THERE IS A BEST ENGINE

AN IDEALIZED CYCLE DUE IN SPIRIT TO THE FRENCH MILITARY ENGINEER

Nicolas Léonard Carnot ~1824

enunciated a version of 2^{nd}_{1} -- which translates into

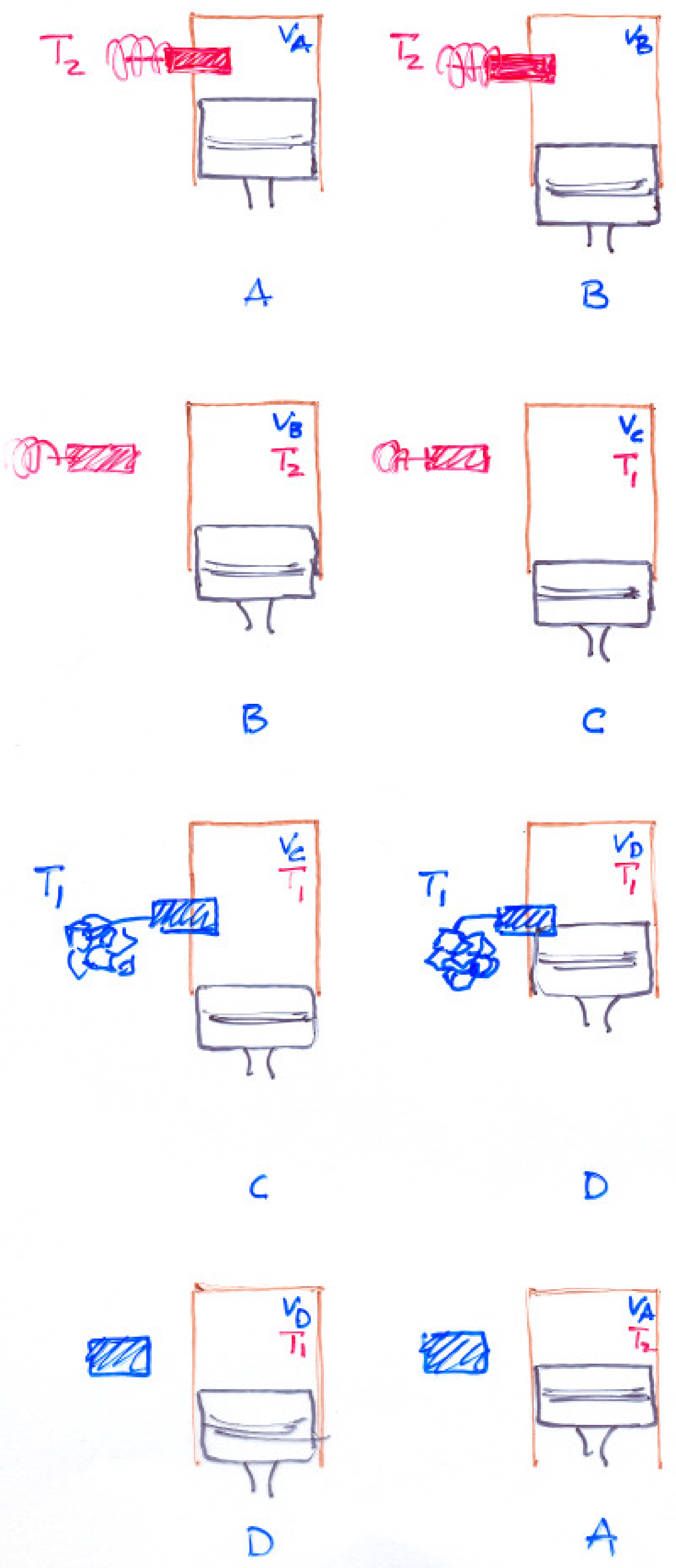
2^{nd}_{3} Thermal energy will not, of its own accord, flow from a cooler object to a warmer object.

and found the maximum efficiency thermal engine --- while still believing in caloric

