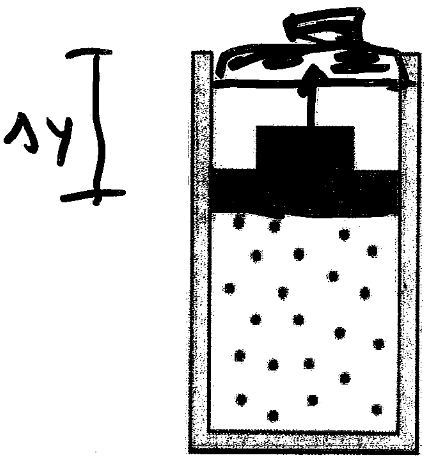
Work done by a gas

1 m^3 of an ideal gas at 300 K supports a weight in a piston such that the pressure in the gas is 200,000 Pa (about 2 atm). The gas is heated up. It expands to 3 m^3. How much work did the gas do as it expanded?



$W = F \cdot \Delta y \qquad (P = F/A)$

$W = (PA)\,\Delta y$

$\underline{W = P\,\Delta V}$

$= (2 \times 10^5\ Pa)(2\ m^3)$

$\frac{N}{m^2} \quad m^3$

$Nm = J$

Result: $\boxed{W_{by\ gas} = P\Delta V}$ $= P_{ave}\,\Delta V$ in general $\boxed{5^{th}\text{ edition}}$

(for constant P)

$W_{by\ gas} > 0$ when… gas is expanding

Work done on a gas

$\boxed{W_{on\ gas} = -P\Delta V}$ $\boxed{6^{th}, 7^{th}, 8^{th}\text{ editions}}$

(for constant P) $W_{on\ gas} > 0$ when… gas is contracting

Internal energy of an ideal gas: U

Return to Equipartition Theorem:

The total kinetic energy of a system is shared equally among all of its <u>independent parts</u>, on the average, once the system has reached thermal equilibrium.

Each "degree of freedom", of each molecule, has an energy of: $\frac{1}{2} k_B T$

<u>independent parts</u>: larger for molecules that can
- rotate
- vibrate

(requires more than one atom)

$\rightarrow$ **such molecules have more "internal energy"**

Monatomic ideal gas: only kinetic energy possible (3 directions)

average KE/molecule = $3/2\ k_B T$

total KE = $N \times (3/2\ k_B T)$

★ $\rightarrow$ $\boxed{U = 3/2\ N k_B T = 3/2\ nRT}$ (monoatomic)

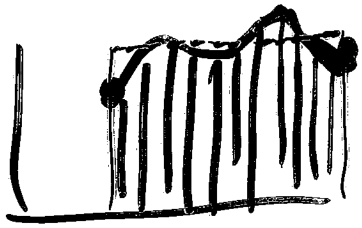
Other substances: U is more complicated, depends on temperature

Diatomic, around 300K: $U = 5/2\ nRT$

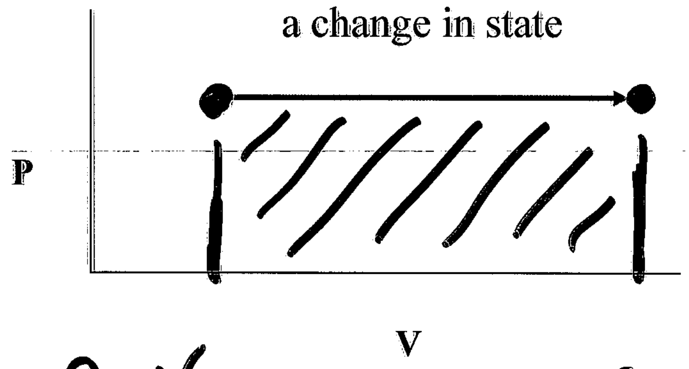
(2 rotational directions that take energy)

Don't need to know details

P-V diagrams



> *State postulate*: any two (independent) variables determine the state: P, V, T, U, etc.



