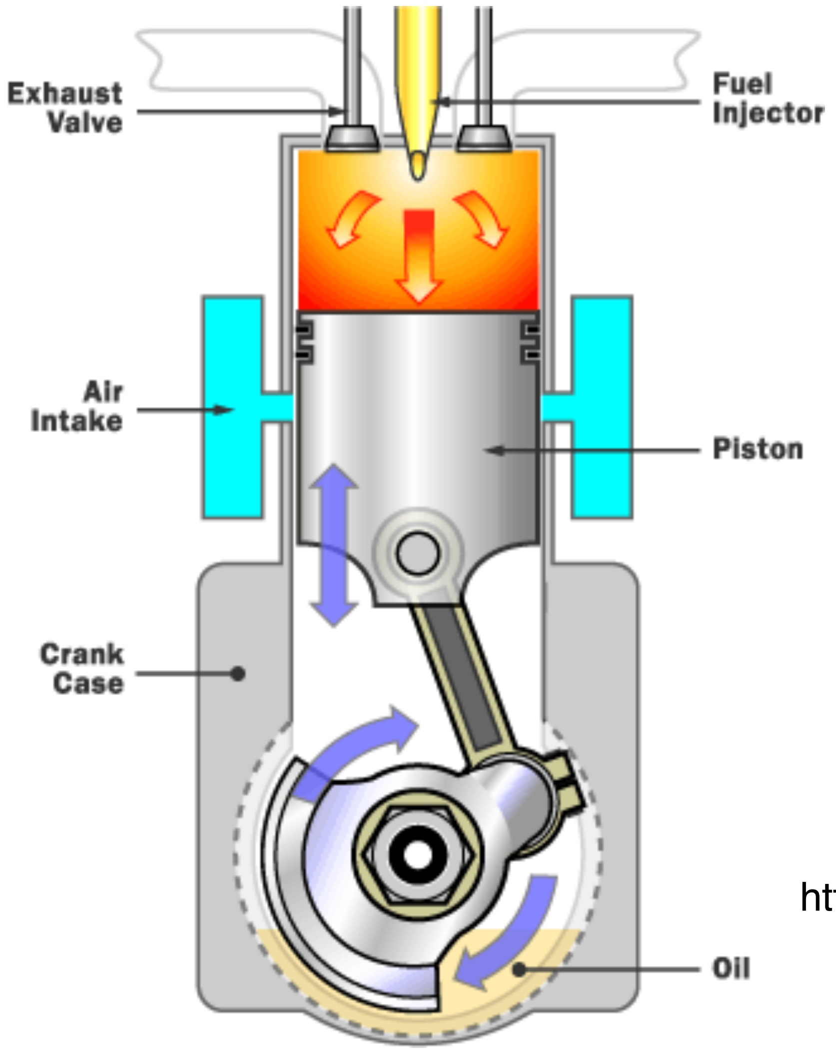
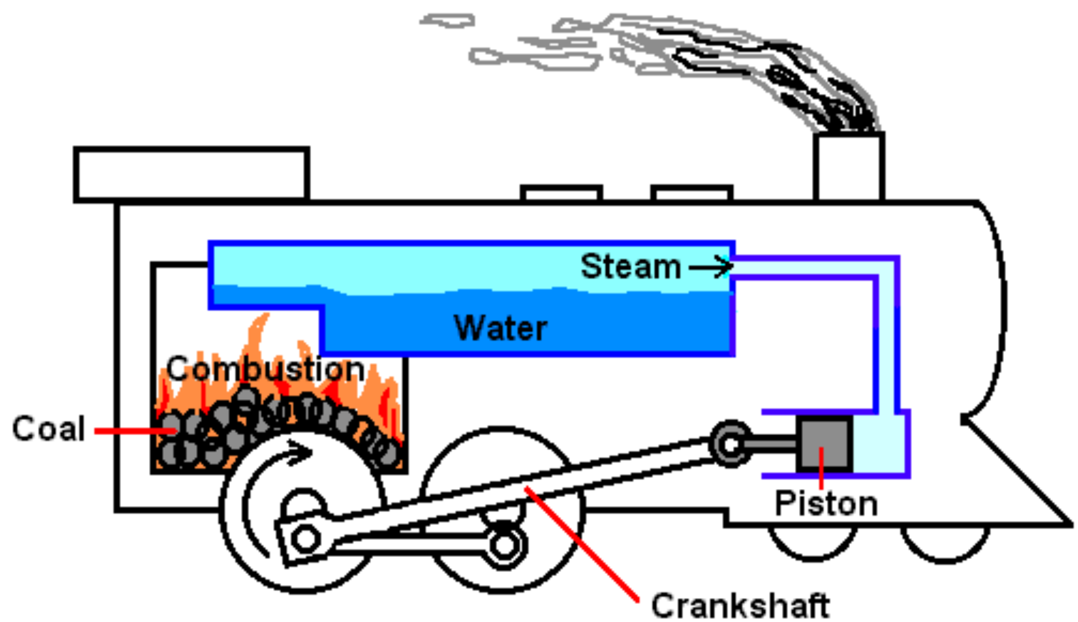
Physics 141.
Lecture 24.





http://mightymech.rf.gd/2018/11/13/heat-engine-classification/?i=1

Physics 141.
Lecture 24.

- Course Information.
- Quiz
- Continue our discussion of Chapter 13:
  - Equation of state.
  - The energy distribution of an ideal gas and energy exchange with its environment.

Physics 141.
Course information.

