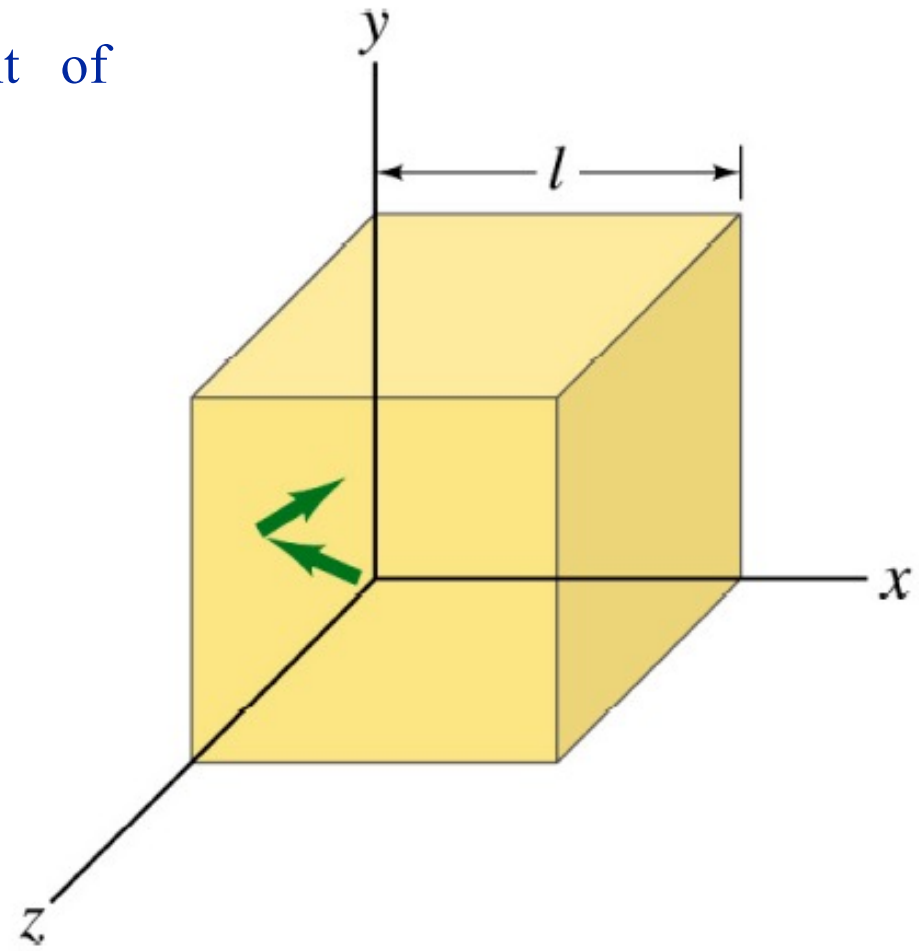
$$pV = mN(v^2)_{average}/3$$

- Obtained using the ideal gas law:

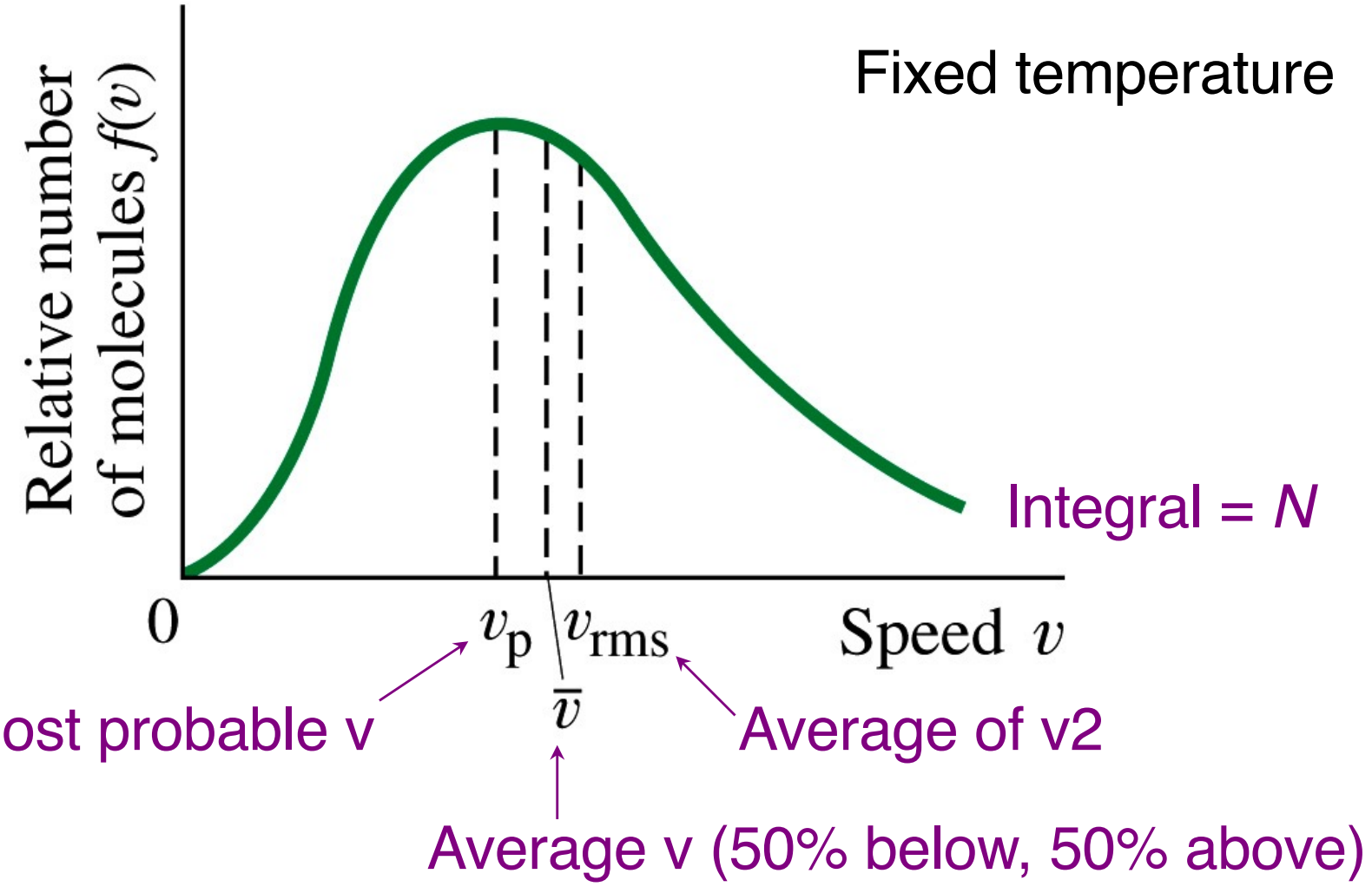
$$pV = NkT$$

- The two points of view show that

$$kT = \frac{mN(v^2)_{average}}{3} = \frac{2}{3}K_{average}$$

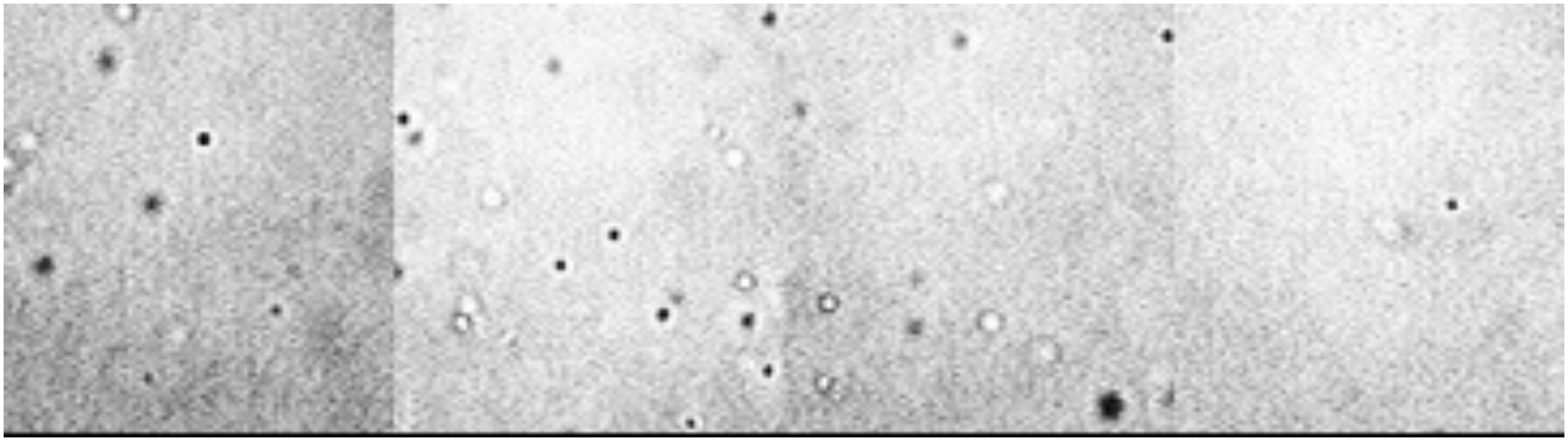


Distribution of molecular speeds. The Maxwell distribution.



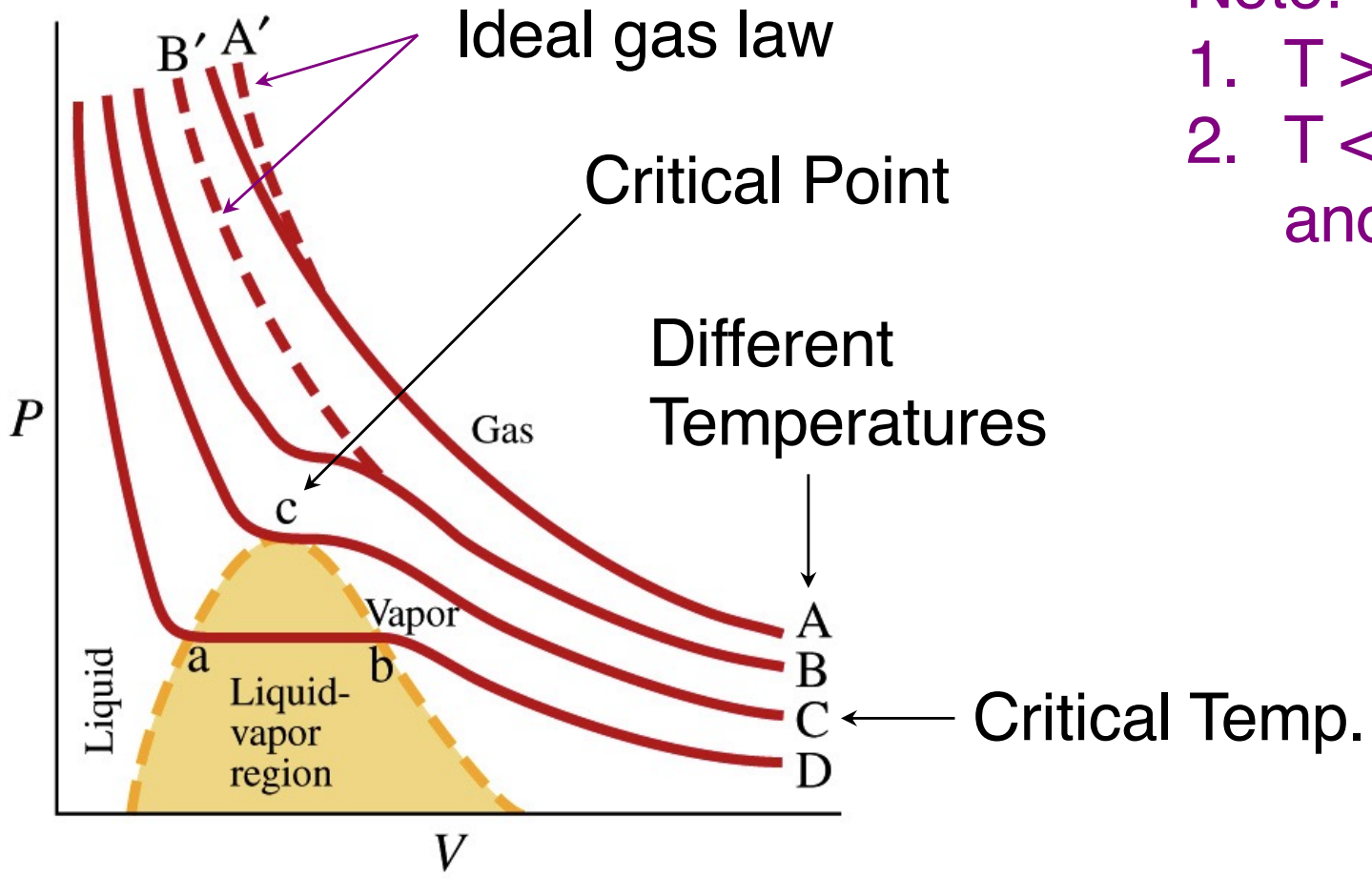
Probing molecular speeds in liquids.

0.5 μm particles in water, 50/50 glycerol-water, 75/25 glycerol-water, glycerol



http://www.physics.emory.edu/~weeks/squishy/BrownianMotionLab.html

The real equation of state. Different points of view.

