

Isothermal process (const. T) b/w state 1 & state 2

Work done in this process: $W = \int P dV$

Assume ideal gas system: $PV = nRT$ or $P = \frac{nRT}{V}$

$$\begin{aligned} \rightarrow W &= \int_1^2 \frac{nRT}{V} dV = nRT \int_1^2 \frac{dV}{V} = nRT [\ln V]_1^2 = nRT [\ln V_2 - \ln V_1] \\ &= nRT \ln \left(\frac{V_2}{V_1} \right) \end{aligned}$$

$\rightarrow \Delta U = 0$ no interaction in an ideal gas, all internal energy comes from K.E.

$$\Delta U = \Delta KE$$

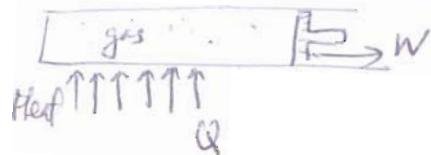
2) $\frac{1}{2} m \bar{v}^2 = \frac{3}{2} kT$ (average KE per molecule is related to the macroscopic Temperature)

3) since $T_1 = T_2$ in isothermal process $\rightarrow KE_1 = KE_2$

$$\rightarrow \Delta U = 0 \text{ in isothermal}$$

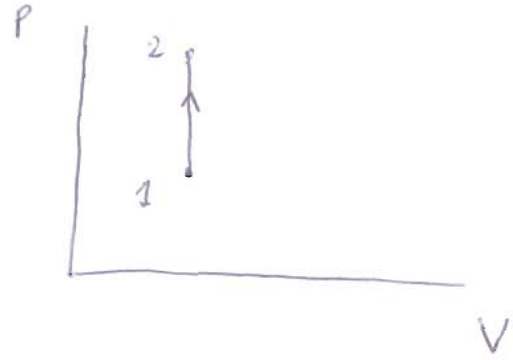
$$\rightarrow Q = W = nRT \ln \left(\frac{V_2}{V_1} \right) \text{ (isothermal)}$$

(heating gas in a piston slowly at const. T , heat supplied equals work delivered by gas through piston)



Isochoric (const. V) b/w state 1 & state 2

$$\rightarrow W = \int_1^2 P \underline{dV} = 0$$



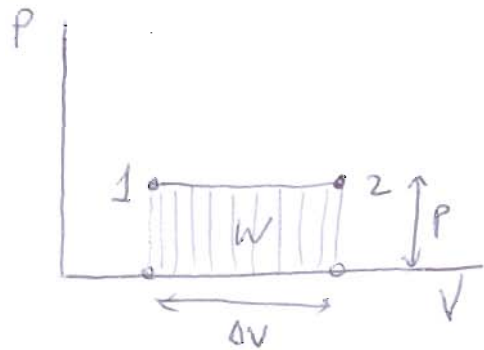
$$\rightarrow Q = \Delta U$$

Specific heat at constant volume c_v : $Q = n c_v \Delta T$

$$\boxed{c_v = \frac{1}{n} \frac{Q}{\Delta T} = \frac{1}{n} \frac{\Delta U}{\Delta T}}$$

Isobaric (const. P) b/w state 1 & state 2

$$W = \int_1^2 P dV = P \Delta V$$



Specific heat at constant P = c_p : $Q = n c_p \Delta T$

Ideal gas system : $P \Delta V = n R \Delta T = W$ (isobaric)

1st Law of TD : $\Delta U = Q - W = Q - P \Delta V$

$$\Delta U = Q - P \Delta V$$

$$n c_p \Delta T = n c_p \Delta T - n R \Delta T$$

$$\rightarrow \boxed{c_v = c_p - R} \quad R = 8.314 \frac{\text{J}}{\text{K mol}}$$

or $c_p = c_v + R$

Adiabatic Process ($Q=0$) b/w state 1 & state 2

1st Law T.D :

$$\Delta U = -W$$

$$PV^\gamma \text{ is constant } (P_1 V_1^\gamma = P_2 V_2^\gamma)$$

$$\gamma \equiv \frac{C_p}{C_v} > 1 \quad (\text{dimensionless coefficient})$$

$$TV^{\gamma-1} \text{ is constant } (T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1})$$

$$\text{Coefficient } \gamma = \frac{C_p}{C_v} > 1$$

$$(C_p = C_v + R)$$

$$\text{also: } \Delta U = Q - W \rightarrow \boxed{Q = \Delta U + W}$$

$$\begin{cases} \text{const } P = & W > 0 \quad W = P\Delta V \\ \text{const } V = & W = 0 \end{cases}$$

(\therefore system can absorb more heat at const P than at const V b/c at const P it can do some work)
so $C_p > C_v$.

