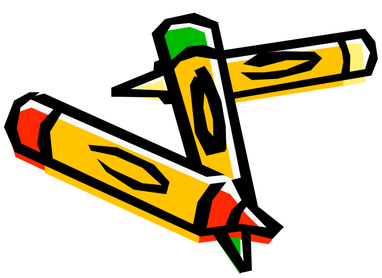
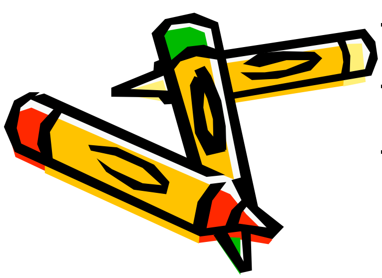
Putting it all together - Thermodynamics

- Study the relationship of work, heat and energy
- Understand relationships between density, pressure, temperature, energy
- Understand properties of gases, liquids, solids, phase transitions,…
- Understand heat engines and their limits
- new concept: Entropy (disorder <=> likelihood)



Work, Heat, Internal Energy

- **1st Law of Thermodynamics:** ΔE(internal) = Heat added **to** + Work done **on** system (Energy conservation; “You cannot win”)
- Examples:
  - Flame (or anything hotter than the system) => heat flow
  - Resistive heating, friction, impact heating, radiation…
  - Special case: Gases -> can do work by changing volume
    - move surface area *A* by a distance *d* inwards:
      - Need to exert force $F = P \cdot A$ on surface
      - Work done **on** system $Fd = P \cdot Ad = P(-\Delta V)$ (general rule)
      - either internal energy (temperature!) increases, or the system gives off heat. Example: Bicycle pump



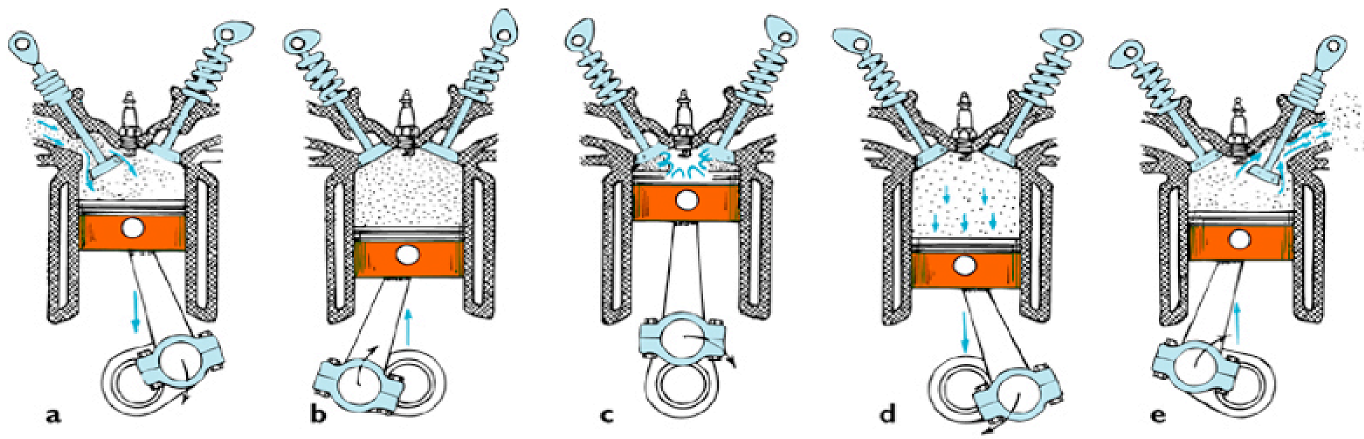
Consequences

- If you add heat to a system while letting it do work (steam engine!), its internal energy will increase **less** (steam less hot)
- If you do **not** add heat to a system while letting it do work (releasing gas from a pressure bottle, air rising up and expanding) the system will lose internal energy (gets **colder!**) [Adiabatic Processes]
- Note: decreasing volume of gas increases pressure (Boyle's Law); but temperature increases (if process is adiabatic) -> pressure increases even more!
  - $P \propto 1/V$ (Boyle's Law: more frequent bouncing off walls)
  - ΔE(internal) = $P(-\Delta V)$; E(intl) increases; T [in Kelvin] $\propto E$(intl)
  - $P \propto T$ [in Kelvin] (more energy/molecule -> more and harder bouncing off walls)

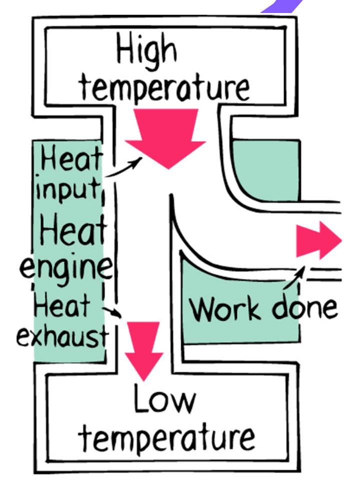
Putting it all together - The ideal gas law

- $PV = nRT$
  - P = pressure in Pascal, V = volume in m^3
  - n = number of mols, T = temperature in K
  - R = 8.3 J/mol/K universal (gas) constant
- $E_{internal} = {}^3/_2\ nRT$
  (1/2 for each direction of space = degree of freedom)
- $\Delta E_{internal} = P(-\Delta V)$ + Heat added
- Example: Volume of 1 mol of air at 0^{o}C and normal atmospheric pressure = 22.4 liters

Heat engines

- Any device that converts **some** of the heat transferred to it into mechanical work
- 

- Physicists dream engine:
  "Perfectly reversible Carnot Machine"
  (as efficient as possible, but runs infinitely slowly…)



The hitch: Need low T "heat exhaust" (reservoir)

- Why?
  - Example hot gas turbine: You have to cool gas down **after** turbine to avoid "back pressure" (or machine comes to a halt)
  - Heat input at T_{hot}, heat exhaust at T_{cool} => at most $1 - T_{cool}/T_{hot}$ of heat can be converted to useful work; rest (T_{cool}/T_{hot}) is exhaust heat (Sadi Carnot)
  - Car engine: exhaust simply gets blown into (colder) atmosphere; limit on efficiency (50% theor., 25% in practice)

Cooling engine (refrigerator, AC, heat pump) = heat engine in reverse: Move heat from cold reservoir to hot reservoir; requires mechanical energy input (less than generated heat output!)

=> 2nd Law of Thermodynamics

Many equivalent formulations - e.g. the following:

1. No machine can simply convert heat into work without exhausting heat into a colder reservoir; no machine can beat the Carnot efficiency
2. Heat can never flow spontaneously from cold to warm without external input of work
3. Entropy*) can never decrease; it always tends to increase over time (e.g. when heat flows from warm to cold); "you can't get even"

*) Entropy = measure of disorder; the more different states a system can be in (compatible with "macroscopic" observables), the higher its entropy. All closed systems move towards maximal entropy