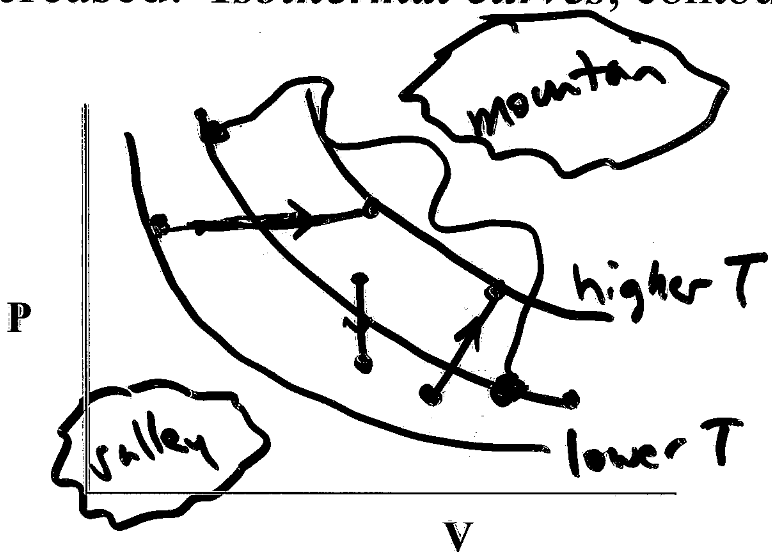
$PV = nRT$

$T = \frac{PV}{nR}$

$W = P_{ave} \Delta V$ $\qquad$ $W = \int P \, dV$

Work done: area under curve (but careful with sign)

How to tell at a glance if the temperature has increased or decreased: ***Isothermal curves***, contours of constant T



$PV = \text{const}$

$P = \frac{\text{const}}{V}$

$y = \frac{A}{x}$

ΔU for an isothermal process is <u>0</u> because… $T_f = T_i$

$U = \frac{3}{2} nRT \rightarrow \Delta U = \frac{3}{2} nR \Delta T$

What is ΔU for the constant P process at top of page?

$\Delta U > 0$

1^{st} Law of Thermodynamics

$$\boxed{\Delta U = Q_{added} + W_{on\ system}}$$

(note: 5^{th} edition uses $-W_{by\ system}$)

System: the object you are studying.
Environment: what it interacts with
typically "where heat comes from"

What does it mean?? Use 5^{th} edition version:

$$\Delta U = Q_{added} - W_{by\ system} \rightarrow Q_{added} = \Delta U + W_{by\ system}$$

Meaning of 1^{st} Law:
Heat added can go either towards

- increasing internal energy (temperature), or
- doing work by the gas

Final warning: Be careful with all the signs!!!