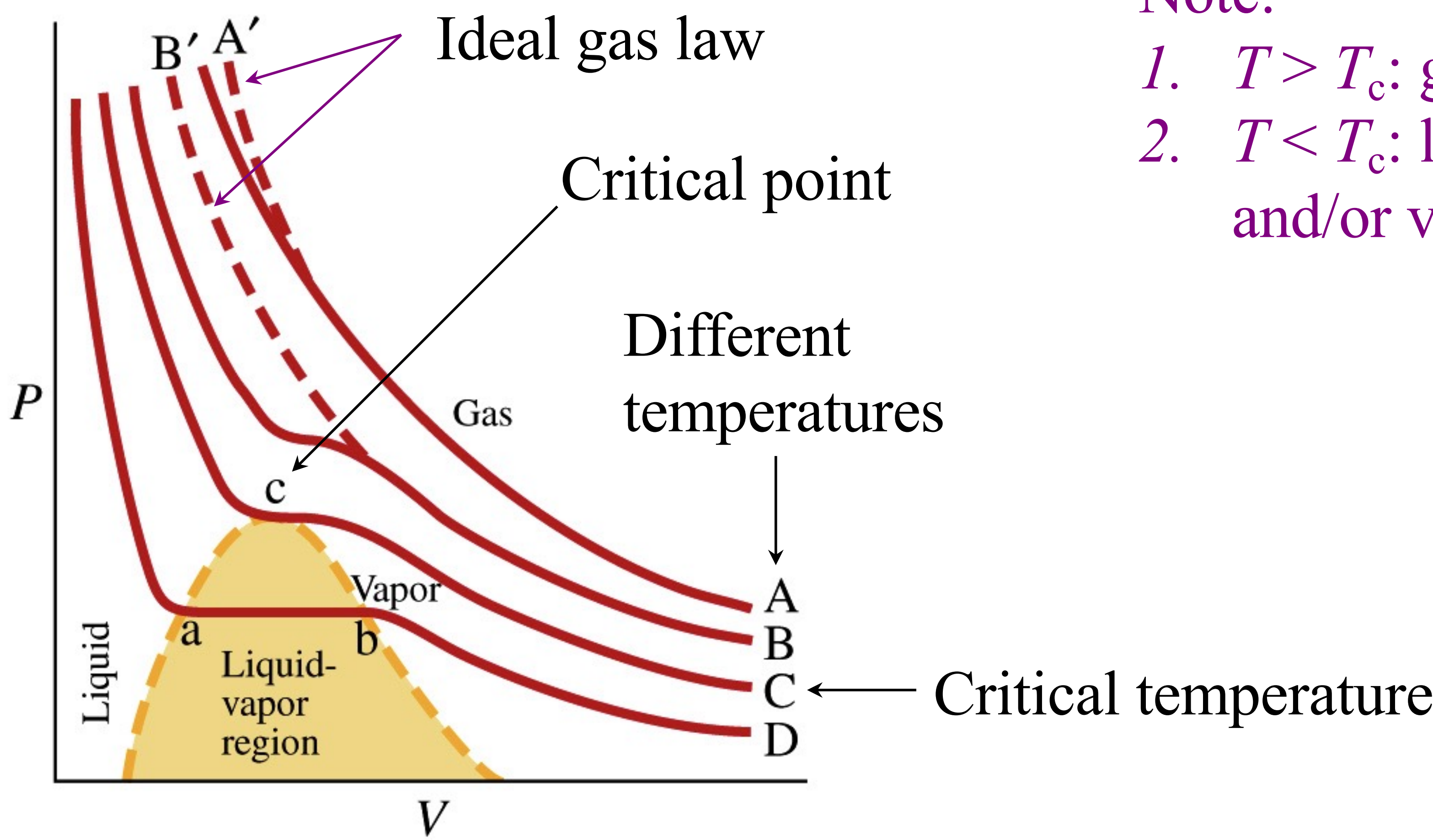
- Homework 10 is due on Friday December 8 at noon.
- Homework set 11 is due on Friday December 15 at noon.
- To calculate the final homework grade, I remove the lowest homework grade and then take the average of the remaining 10 homework grades. If you are happy with homework grades 1 – 10, you can consider homework 11 as optional.

- I will send a summary of all your grades in the course on Wednesday 12/13, including the results of a calculation that will show what grade you need to get on the final exam to get an A-, a B-, and a C- in this course.

- The final exam will take place on Wednesday 12/20 at 4 pm in Hoyt. The exam will take 3 hours and cover all the material discussed in Phy 141, except the error analysis.

- Extra office hours will be scheduled before the final exam. Details will be announced via email.

The real equation of state. Different points of view.