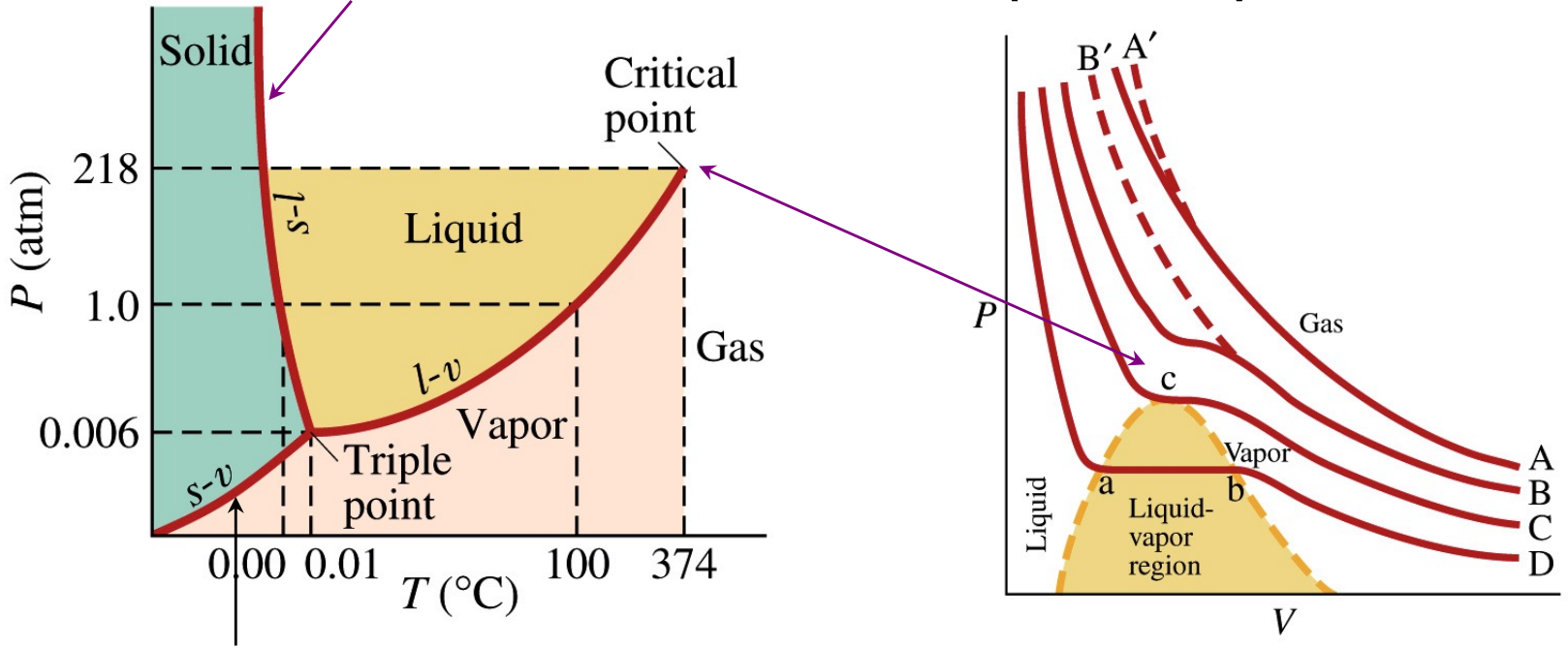


Note:

1. $T > T_c$: gas
2. $T < T_c$: liquid and/or vapor.

The real equation of state. Different points of view.

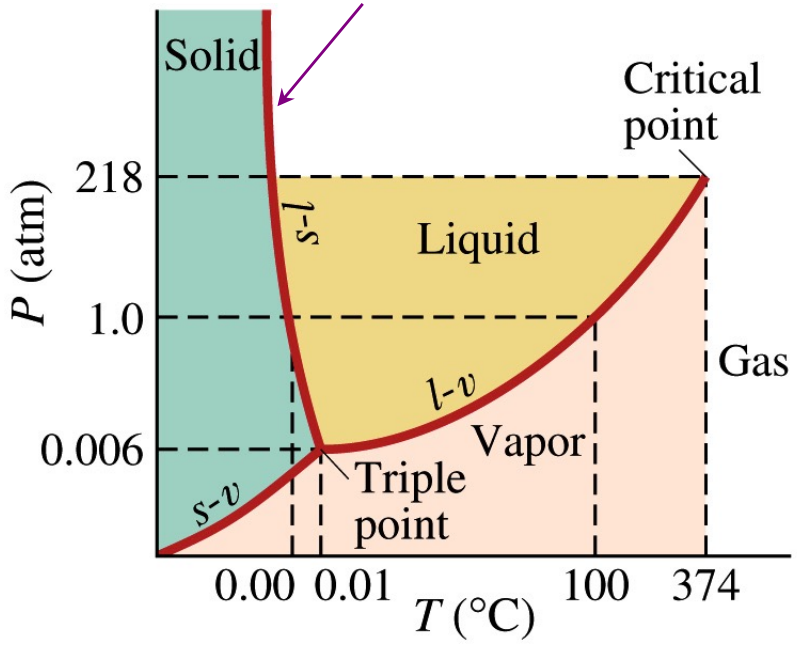
Note the curvature of the solid-liquid line.
Curvature to the left implies expansion on cooling.



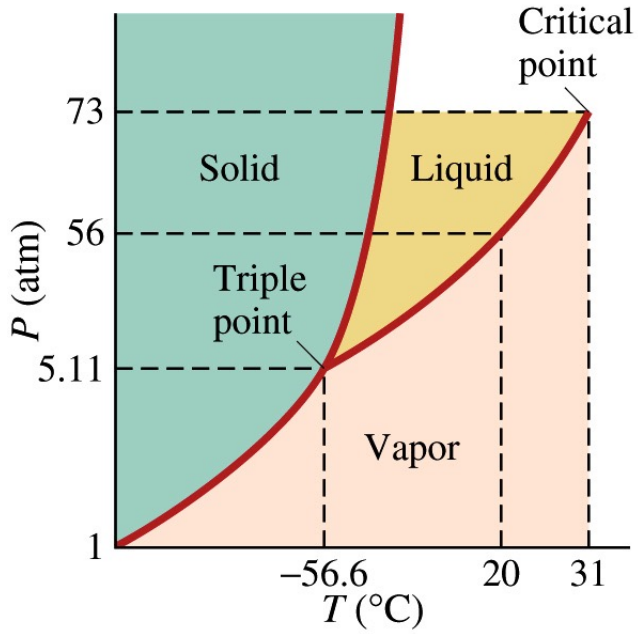
Direct change from solid to vapor.

The real equation of state. Different points of view.

Note the curvature of the solid-liquid line.
Curvature to the left implies expansion on cooling.