ΔU is positive if: temp increases

Q_{added} is positive if: heat flows into the system

$W_{on\ system}$ is positive if: volume decreases

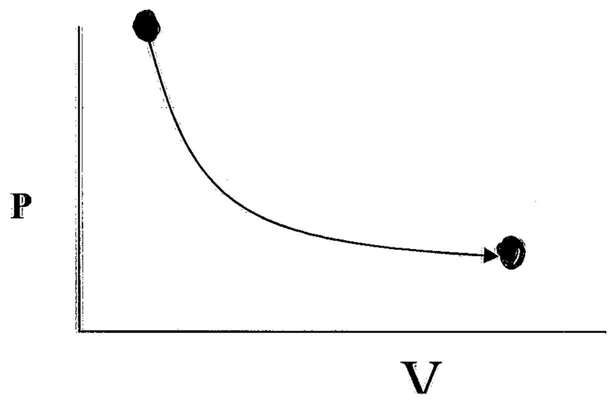
P-V diagram examples

$\Delta U = Q_{added} + W_{on\,gas}$

$0 = Q_{added} + W_{on}$

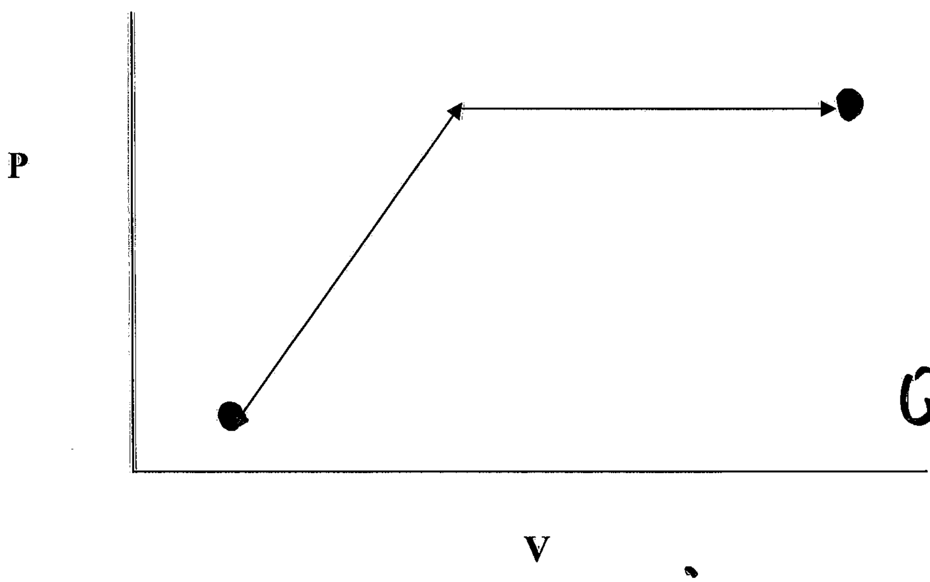
$Q_{added} = -W_{on\,gas}$

Isothermal process



$\Delta U = 0$ $W_{on\,gas}$ negative Q positive

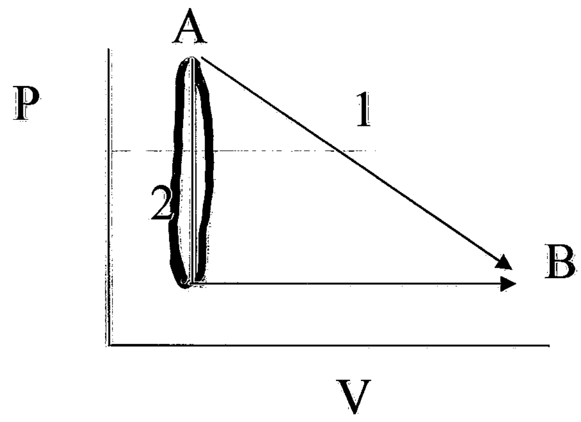
Another process



$Q_{added} = \Delta U - W_{on}$

ΔU positive $W_{on\,gas}$ negative Q positive

A gas in a piston expands from point A to point B on the P-V plot, via either path 1 or path 2. Path 2 is a "combo path," going down first then over.



Clicker quiz 1: The gas does the most work in:

a. path 1
b. path 2
c. neither; it's the same

Clicker quiz 2: In process 1, the *work* done:

a. puts energy into the system $W_{on} > 0$
b. takes energy out of the system $W_{on} < 0$
c. has no effect on the energy of the system

Clicker quiz 3: The process in which ΔU is the greatest (magnitude) is: (total)

a. path 1
b. path 2
c. neither; it's the same

How much work is done in first half of path 2? What is this path physically?

$\Delta U = \cancel{Q_{added}}^{\,0} + W_{on}$

Adiabatic expansion or compression

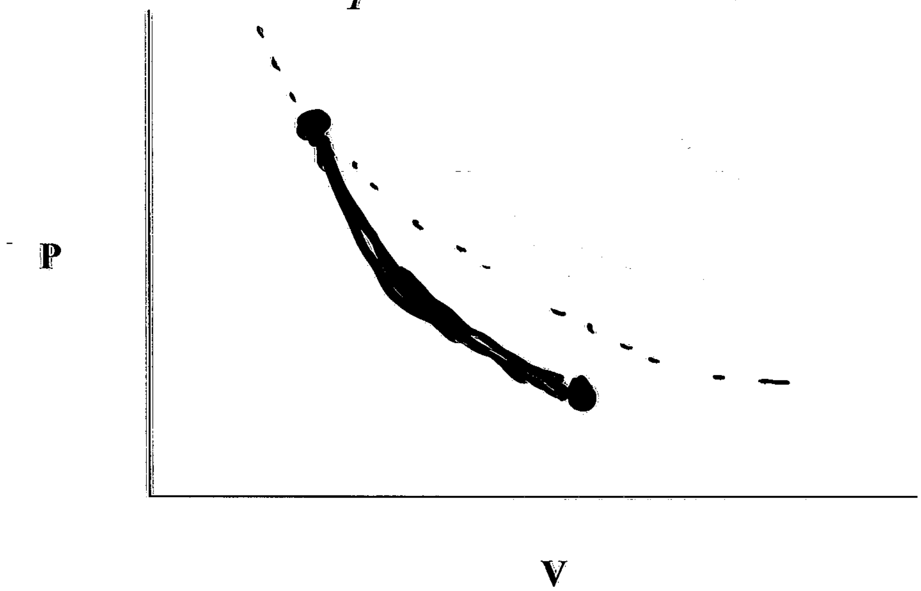
Adiabatic: **no heat added**, either because…