→ What are the possible values for γ ?

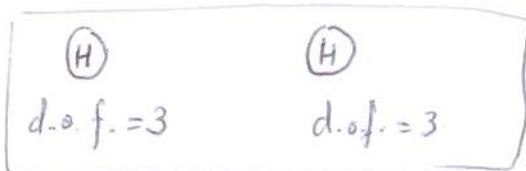
Equipartition Theorem : $\frac{1}{2} m \overline{v^2} = \frac{3}{2} kT$: average KE per molecule per degree of freedom (or per dimension) : $\boxed{\frac{1}{2} kT}$

→ Monoatomic molecules (Ne, Ar, etc.) : average KE per molecule is $\frac{3}{2} kT$ (3 dimensions)

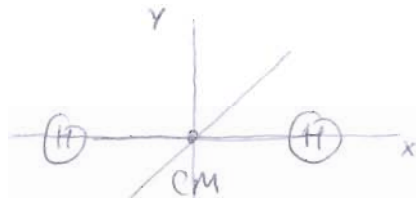
→ Diatomic molecules ($H_2, O_2, \text{etc.}$)



$$\text{d.o.f.} = 6 - 1 = 5$$



$$\text{d.o.f.} = 6$$



$$\text{d.o.f.} = 3 \text{ of CM}$$

rotation w.r.t. y & z

$$3 + 2 = 5$$

av. KE per diatomic molecule is

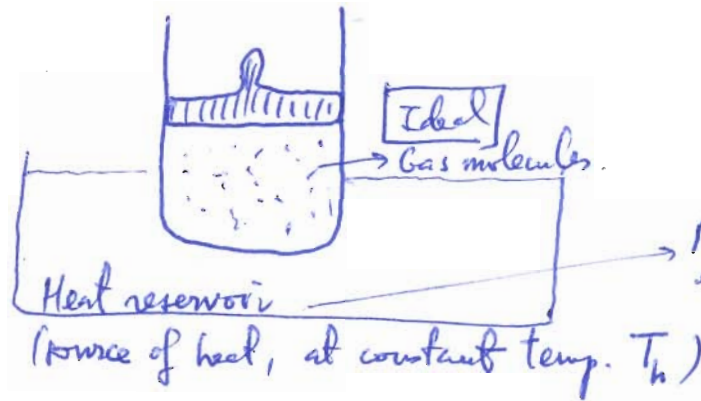
$$\frac{5}{2} kT$$

$$C_V = \frac{1}{n} \frac{\Delta U}{\Delta T} \left\{ \begin{array}{l} \text{Monoatomic: } \Delta U = N \times \frac{3}{2} kT \rightarrow C_V = \frac{3}{2} R \\ \quad \quad \quad n = \frac{N}{N_A} \\ \text{Diatomic: } \Delta U = N \times \frac{5}{2} kT \rightarrow C_V = \frac{5}{2} R \end{array} \right.$$

$$\gamma = \frac{C_p}{C_v} = \frac{C_v + R}{C_v} \left\{ \begin{array}{l} \text{Monoatomic: } \gamma = 1.67 \\ \text{Diatomic: } \gamma = 1.4 \end{array} \right.$$

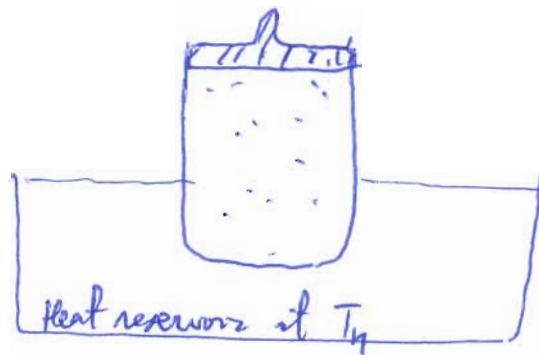
Ch. 22 Second Law of Thermodynamics

Heat engines:

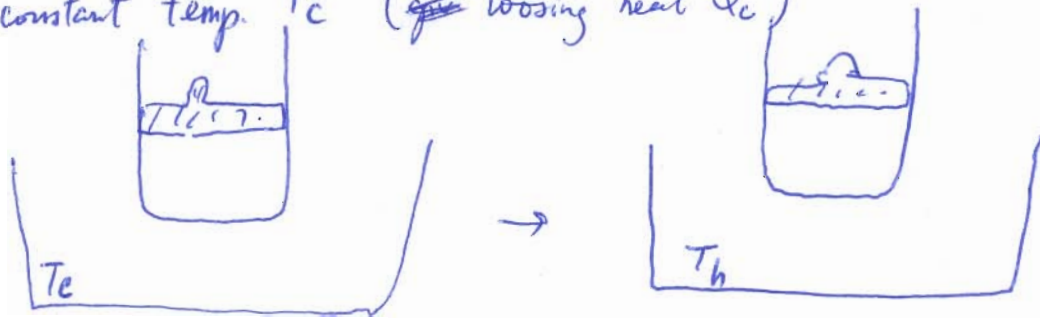


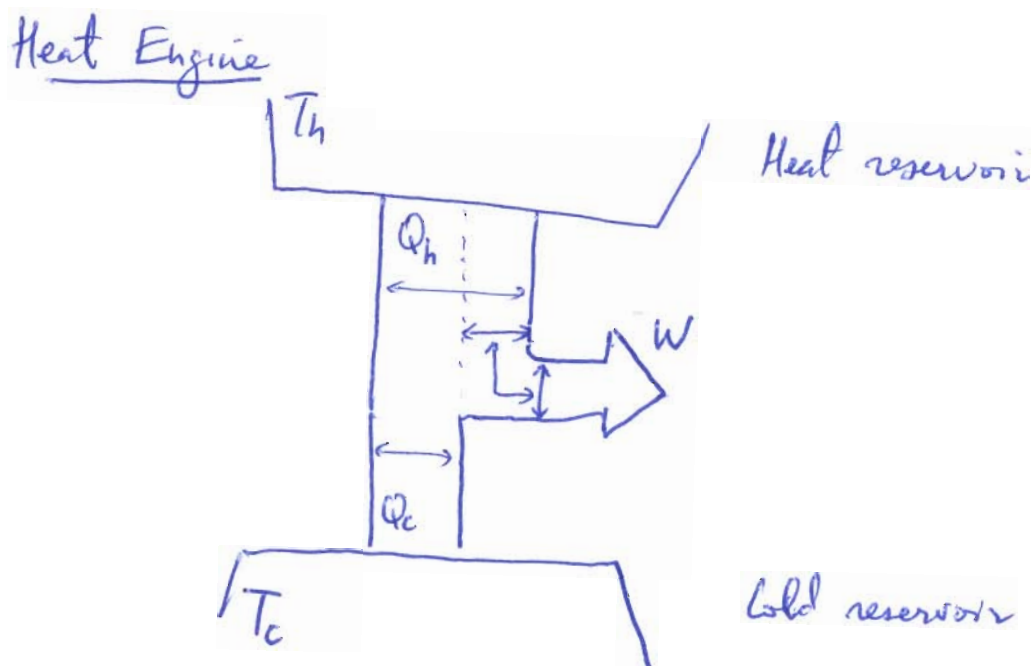
Makes sure the expansion is isothermal
 $\Delta U = 0$

$Q = W$
(heat absorbed is returned as work done by piston)
↓
going up



For this system to keep working: need to bring piston ^{back} down by ~~putting~~ putting it in thermal contact with a cold reservoir at constant temp. T_c (~~is~~ losing heat Q_c)





$$\Delta U_{\text{engine}} = Q_h - Q_c - W = 0$$

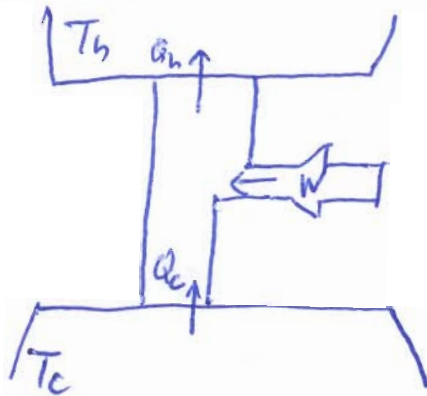
\downarrow 1st law of T.D. \downarrow ideal gas, under isothermal processes.

$$\text{efficiency} : \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \left(\frac{Q_c}{Q_h} \right) < 1$$

\downarrow positive and $Q_c < Q_h$

Second law of T.D. : it is impossible to build a heat engine operating in a cycle that extracts heat from a hot reservoir and delivers an equal amount of work -
 (requires bringing system back to original state)

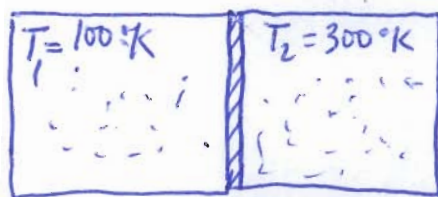
Refrigerators : reversed heat engines.



Sec. law of T.D.: it is impossible to transfer heat from a cold reservoir to a hot reservoir w/o requiring any work.

