Thermodynamics → effects of temperature
relations b/w internal (thermal) energy, work and heat

Liquids & solids → complex ~~sys~~ interacting systems, treated phenomenologically

Thermal expansion: $\frac{\Delta L}{L} = \alpha \Delta T$; $\frac{\Delta V}{V} = \beta \Delta T$

linear / volume coefficient of ~~linear~~ thermal expansion

Heating: $Q = m c \Delta T$ — c - specific heat capacity.

Phase transition: $Q = m \cdot L$

Entropy change: $dS = \frac{dQ}{T}$

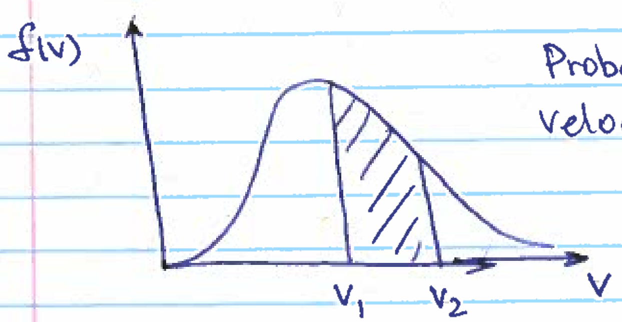
phase transition: $\Delta S = mL/T$

heating / cooling: $S = \int_{T_1}^{T_2} \frac{mL\,dT}{T} = mL \ln\left(\frac{T_2}{T_1}\right)$

Gases: ~~[illegible]~~ simple non-interacting particles

Velocity distribution: (Maxwell-Boltzmann distribution)

Probabylity density $f(v) = 4\pi \left(\frac{m}{2\pi k_B T}\right) v^2 e^{-\frac{mv^2}{2k_BT}}$



Probability to find particle with velocity v $v_1 < v < v_2$

$$P = \int_{v_1}^{v_2} f(v)\,dv$$

Average velocity $\langle v \rangle = \int_0^\infty v\, f(v)\,dv = \sqrt{\frac{8k_BT}{\pi m}}$

Root-mean square $v_{rms} = \sqrt{\langle v^2 \rangle} = \sqrt{\frac{3k_BT}{m}}$

Internal energy of an ideal gas

$E_{int} = N \cdot \langle K \rangle$ kinetic energy $\qquad \langle K \rangle = \left\langle \begin{matrix} \text{\# of degrees} \\ \text{of freedom} \end{matrix} \right\rangle \cdot \frac{k_B T}{2}$

Monoatomic gas: 3 d.o.f $\qquad \langle K \rangle_{mono} = \frac{3}{2} k_B T \quad E_{int} = \frac{3}{2} N k_B$

Diatomic gas: 5 (or 7) d.o.f $\qquad \langle K \rangle_{dia} = \frac{5}{2} k_B T$ (air) or $\frac{7}{2} k_B T$

Ideal gas law $\qquad PV = nRT = N \cdot k_B T$

$n = \frac{N}{N_A}$ $\qquad N_A = 6 \cdot 10^{23}$ Avogadro number

$k_B \cdot N_A = R$ universal gas constant

The first law of thermodynamics

$Q = \Delta E_{int} + W$

$$\Delta E_{int} = \frac{[\# \text{dof}]}{2} N k_B \Delta T = \frac{[\# \text{dof}]}{2} n R \Delta T$$

depends only on temperature change

Work $\qquad W = \int_{V_1}^{V_2} \frac{1}{V} dP$ $\qquad$ depends on the process.

Entropy change $\qquad dS = \frac{dQ}{T}$

Isothermal $\qquad Q = W = nRT \ln \frac{V_2}{V_1} \qquad \Delta S = \frac{Q}{T} = nR \ln \frac{V_2}{V_1}$

Isochoric $\qquad Q = n C_V T \qquad \Delta S = n C_V \int_{T_1}^{T_2} \frac{dT}{T} = n C_V \ln \frac{T_2}{T_1}$