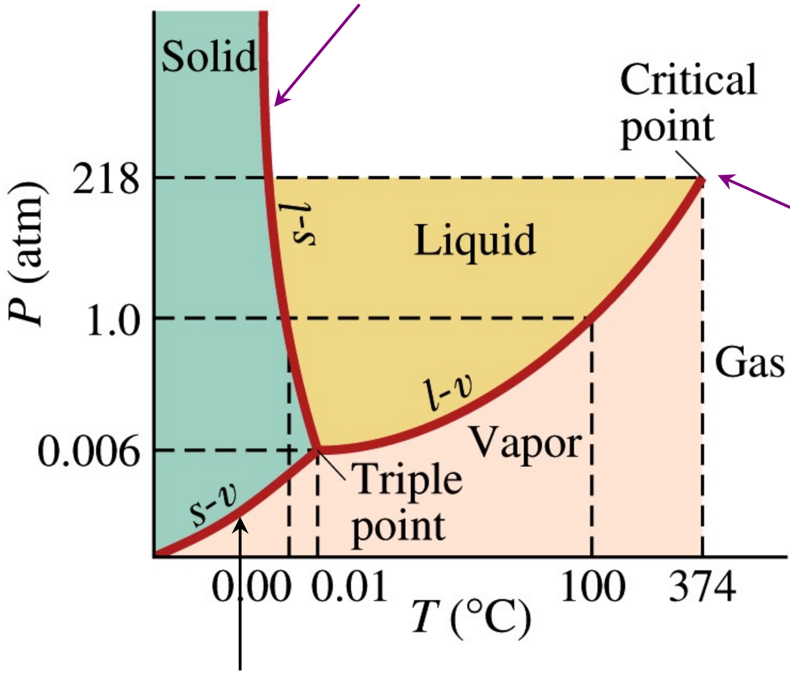


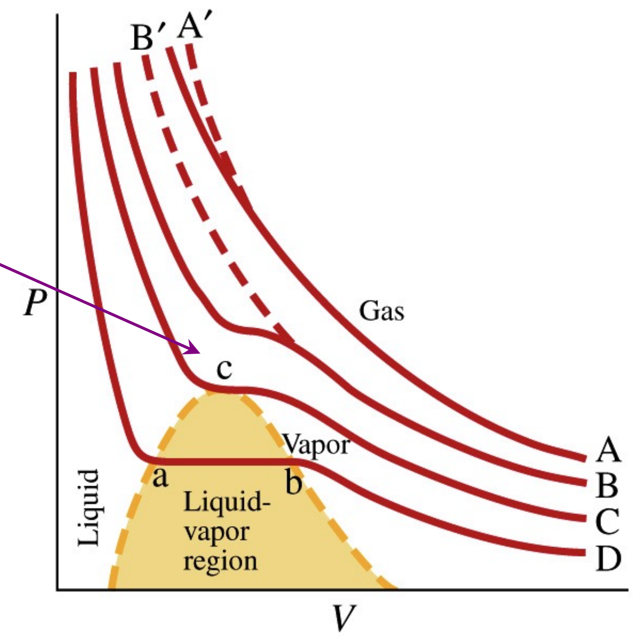
Note:

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.

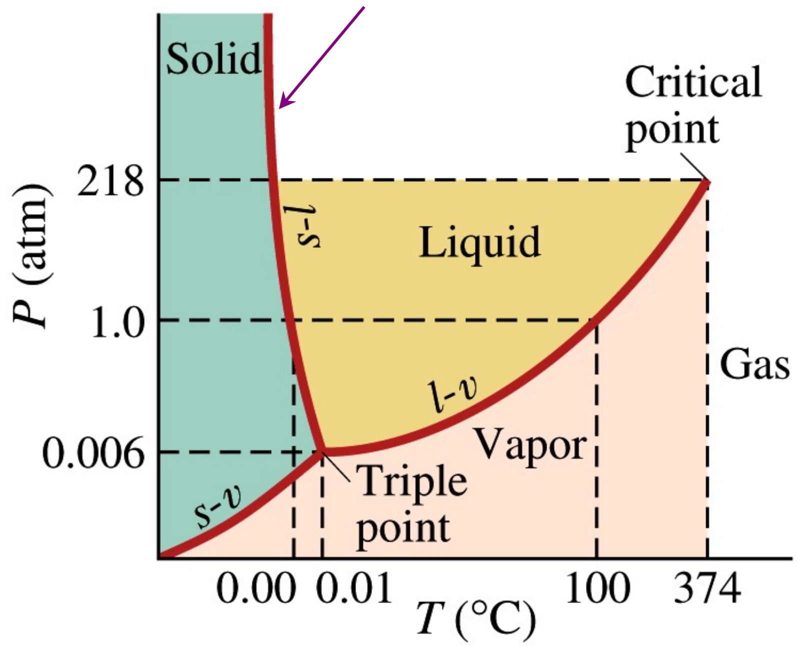




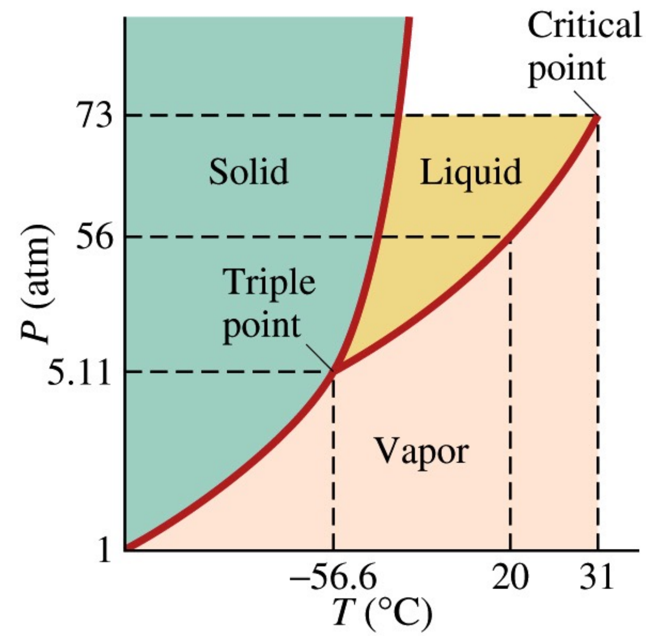
Direct change from solid to vapor.

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

The first law of thermodynamics. Adding/removing heat from a system.