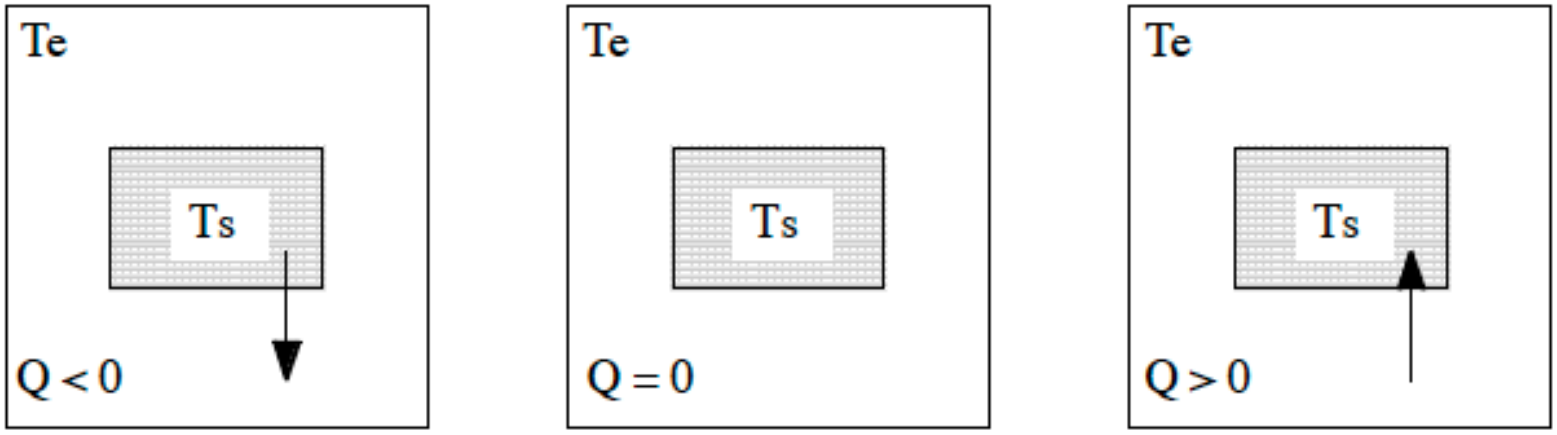
Water



CO_2

Heat and thermal equilibrium.

- When two objects are brought in thermal contact they can achieve thermal equilibrium via the exchange of heat.
- The exchange of heat will continue until the two objects have the same temperature.
- Energy can also be exchanged if work is done.



Heat.

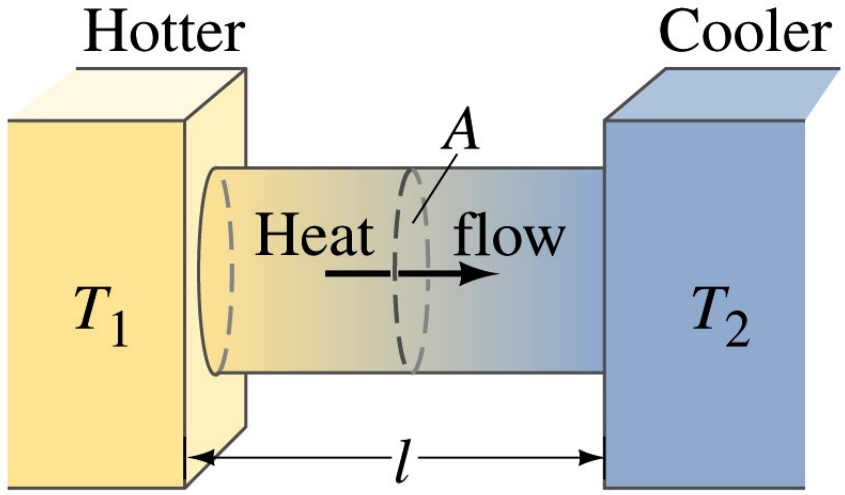
- We commonly use Q to indicate the amount of heat transferred.
- Since heat is a form of energy, its unit is the Joule.
- Another commonly used unit for heat is the calorie. One calorie is defined as the mount of heat required to raise the temperature of 1 g of water from 14.5°C to 15.5°C. 1 cal = 4.186 J.

Transfer of heat.

- Heat can be transferred in a number of different ways:
  - **Conduction**: transfer of heat via molecular collisions. Usually the dominant mechanism for heat transfer in metals.
  - **Convection**: transfer of heat of mass movement of molecules. Usually the dominant mechanism of heat transfer in liquids and gases.
  - **Radiation**: transfer of heat using electromagnetic radiation (e.g. light).
- We will now briefly discuss each of these mechanisms in more detail.

Transfer of heat. Conduction.

- The rate of heat transfer (Q/t) via conduction depends on
  - The temperature difference ΔT
  - The cross-sectional area A
  - The length of the conductor l
  - The properties of the material
- The following expression for Q/t was found experimentally:



$$H = \frac{Q}{t} = kA\,\frac{T_H - T_C}{L}$$

k: Thermal Conductivity

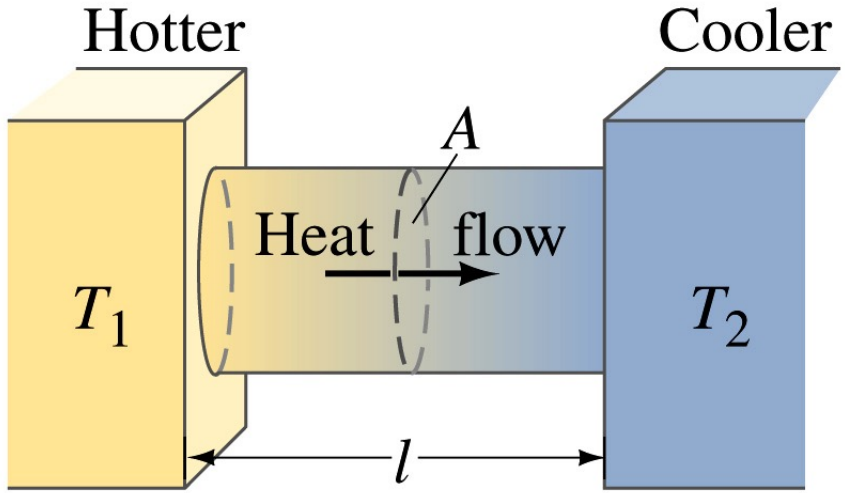
Transfer of heat. Conduction.

$$H = \frac{Q}{t} = kA\,\frac{T_H - T_C}{L}$$

- Large values of k (200 - 400 J/(s m °C) occur for good heat conductors.
- Poor conductors have small values of k: 0.01 – 1 J/(s m °C).
- Instead of the thermal conductivity, we often specify the thermal resistance R for insulators:

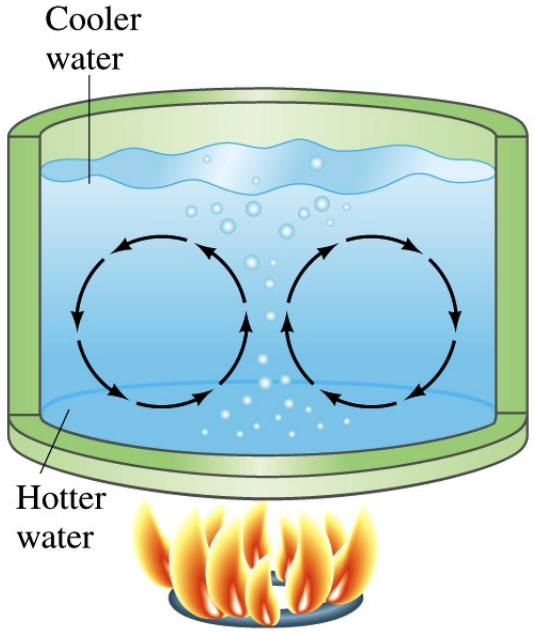
$$R = l/k$$

- R is called the R value of the insulator.



Transfer of heat.
Convection.