Isobaric $\qquad Q = n C_p T \qquad \Delta S = n C_p \ln T_2/T_1$

Adiabatic $\qquad \Delta S = 0$

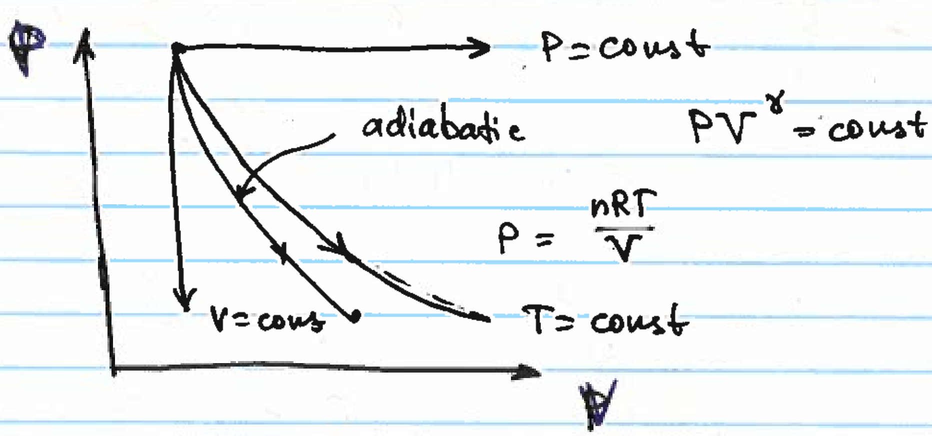
Let's gather together relevant information about different cycles

	ΔE_{int}	W	Q
Isothermal $T = const$	0	$\int_{V_1}^{V_2} P dV = nRT \ln \frac{V_2}{V_1}$	$nRT \ln \frac{V_2}{V_1}$
Isobaric $P = const$	$nC_V \Delta T$ $\left[\frac{3}{2} nR\Delta T\right]$	$P \Delta V = nR\Delta T$	$\Delta E_{int} + W = nC_p \Delta T$ $nC_V\Delta T + nR\Delta T = n(C_V + R)\Delta T$
Isochoric $V = const$	$nC_V \cdot \Delta T$ $\left[\frac{3}{2} nR\Delta T\right]$	0	$nC_V \Delta T$
Adiabatic $Q = \cancel{const}\ 0$ $PV^\gamma = const$	$nC_V \cdot \Delta T$ $\left[\frac{3}{2} nR\Delta T\right]$ for monoatomic gas	$\int_{V_1}^{V_2} P dV = \frac{P_1V_1 - P_2V_2}{\gamma - 1}$	0

Adiabatic process: $W = \int_{V_1}^{V_2} P dV = P_1 V_1^\gamma \int_{V_1}^{V_2} \frac{dV}{V^\gamma} =$

$$= P_1V_1^\gamma \left(-\frac{1}{\gamma-1}\right) \frac{1}{V^{\gamma-1}}\Bigg|_{V_1}^{V_2} = P_1V_1^\gamma \frac{1}{\gamma-1}\left[\frac{1}{V_1^{\gamma-1}} - \frac{1}{V_2^{\gamma-1}}\right] =$$

$$= \frac{1}{\gamma-1}\left[\frac{P_1V_1^\gamma}{V_1^{\gamma-1}} - \frac{\overset{P_2V_2^\gamma}{\boxed{P_1V_1^\gamma}}}{V_2^{\gamma-1}}\right] = \frac{1}{\gamma-1}\left[P_1V_1 - P_2V_2\right]$$



$\gamma = \frac{C_P}{C_V}$

Thermodynamical cycles : for each step calculate $W, \Delta E_{int}$, $Q = W + \Delta E_{int}$

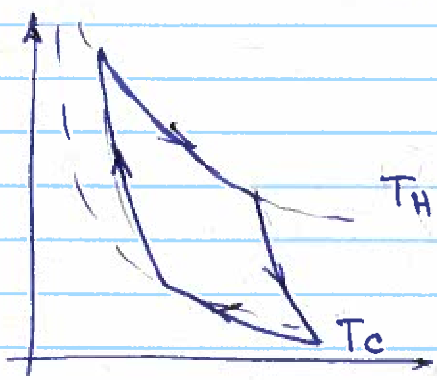
$W_{total} = \sum W_{each\ step}$

$Q > 0$ added heat $\quad Q < 0$ extracted heat

$$\text{efficiency} = \frac{\text{useful outcome}}{\text{cost}}$$

	Heat engine	Heat pump	Refrigirator
outcome	~~outcome~~ W	Q_H	Q_c
cost	Q_H	W	W
	$e = \frac{W}{Q_H} = \frac{Q_H - \lvert Q_c \rvert}{Q_H}$	$COP = \frac{Q_H}{W} = \frac{\lvert Q_H \rvert}{\lvert Q_H \rvert - Q_c}$	$COP = \frac{Q_c}{W} = \frac{Q_c}{\lvert Q_H \rvert - Q_c}$

Ideal heat engine → Carnot cycle (fully reversible)
(two isothermal + two ideabatic processes)



$$e_{carnot} = 1 - \frac{T_c}{T_H}$$

max achievable efficiency for a heat engine