- system is *insulated* , or
- ΔV is *fast,* so no time for much heat to go in/out of gas

Q = 0 W expanding < 0 ΔU negative

compressing > 0 positive

Adiabatic curves are *steeper* than isothermal curves



→ "No heat added" does <u>not</u> mean "no temperature change"

Demos: adiabatic compression and cotton
freezing by expansion

Ralph question: how does isothermal compression work?

Two situations…

$Q = 0$

Clicker quiz: You compress air "very quickly" in an engine cylinder. Determine the signs of Q, W, and ΔU.

a. $Q_{added} = +$ $W_{on\ gas} = +$ $\Delta U = +$
b. $Q_{added} = 0$ $W_{on\ gas} = +$ $\Delta U = +$
c. $Q_{added} = +$ $W_{on\ gas} = -$ $\Delta U = +$
d. $Q_{added} = +$ $W_{on\ gas} = 0$ $\Delta U = +$
e. $Q_{added} = -$ $W_{on\ gas} = +$ $\Delta U = 0$

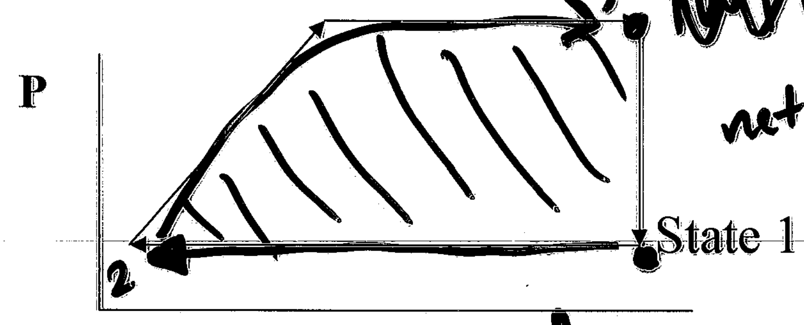
$W = 0$

Clicker quiz: You heat a spray can in a fire, and volume stays about the same (it doesn't explode). System = gas in the can. Determine the signs of Q, W, and ΔU.

a. $Q_{added} = +$ $W_{on\ gas} = +$ $\Delta U = +$
b. $Q_{added} = 0$ $W_{on\ gas} = +$ $\Delta U = +$
c. $Q_{added} = +$ $W_{on\ gas} = -$ $\Delta U = +$
d. $Q_{added} = +$ $W_{on\ gas} = 0$ $\Delta U = +$
e. $Q_{added} = -$ $W_{on\ gas} = +$ $\Delta U = 0$