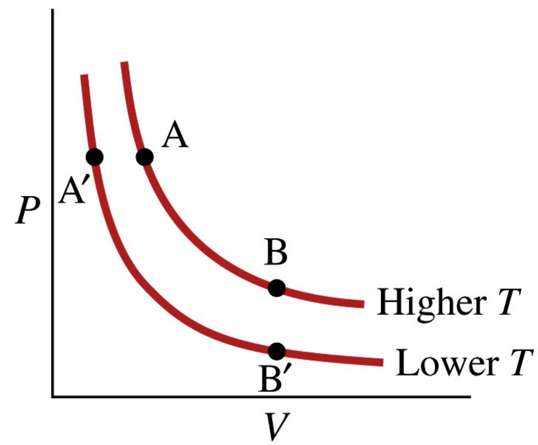
- Consider a closed system:
  - Closed system
    - No change in mass
    - Change in energy allowed (exchange with environment)
  - Isolated system:
    - Closed system that does not allow an exchange of energy

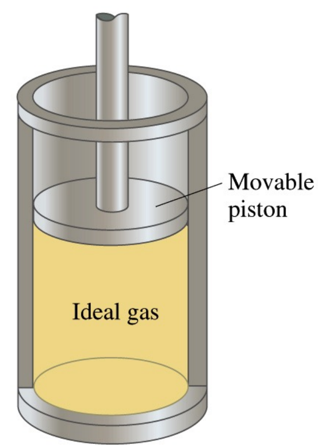
- The internal energy of the system can change and will be equal to the heat added to the system minus the work done by the system: $\Delta U = Q - W$ (note: this is the work-energy theorem).

- Note: keep track of the signs:
  - Heat: $Q > 0$ J means heat added, $Q < 0$ J means heat lost
  - Work: $W > 0$ J mean work done by the system, $W < 0$ J means work done on the system

The first law of thermodynamics. Isothermal processes.

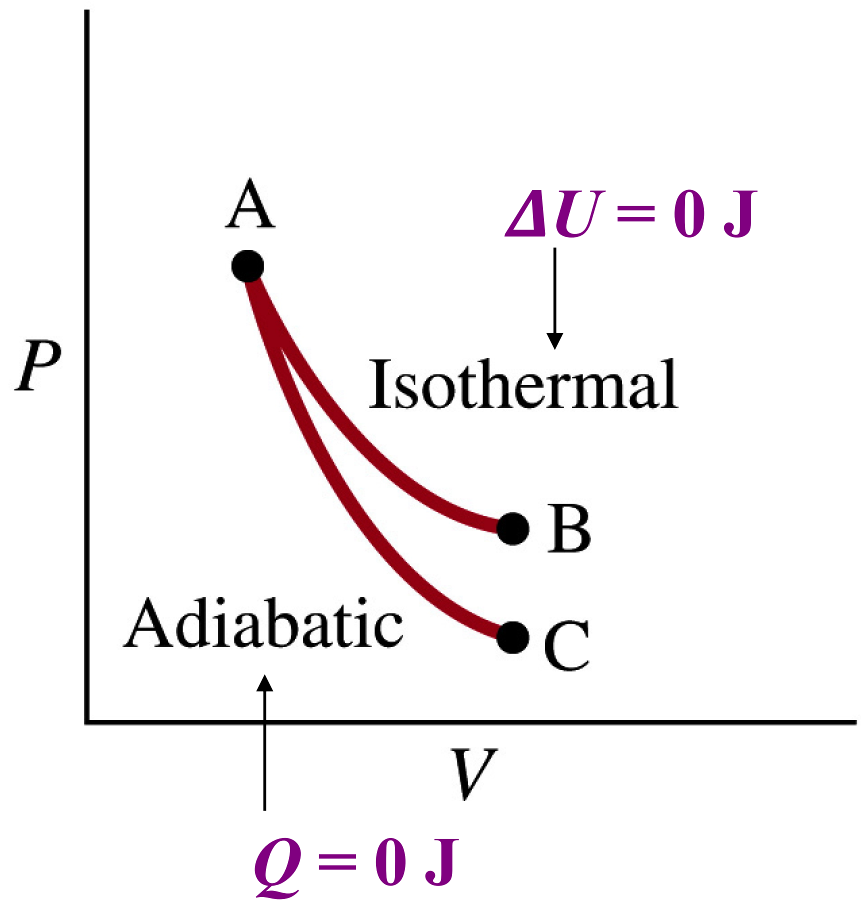
- An isothermal process is a process in which the temperature of the system is kept constant.
- This can be done by keeping the system in contact with a large heat reservoir and making all changes slowly.
- Since the temperature of the system is constant, the internal energy of the system is constant: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





The 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).



Work done during expansion/compression.

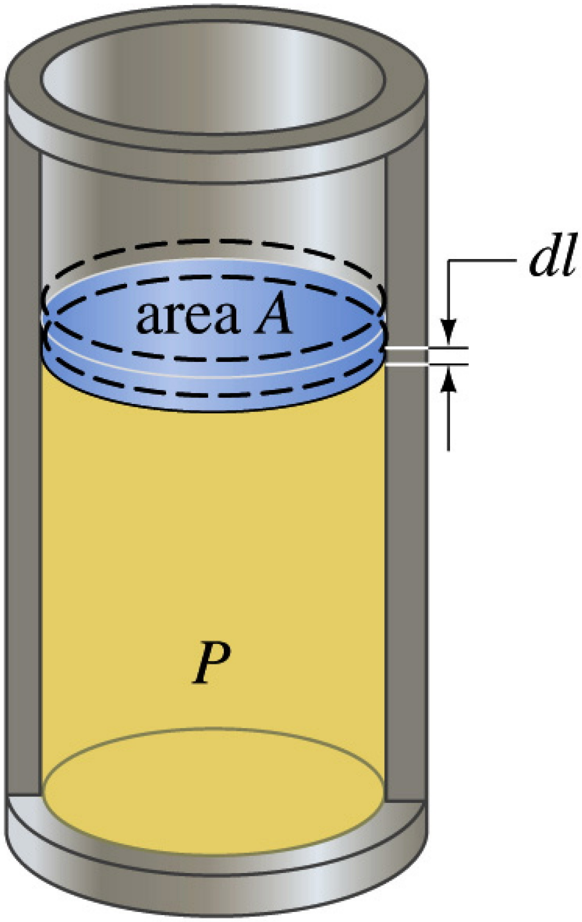
- Consider an ideal gas at pressure p.
- The gas exerts a force F on a moveable piston, and $F = pA$.
- If the piston moves a distance dl, the gas will do work:

$$dW = Fdl$$

Note: F and dl are parallel.