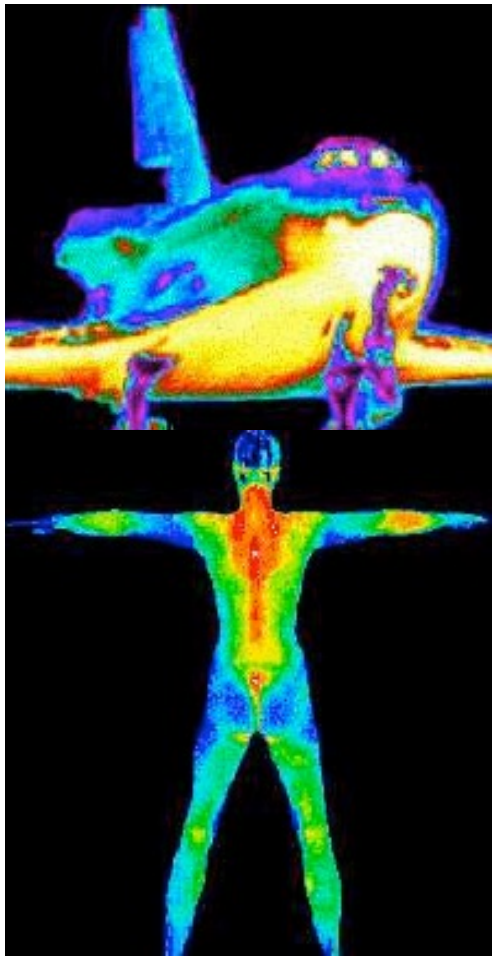
- Convection transfers heat by the mass movement of molecules from one location to another location.
- The driving force behind convection is thermal expansion, which results in a decrease in density with an increase in temperature.



Transfer of heat. Radiation.

- Conduction and convection require a medium to transfer heat.
- If the medium is absent, heat can still be transferred, but only via radiation.
- Good example of transfer of heat via radiation:
  - The sunlight that heats up the earth.
  - Infra-red radiation allowing us to see in the dark.

Courtesy of Inframetrics



Courtesy of Meditherm

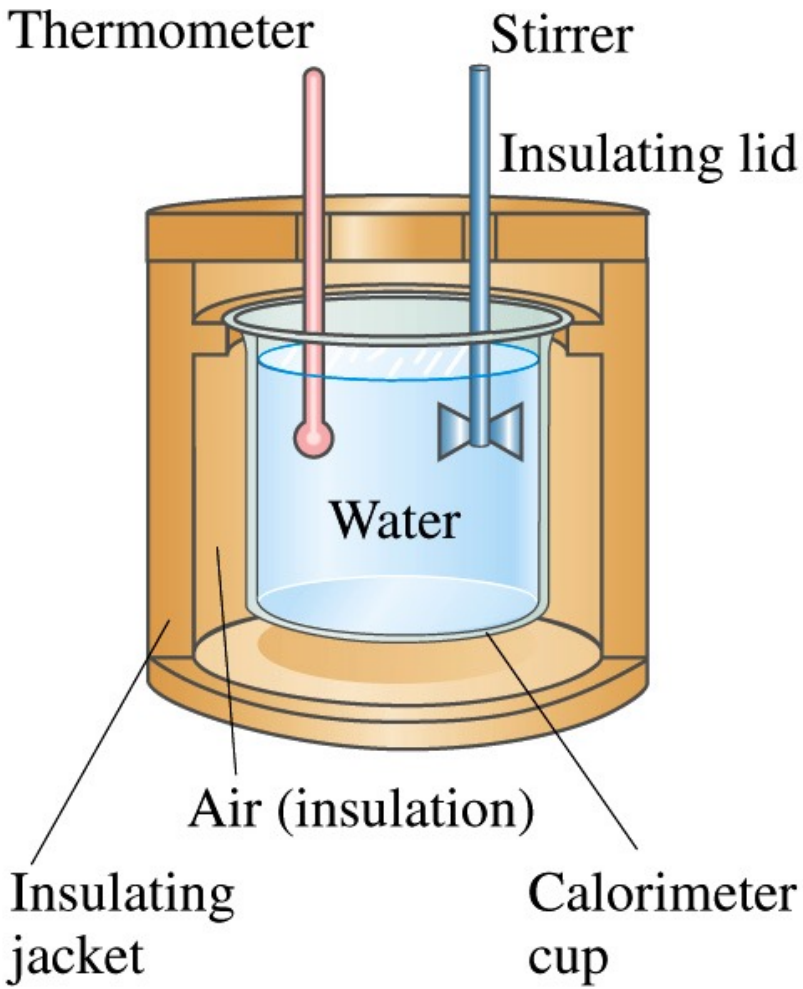
Heat and heat capacity.

- When heat is added to an object, its temperature will increase:

$$Q = C(T_f - T_i)$$

- The coefficient C is the heat capacity of the object. It depends on the type and the amount of material used.
- In order to remove the dependence on the amount of material, we prefer to use the heat capacity per unit mass c:

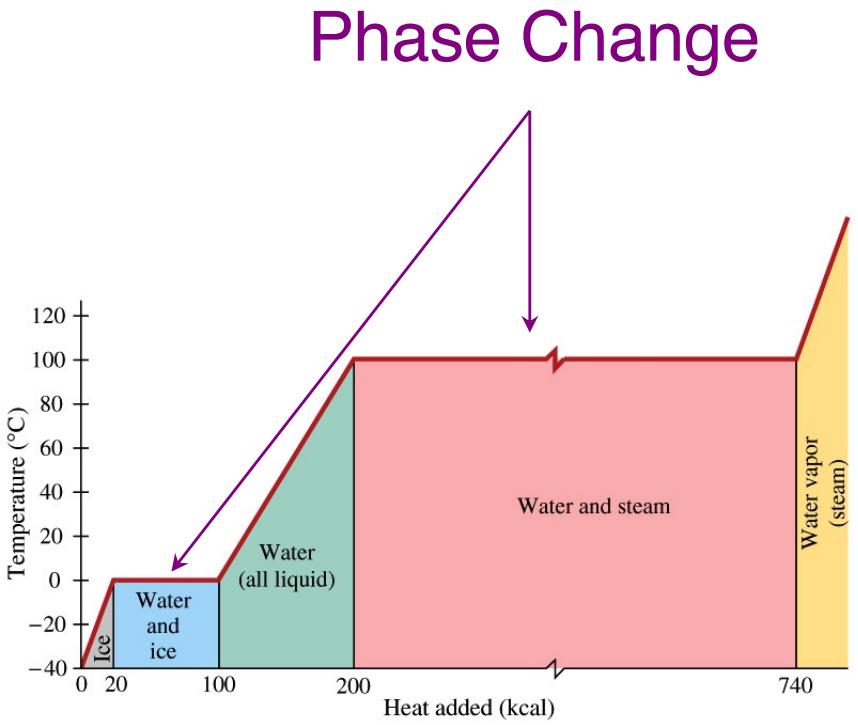
$$Q = mc(T_f - T_i)$$



Latent heat.

- When heat is added to a solid or a liquid, the temperature of the sample does not necessarily rise.
- During a phase change (melting, boiling) heat is added to the sample without an increase in temperature.
- The amount of heat transferred per mass unit during a phase change is called the **heat of transformation** $\boldsymbol{L}$:

$$Q = Lm$$



3 Minute 19 Second Intermission.

- Since paying attention for 1 hour and 15 minutes is hard when the topic is physics, let's take a 3 minute 19 second intermission.

