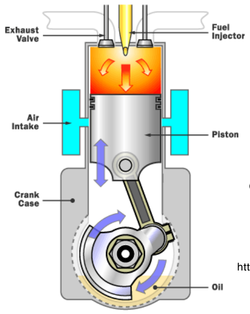
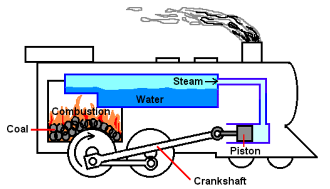
Physics 141.
Lecture 24.





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

1

Physics 141.
Lecture 24.

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

2

Physics 141.
Course information.

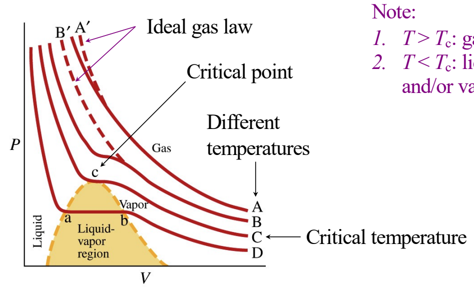
- Homework 10 is due on Friday December 8 at noon.
- Homework set 11 is due on Friday December 15 at noon.
- To calculate the final homework grade, I remove the lowest homework grade and then take the average of the remaining 10 homework grades. If you are happy with homework grades 1 – 10, you can consider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

3

- 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.

4

The real equation of state. Different points of view.

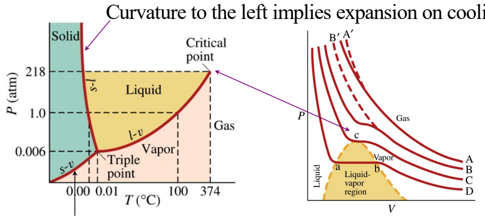


Note:
1. $T > T_c$: gas
2. $T < T_c$: liquid and/or vapor.

5

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.

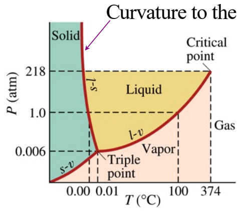


Direct change from solid to vapor.

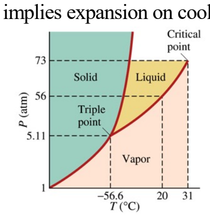
6

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

7

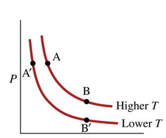
The first law of thermodynamics.
Adding/removing heat from a system.

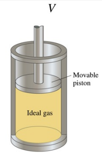
- Consider a closed system:
  - Closed system
    - No change in mass
    - Change in energy allowed (exchange with environment)
  - Isolated system:
    - Closed system that does not allow an exchange of energy
- The internal energy of the system can change and will be equal to the heat added to the 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

8

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 $Q = W$.

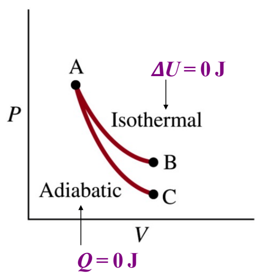




9

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).



10

Work done during expansion/compression.

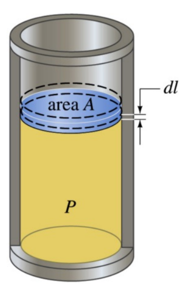
- Consider an ideal gas at pressure p.
- The gas exerts a force F on a moveable piston, and $F = pA$.
- If the piston moves a distance dl, the gas will do work:

$$dW = Fdl$$

Note: F and dl are parallel.

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

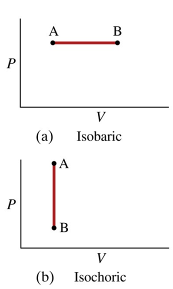
$$dW = pAdl = pdV$$



11

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

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



12

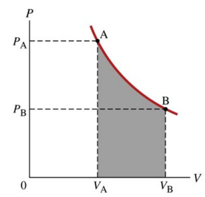
Work done during expansion/compression. Isothermal process.

- **Isothermal process**:

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

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

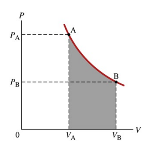
$$W = \int_{V_A}^{V_B} p\,dV = NkT \int_{V_A}^{V_B} \frac{1}{V}\,dV = NkT \ln\left(\frac{V_B}{V_A}\right)$$

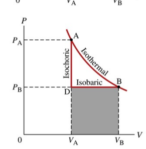


13

Work done during expansion/compression.

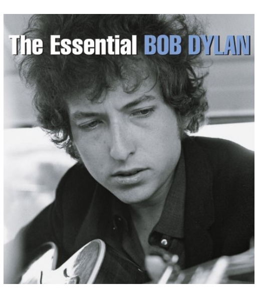
- The work done during the expansion of a gas is equal to the area under the pV curve.
- Since the shape of the pV curve depends on the nature of the expansion, so does the work done:
  - Isothermal: $W = NkT \ln(V_B / V_A)$
  - Isochoric: $W = 0$
  - Isobaric: $W = p_B (V_B - V_A)$
- The work done to move state A to state B can take on any value!





14

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.

15

First law of thermodynamics. Molecular specific heat.

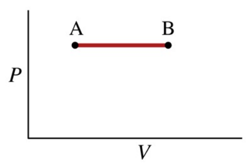
- When we add heat to a system, its temperature will increase.
- For solids and liquids, the increase in temperature is proportional to the heat added, and the constant of proportionality is called the specific heat of the solid or liquid.
- When we add heat to a gas, the increase in temperature will 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.

16

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

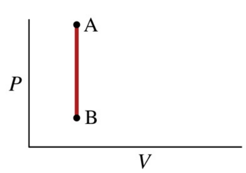


(a) Isobaric

17

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!

18

First law of thermodynamics. Molecular specific heat.

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

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

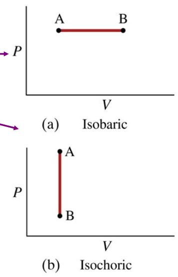
  and

  $\Delta U = NC_V\Delta T$
- 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

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



19

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

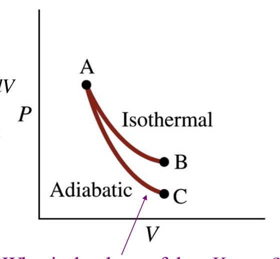
$$NC_V\Delta T = NC_V\int_{V_A}^{V_B} dT = -\int_{V_A}^{V_B} pdV$$

- Comparing the integrands we must require that

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

or

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



20

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

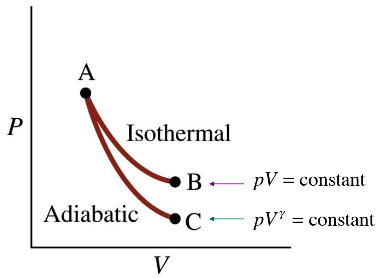
$$VT^{\frac{C_V}{k}} = \left(TV^{\frac{k}{C_V}}\right)^{\frac{C_V}{k}} = \text{constant}$$

- 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):

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

21

What do we conclude?



22

Done for today!

23