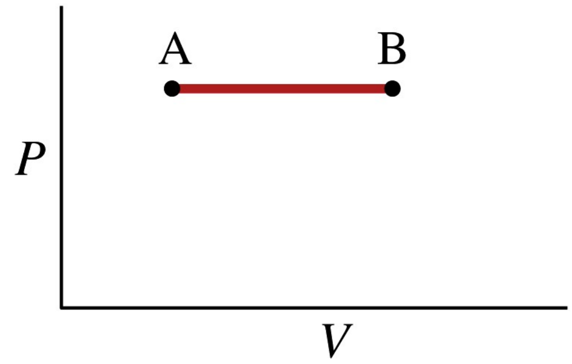
- The work done can be expressed in terms of the pressure and volume of the gas:

$$dW = pAdl = pdV$$



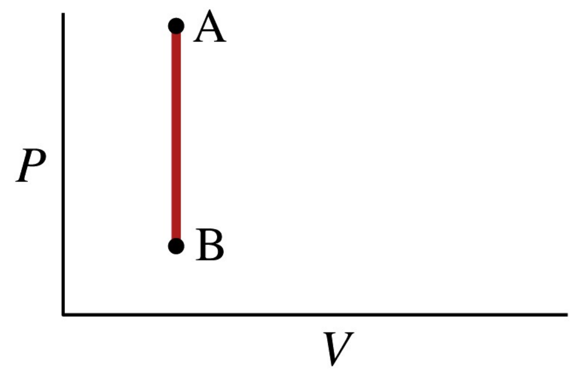
Work done during expansion/compression. Isobaric and isochoric processes.

- **Isobaric process**:
  - Processes in which the pressure is kept constant.
  - $W_{\text{A->B}} = pdV = p_A(V_B - V_A)$



(a) Isobaric

- **Isochoric process**:
  - Processes in which the volume is kept constant.
  - $W_{\text{A->B}} = p_A(V_B - V_A) = 0$



(b) Isochoric

Work done during expansion/compression. Isothermal process.

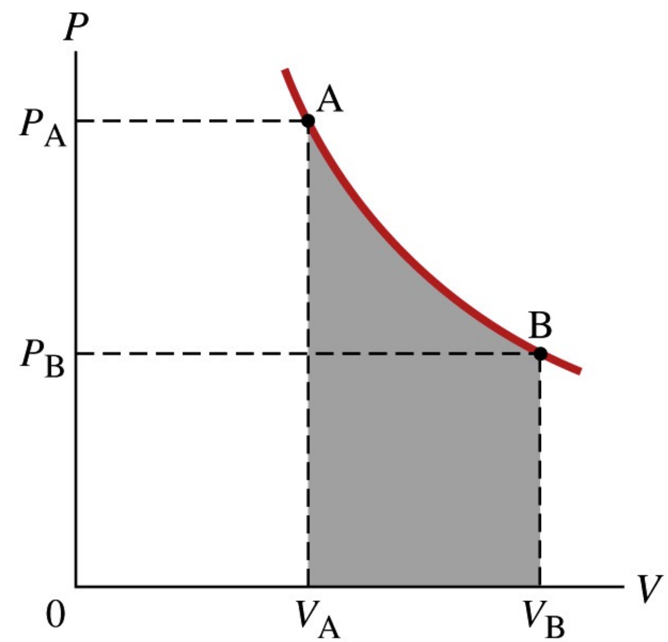
- **Isothermal process**:

$$p = \frac{NkT}{V}$$

- The work done during the change from state *A* to state *B* is

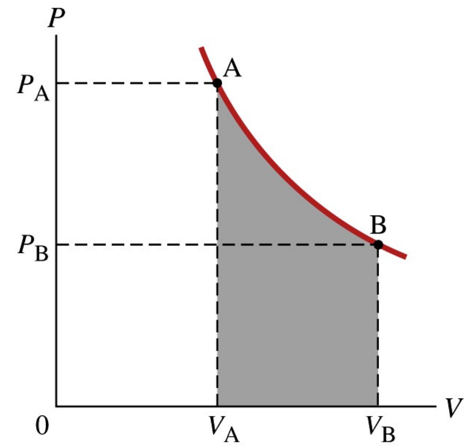
$$W = \int_{V_A}^{V_B} p\,dV = NkT \int_{V_A}^{V_B} \frac{1}{V}\,dV$$

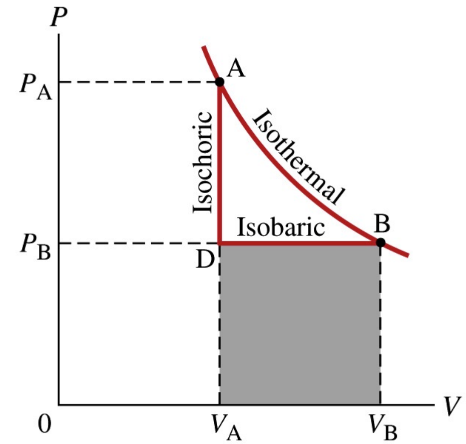
$$= NkT \ln\left(\frac{V_B}{V_A}\right)$$