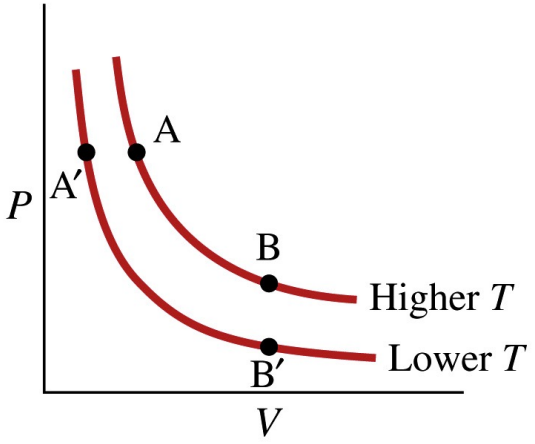
- You can:
  - Stretch out.
  - Talk to your neighbors.
  - Ask me a quick question.
  - Enjoy the fantastic music.

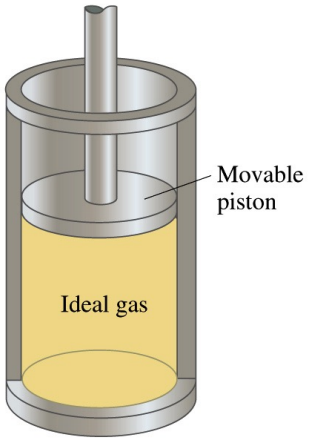
First law of thermodynamics.

- Consider a closed system:
  - Closed system
    - No change in mass
    - Change in energy allowed (exchange with environment)
  - Isolated system:
    - Closed system that does not allow an exchange of energy
- The internal energy of the system can change and will be equal to the heat added tot he system minus the work done by the system: $\Delta U = Q - W$
- Note: keep track of the signs:
  - Heat: Q > 0 means heat added, Q < 0 means heat lost
  - Work: W > 0 mean work done by the system, W < 0 means work done on the system

First law of thermodynamics. Isothermal processes.

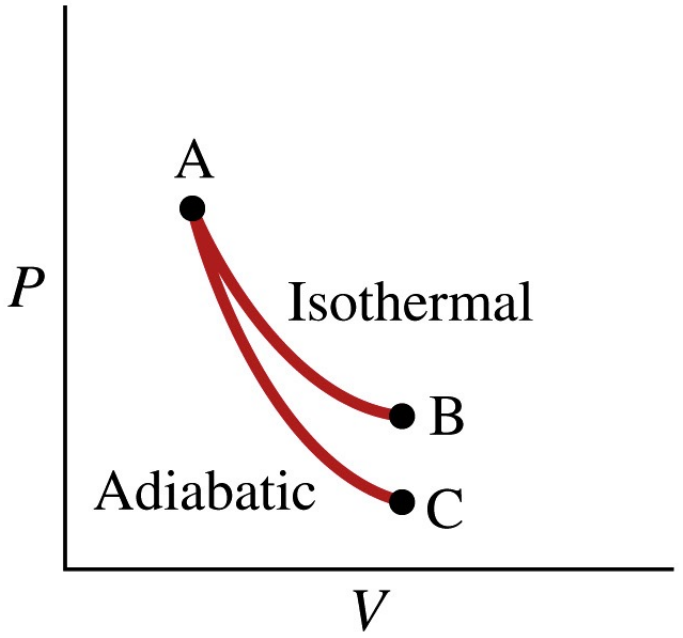
- An isothermal process is a process in which the temperature of the system is kept constant.
- This can be done by keeping the system in contact with a large heat reservoir and making all changes slowly.
- Since the temperature of the system is constant, the internal energy of the system is constant ($\Delta U = 0$ J).
- The first law of thermodynamics thus tells us that $Q = W$.





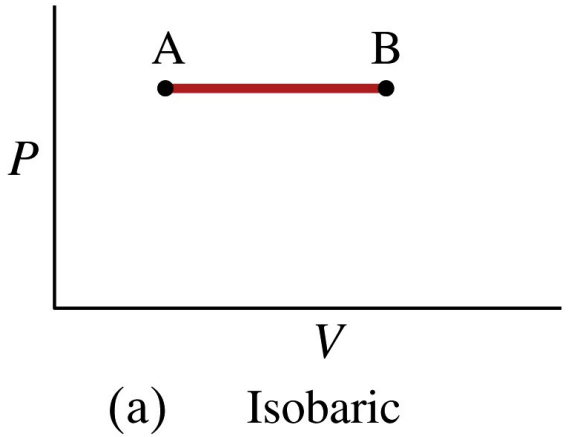
First law of thermodynamics. Adiabatic processes.

- An adiabatic process is a process in which there is no flow of heat (the system is an isolated system).
- Adiabatic processes can also occur in non-isolated systems, if the change in state is carried out rapidly. A rapid change in the state of the system does not allow sufficient time for heat flow.
- The expansion of gases differs greatly depending on the process that is followed (see Figure).



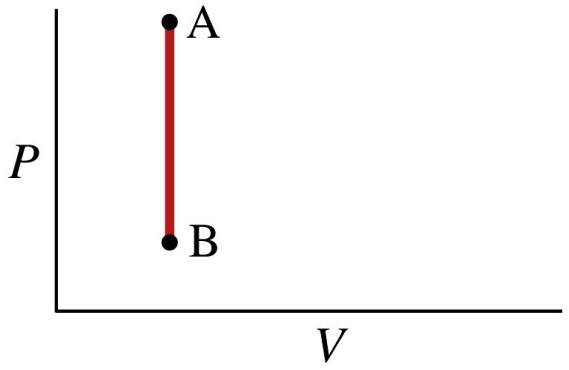
First law of thermodynamics. Isobaric and isochoric processes.

- Isobaric processes:
  - Processes in which the pressure is kept constant.



(a) Isobaric

- Isochoric processes:
  - Processes in which the volume is kept constant.