$\Delta U = Q_{added} + W_{on\,gas}$

Cyclical Processes



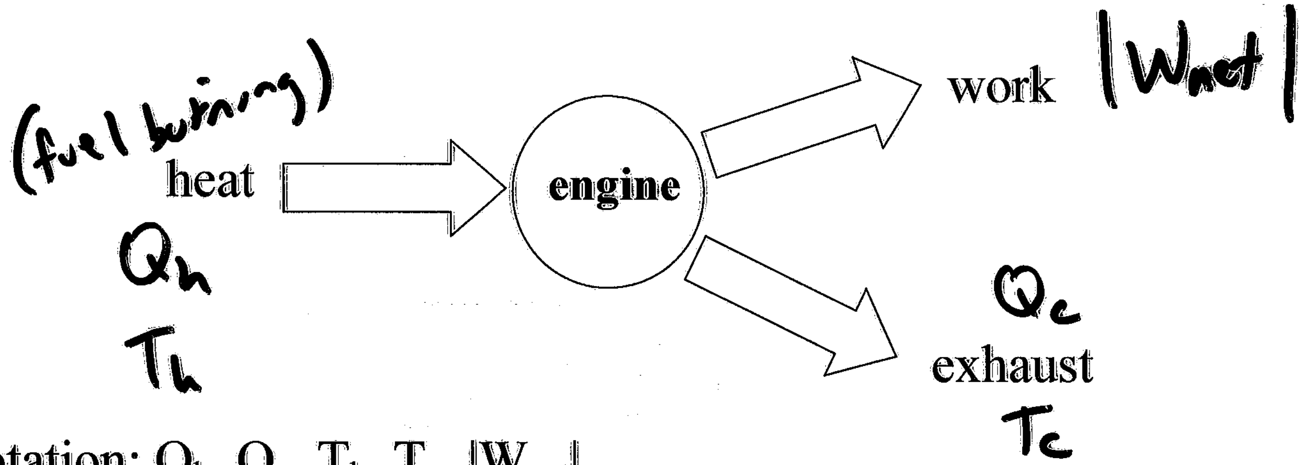
$-$area enclosed

$\Delta U = 0$ $\qquad W_{on\ gas}$ $\qquad Q$ positive

net $Q_{added} = -W_{on\,gas}$

Engines

The basic idea: energy transformation



Notation: Q_h, Q_c, T_h, T_c, $|W_{net}|$

$$\boxed{Q_h = |W_{net}| + Q_c}$$

<u>Efficiency</u>: how good is your engine at converting heat to work?

Definition: $\quad e = \dfrac{|W_{net}|}{Q_h}$

<u>Engine Power</u>: work per time (as usual) $= \dfrac{|W_{net}|}{\text{time for one cycle}}$

Demo: Thermoelectric converter engine

Worked Problem: An engine produces power of 5000 W, at 20 cycles/second. Its efficiency is 20%. What are $|W_{net}|$, Q_h, and Q_c per cycle?

$$P = \frac{|W_{net}|}{\text{time per cycle}} \qquad |W_{net}| = \frac{5000\,J}{\cancel{s}} \times \frac{1\,\cancel{s}}{20\,\text{cycle}}$$

$$= \boxed{250\,J/\text{cycle}}$$

$$e = \frac{|W_{net}|}{Q_h}$$

$$Q_h = \frac{|W_{net}|}{e} = \frac{250\,J}{.2} = \boxed{1250\,J}$$

$$1250 = 250 + Q_c \rightarrow \boxed{Q_c = 1000\,J}$$

What do those quantities represent?

Answers: 250 J, 1250 J, 1000 J

Carnot's Theorem:

You can't even convert *most* of the heat into work

$$\boxed{e_{\max} = "e_C" = 1 - \frac{T_c}{T_h}}$$

T in kelvin

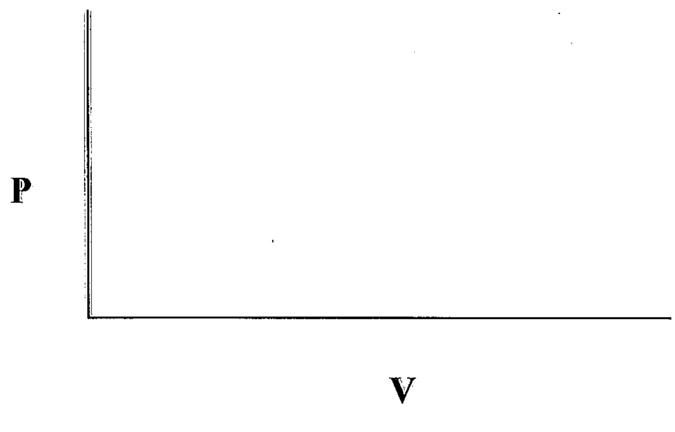
C for Carnot

(Organized) Energy lost by "irreversibilities"

Irreversibilities occur when heat is added during a temperature change

Most efficient engine possible: Carnot engine

→ all heat added during constant temperature processes



How much power?   Isothermal = slow, typically