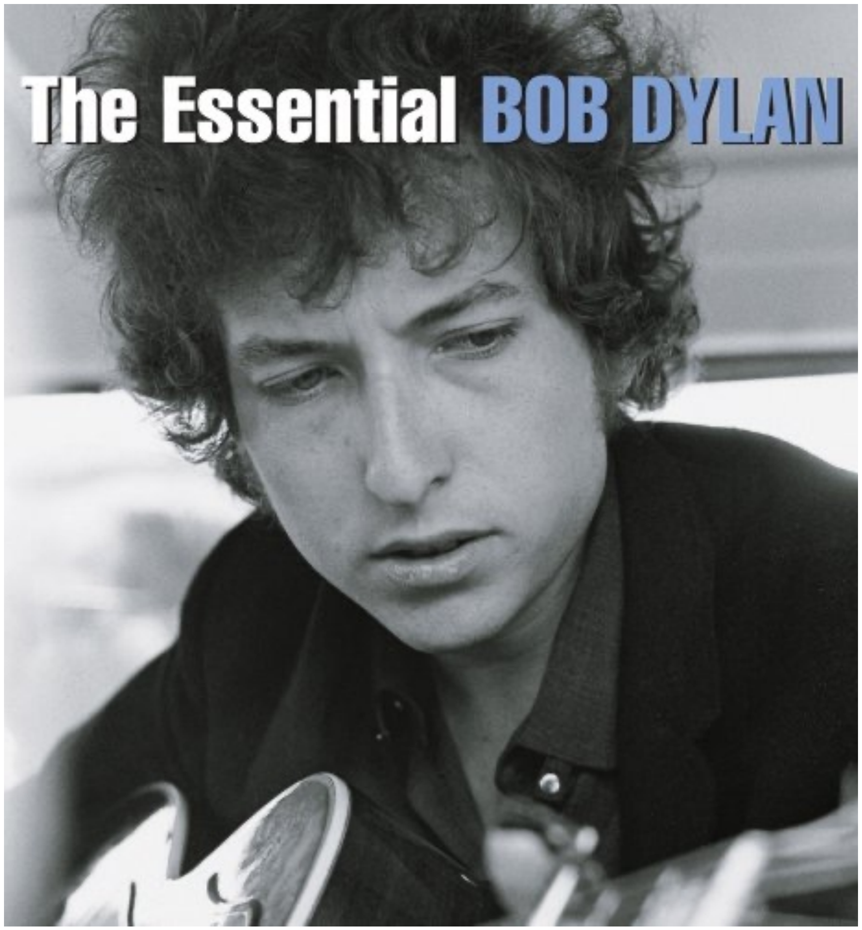
Work done during expansion/compression.

- 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: $W = NkT \ln(V_B / V_A)$
  - Isochoric: $W = 0$
  - Isobaric: $W = p_B (V_B - V_A)$
- The work done to move state A to state B can take on any value!





2 Minute 48 Second Intermission.



- Since paying attention for 1 hour and 15 minutes is hard when the topic is physics, let's take a 2 minute 48 second intermission.

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

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.

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

- Consider what happens when we add Q_p to the system while keeping its pressure constant ($p = NkT/V$ = 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

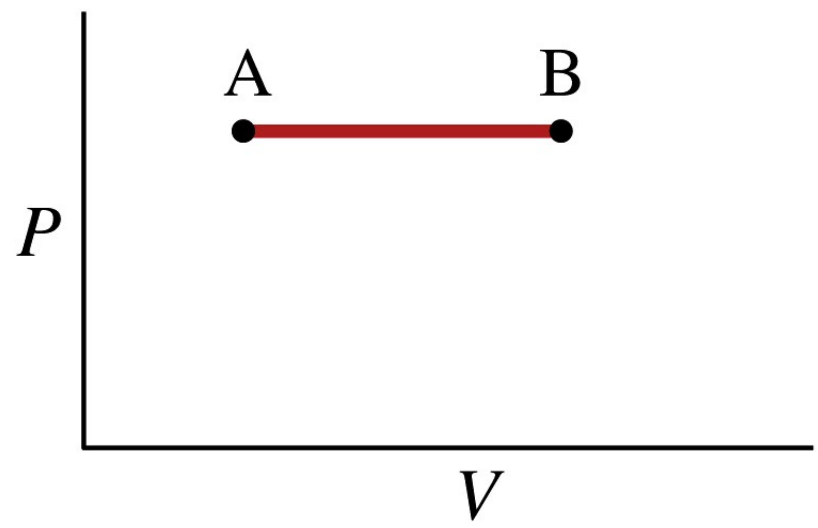
$$W = p\Delta V = Nk\Delta T.$$

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

$$\Delta U = Q_p - W = Q_p - Nk\Delta T$$

- Using the definition of C_P we can rewrite this relation as

$$\Delta U = NC_P\Delta T - Nk\Delta T = N(C_P - k)\,\Delta T$$



(a) Isobaric

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

- Consider what happens when we add Q_V to the system while keeping its volume constant ($V = NkT/p$ = 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