(b) Isochoric

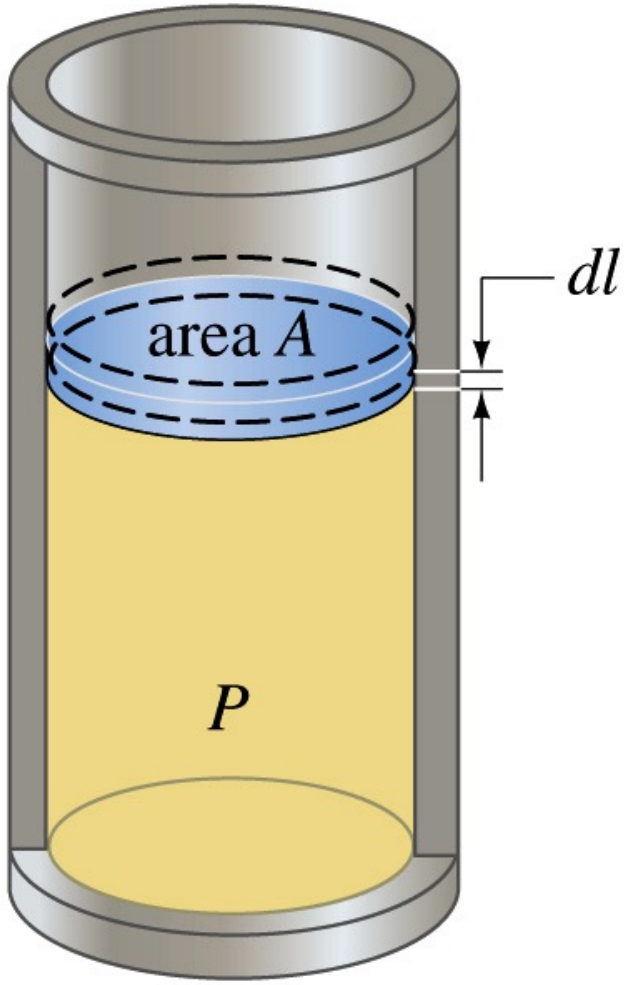
Work done during expansion/compression.

- Consider an ideal gas at pressure p.
- The gas exerts a force F on a moveable piston, and $F = pA$.
- If the piston moves a distance dl, the gas will do work:

$$dW = Fdl$$

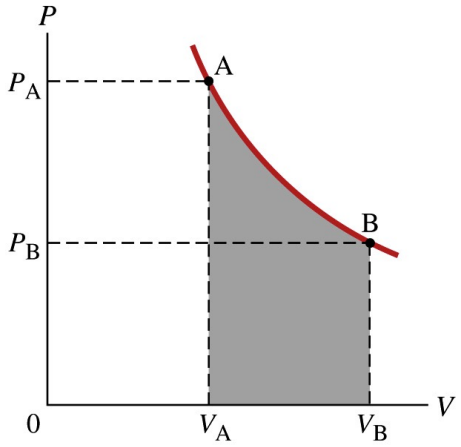
- The work done can be expressed in terms of the pressure and volume of the gas:

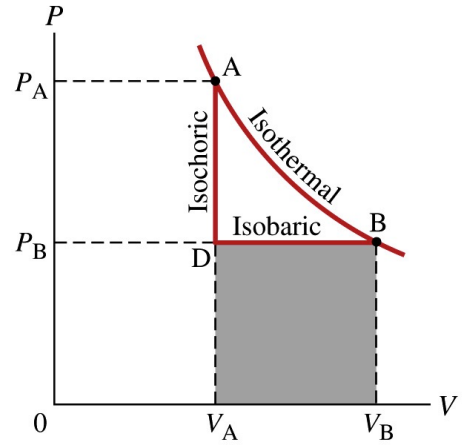
$$dW = pAdl = pdV$$



Work done during expansion/compression.

- The work done during the expansion of a gas is equal to the area under the pV curve.
- Since the shape of the pV curve depends on the nature of the expansion, so does the work done:
  - Isothermal: $W = nRT \ln(V_B / V_A)$
  - Isochoric: $W = 0$
  - Isobaric: $W = p_B (V_B - V_A)$





First law of thermodynamics. Molecular specific heat.

- When we add heat to a system, its temperature will increase.
- For solids and liquids, the increase in temperature is proportional to the heat added, and the constant of proportionality is called the specific heat of the solid or liquid.
- When we add heat to a gas, the increase in temperature will depend on the other parameters of the system. For example, keeping the volume constant will results in a temperature rise that is different from the rise we see when we keep the pressure constant (the heat capacities will differ):
  - $Q = nC_V\Delta T$ (Constant Volume)
  - $Q = nC_P\Delta T$ (Constant Pressure)

  Here, C_V and C_P are the molecular specific heats for constant volume and constant pressure. And n is the number of moles of gas.

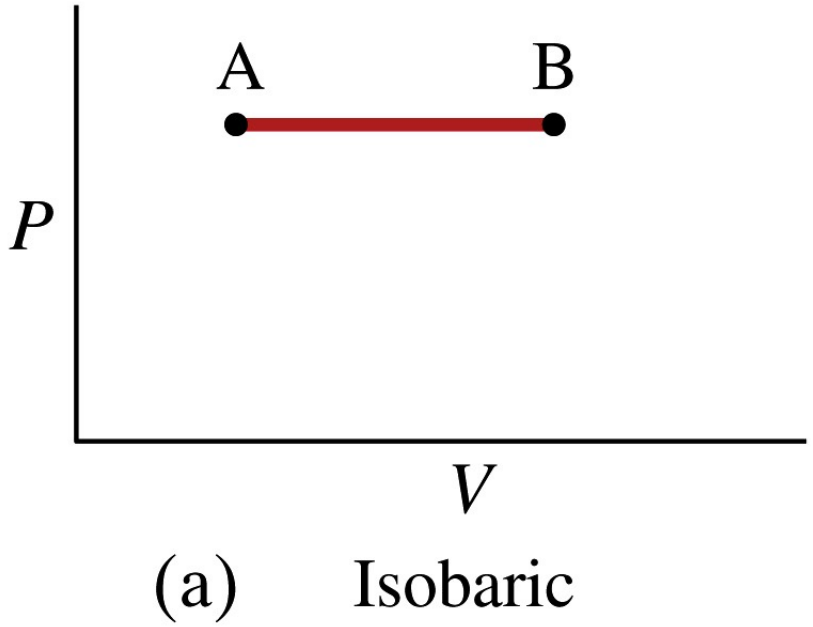
First law of thermodynamics. Molecular specific heat (p = const.).

- Consider what happens when we add Q_p to the system while keeping its pressure constant.
- The work done by the gas will be $p\Delta V$.
- Using the ideal gas law, we can rewrite the work done by the gas as

$$p(nR\Delta T/p) = nR\Delta T.$$

- The change in the internal energy of the gas is thus equal to

$$\Delta U = Q_p - nR\Delta T = nC_P\Delta T - nR\Delta T$$



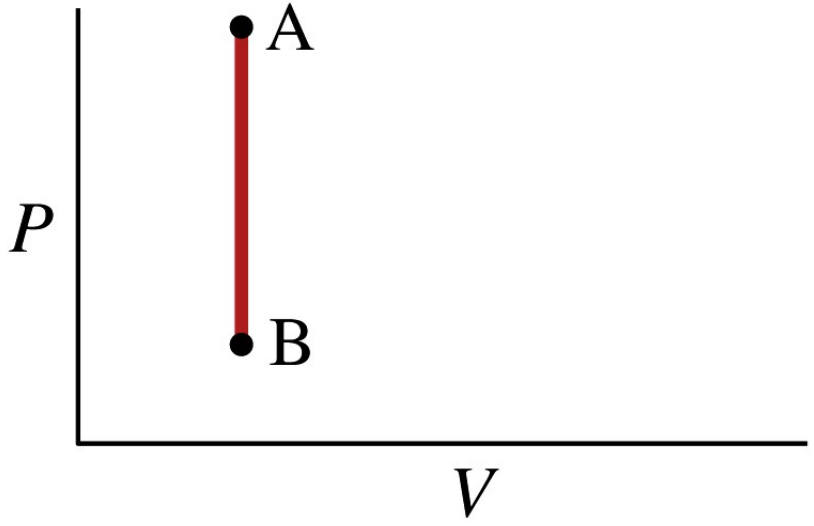
(a) Isobaric

First law of thermodynamics. Molecular specific heat (V = const.).