Coefficient of Performance: C.O.P. $\equiv \frac{Q_c}{W}$

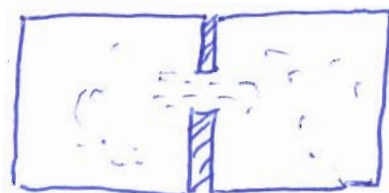
Entropy



$N_1 = 100$ $N_2 = 100$
 v_{rms} v_{rms}

$$\frac{1}{2} m \overline{v^2} = \frac{3}{2} kT$$

higher order



mixed up.
 some fast & some slow
 on either side

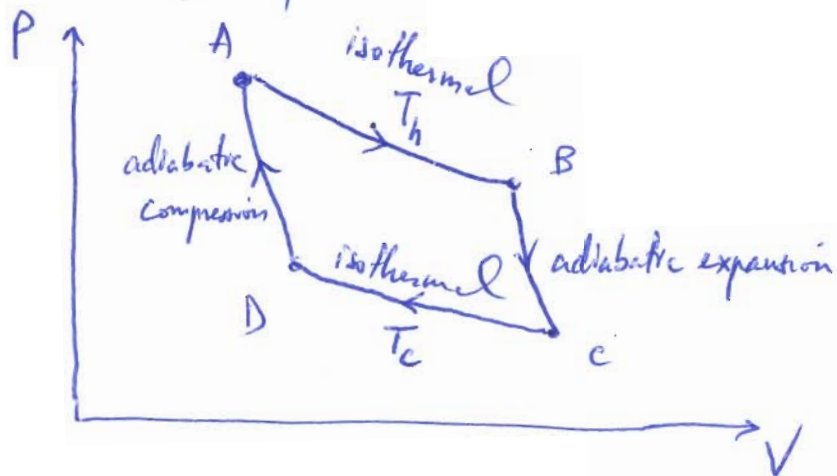
spontaneous \rightarrow less order.

$$\Delta S = \int_1^2 \frac{dQ}{T} > 0$$

Sec. law of T.D.: entropy of a closed system can never decrease.

Carnot Engines : 4 reversible processes. $\left\{ \begin{array}{l} 2 \text{ isothermal} \\ 2 \text{ adiabatic} \end{array} \right.$

↓
ideal with max. efficiency



Heat engine: $e = 1 - \frac{Q_c}{Q_h}$, what is it for a Carnot Engine?

$$Q_h: (A \rightarrow B \text{ isothermal}) = nRT_h \ln\left(\frac{V_B}{V_A}\right)$$

$$Q_c: (C \rightarrow D \text{ isothermal}) = nRT_c \ln\left(\frac{V_D}{V_C}\right)$$

B → C adiabatic: $T_B V_B^{\gamma-1} = T_C V_C^{\gamma-1}$ or $\left(\frac{V_B}{V_C}\right)^{\gamma-1} = \frac{T_C}{T_B} = \frac{T_c}{T_h}$

D → A adiabatic: $T_D V_D^{\gamma-1} = T_A V_A^{\gamma-1}$ or $\left(\frac{V_D}{V_A}\right)^{\gamma-1} = \frac{T_A}{T_D} = \frac{T_h}{T_c}$

$$\frac{V_B}{V_C} = \frac{V_A}{V_D}$$

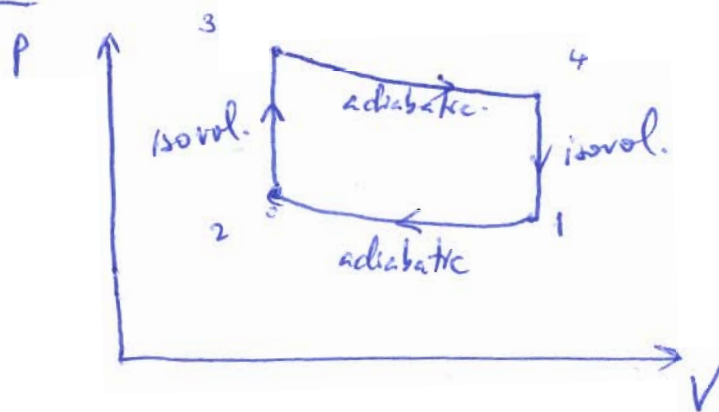
$$\rightarrow e = 1 - \frac{nRT_c \ln\left(\frac{V_D}{V_C}\right)}{nRT_h \ln\left(\frac{V_B}{V_A}\right)}$$

$$e = 1 - \frac{T_c}{T_h}$$

Carnot engines operating b/w T_h, T_c will have the max. efficiency given

$$1 - \frac{T_c}{T_h}$$

Otto Cycle Engines :



$$27-61. \rightarrow e_o = 1 - \frac{1}{5^{\gamma-1}} \quad (\text{Otto cycle})$$

$$e_c = 1 - \frac{1}{3 \times 5^{\gamma-1}} \quad (\text{Carnot}) > e_o$$