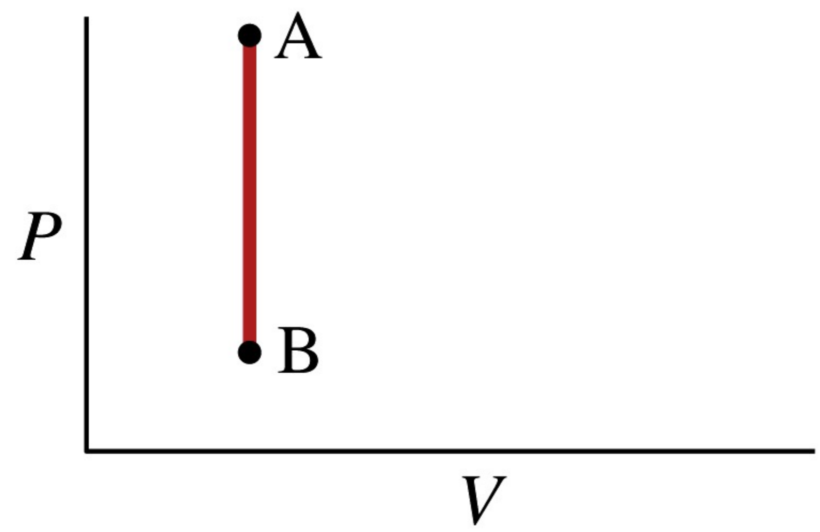
$$\Delta U = Q_V = NC_V\Delta T$$

- Note: we also know from the Boltzmann distribution that

$$\Delta U = (3/2)Nk\Delta T$$

- We thus conclude that

$$C_V = (3/2)k.$$



(b) Isochoric

Note: if the molecules have more than 3 degrees of freedom, C_V will increase!

First law of thermodynamics. Molecular specific heat.

- Compare the isobaric and isochoric transitions that produce the same temperature change:

$$\Delta U = NC_P\Delta T - Nk\Delta T$$

and

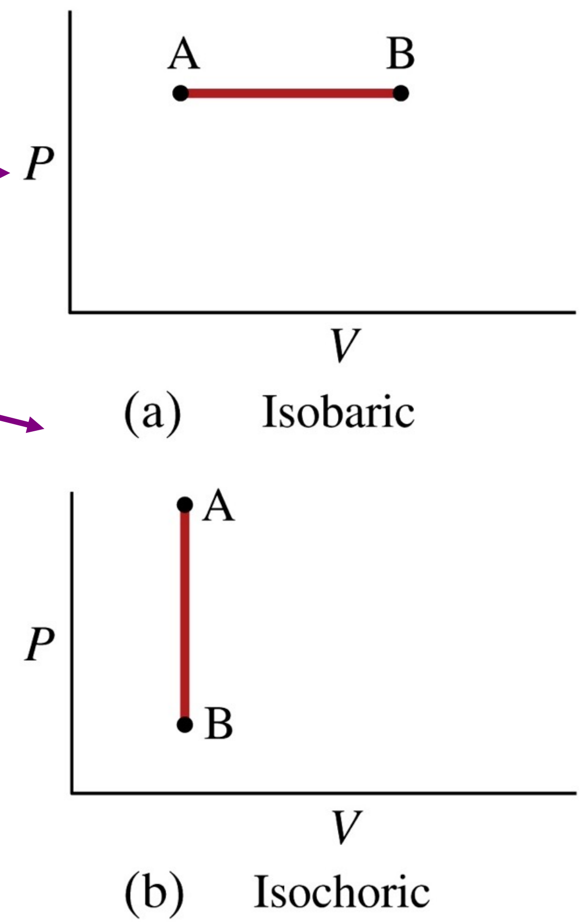
$$\Delta U = NC_V\Delta T$$

- Since 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

$$C_P - k = C_V$$

or

$$C_P = C_V + k = (3/2)k + k = (5/2)k$$



Adiabatic processes (Q = 0 J). What is the shape of the pV curve?

- The change in the internal energy of the gas is $N(3/2k)\,\Delta T = NC_V\,\Delta T$.
- The first law of thermodynamics thus tells us that

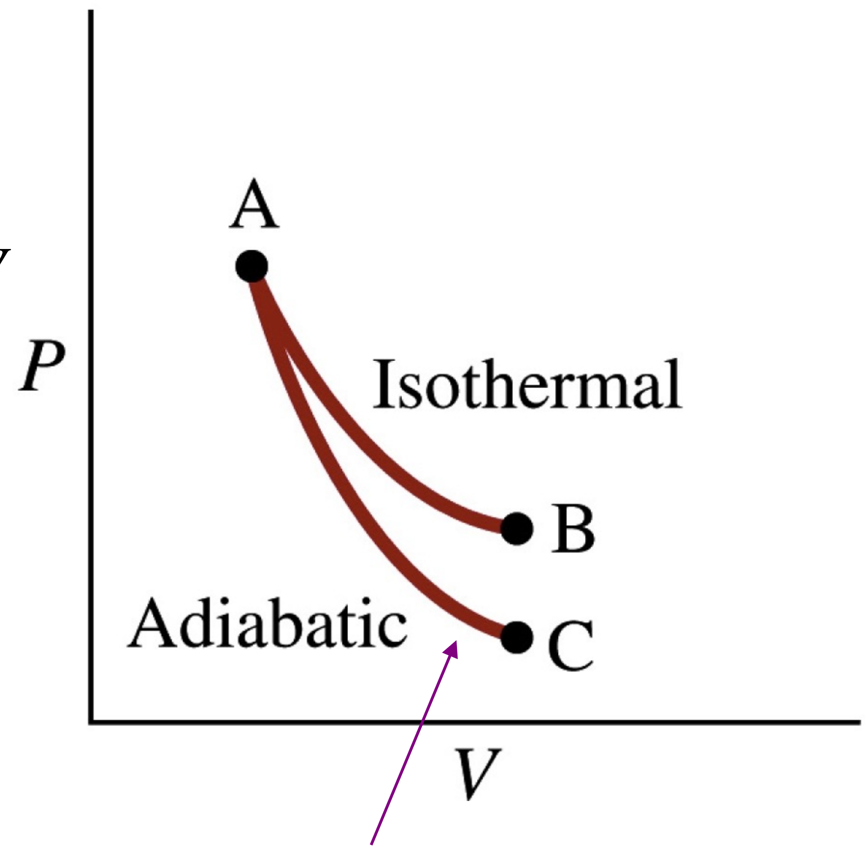
$$NC_V\Delta T = NC_V\int_{V_A}^{V_B} dT = -\int_{V_A}^{V_B} p\,dV$$

- Comparing the integrands we must require that

$$NC_V dT = -p\,dV = -\frac{NkT}{V}dV$$

or

$$\frac{C_V}{k}\frac{dT}{T} + \frac{dV}{V} = 0$$



What is the shape of the pV curve?