- Consider what happens when we add Q_V to the system while keeping its pressure constant.
- The work done by the gas will be $p\Delta V = 0$ J.
- The change in the internal energy of the gas is thus equal to

$$\Delta U = Q_V = nC_V\Delta T$$

- Note: we also know that $U(\Delta T) = (3/2)nR\Delta T$ and we can thus conclude that $C_V = (3/2)R$.



(b) Isochoric

First law of thermodynamics. Molecular specific heat.

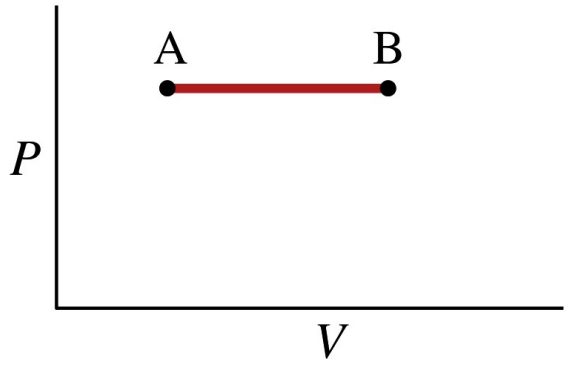
- Compare the two previous results:

$$\Delta U = nC_P\Delta T - nR\Delta T$$

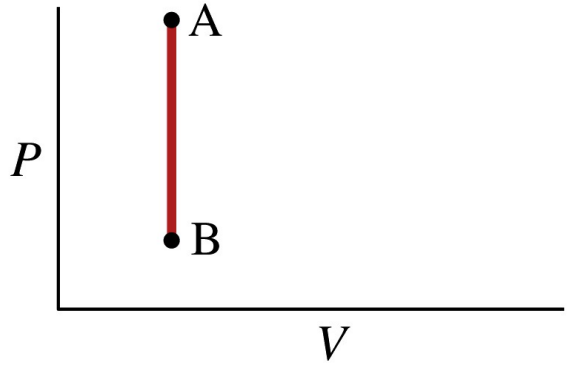
$$\Delta U = nC_V\Delta T$$

- If in both cases the temperature changes by the same amount ΔT the change in the internal energy ΔU will also be the same.
- We thus conclude that $C_P - R = C_V$ or

$$C_P - C_V = R.$$



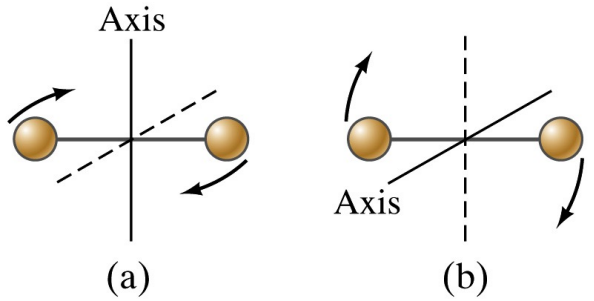
(a) Isobaric

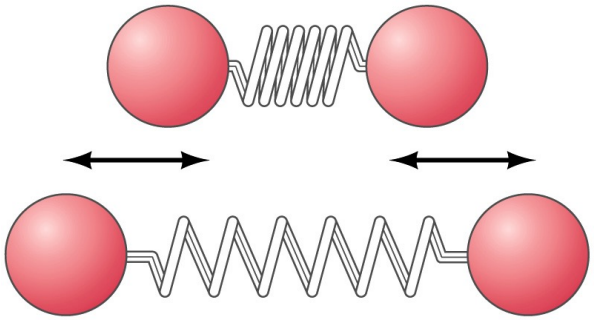


(b) Isochoric

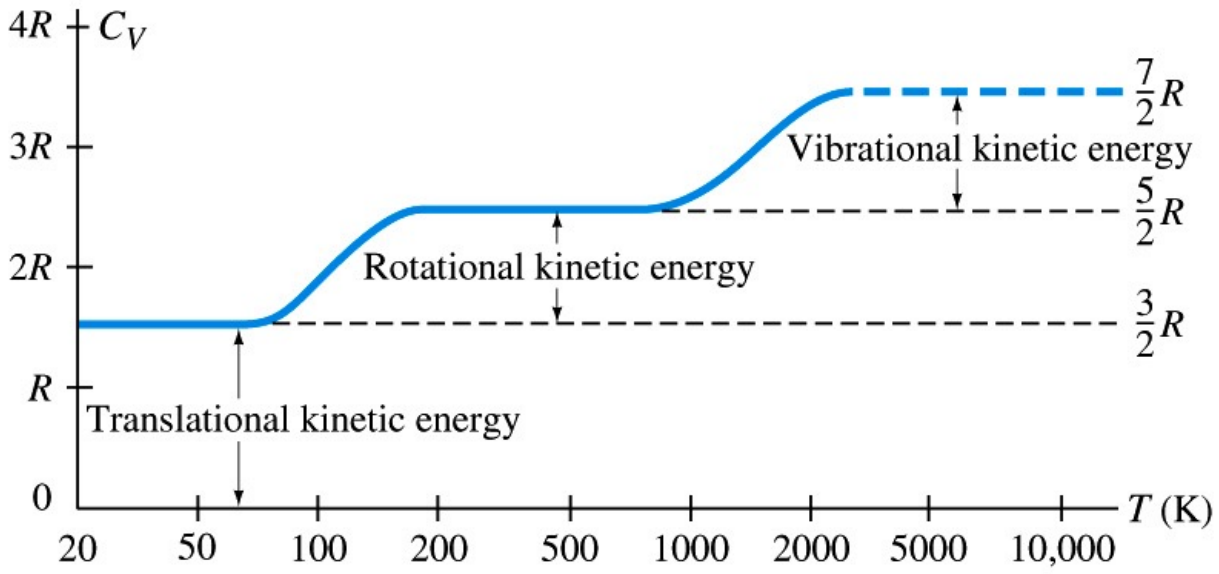
First law of thermodynamics. The internal energy.

- Up to now we have assumed that the internal energy U of a gas is equal to $(3/2)kT$.
- This is correct for a monatomic gas, but is not correct for diatomic or triatomic gases.
- It turns out that each degree of freedom carried an internal energy of $(1/2)kT$.
- Predictions for a diatomic molecule:
  - Linear motion: 3 degrees of freedom.
  - Rotational motion: 2 degrees of freedom.
  - Vibrational motion: 2 degrees of freedom.
- The number of degrees of freedom excited depend on the temperature.





First law of thermodynamics. Using C_V to measure the degrees of freedom.



Done for today!
Next: The second law of thermodynamics.

Massive Star Forming Region DR21 in Infrared.
Credit: A. Marston (ESTEC/ESA) et al., JPL, Caltech, NASA