Adiabatic processes ($Q = 0$ J).

- Integrating each term in the previous expression shows that

$$\frac{C_V}{k}\ln T + \ln V = \ln T^{\frac{C_V}{k}} + \ln V = \ln VT^{\frac{C_V}{k}} = \text{constant}$$

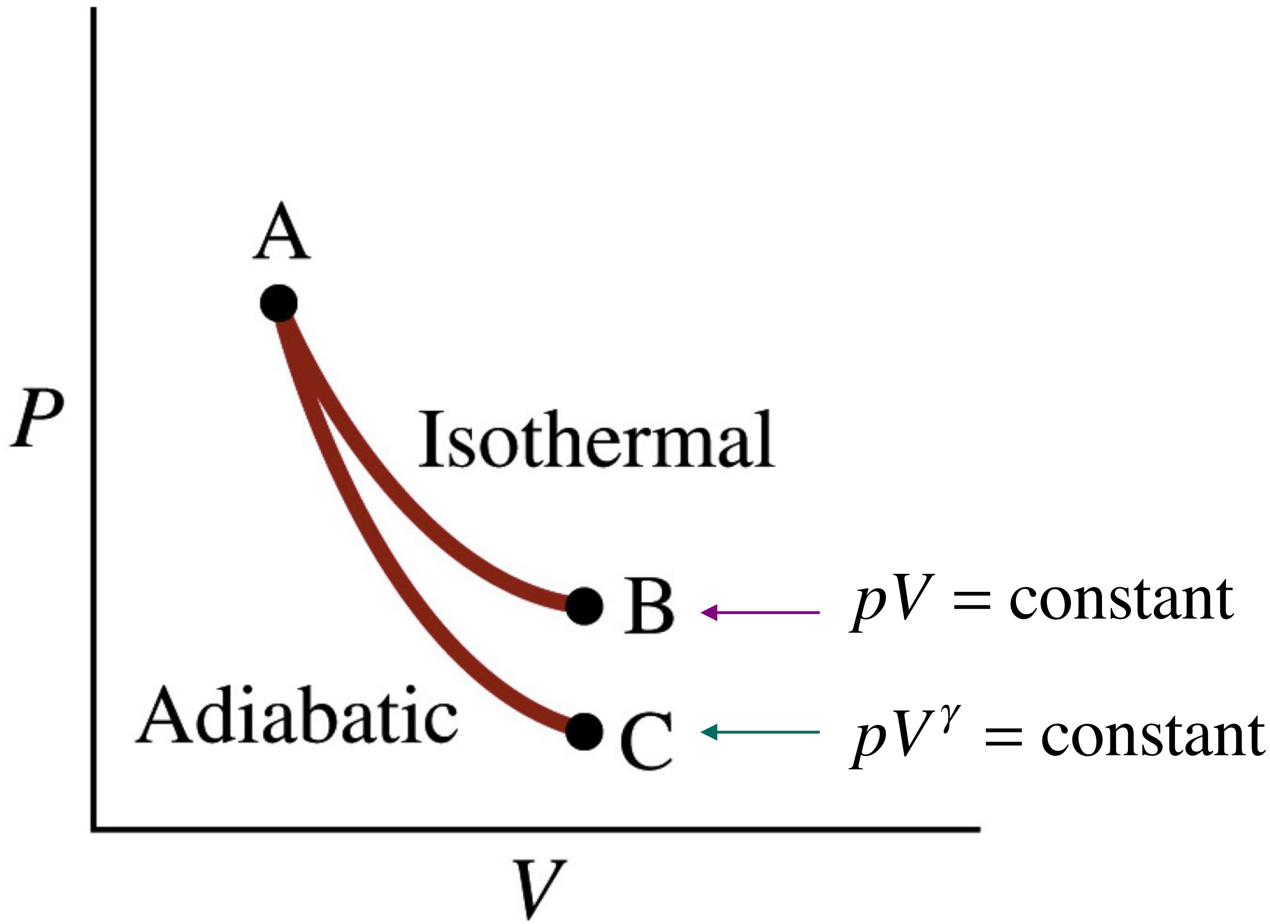
or

$$VT^{\frac{C_V}{k}} = \left(TV^{\frac{k}{C_V}} \right)^{\frac{C_V}{k}} = \text{constant}$$

- This expression can also be written in terms of the pressure and volume (which is of course what we need to defined the curve in the pressure versus volume graph):

$$TV^{\frac{k}{C_V}} = \left(\frac{pV}{Nk} \right) V^{\frac{k}{C_V}} = \frac{pV^{\frac{C_V + k}{C_V}}}{Nk} = \frac{pV^{\frac{C_p}{C_V}}}{Nk} = \frac{pV^{\gamma}}{Nk} = \text{constant}$$

What do we conclude?



Done for today!

http://www.chinfo.navy.mil/navpalib/images/sndbarphoto.html