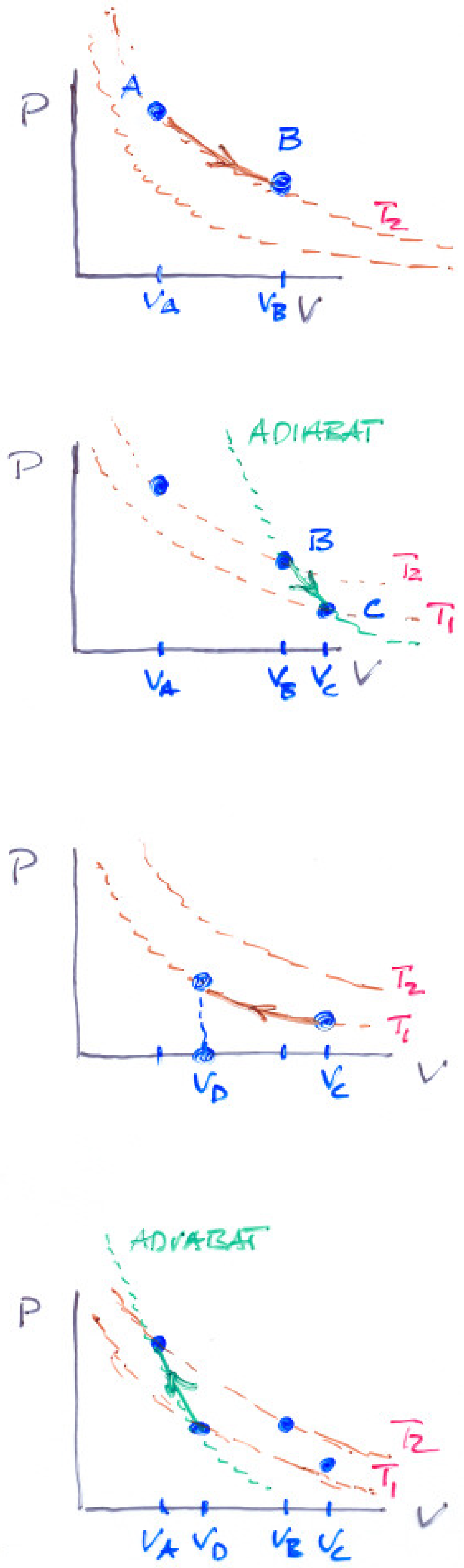
THE "CARNOT CYCLE":

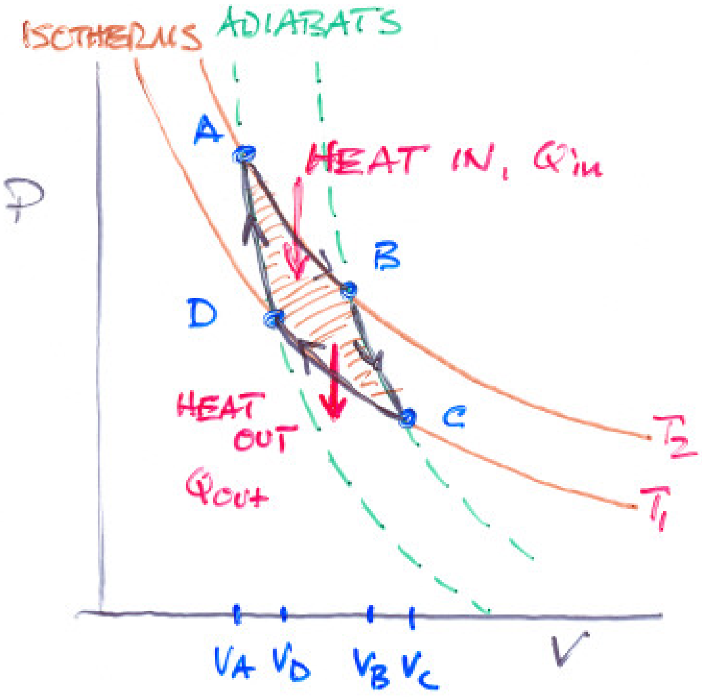
$\left.\begin{array}{l}\text{2 adiabatic transitions}\\ \text{2 isothermal transitions}\end{array}\right\}$ single cycle

CARNOT ENGINE



CARNOT CYCLE





$$\epsilon = \frac{W}{Q_{in}}$$

$$= \frac{Q_{o} - Q_{in}}{Q_{in}}$$

$$\epsilon = 1 - \frac{Q_{out}}{Q_{in}}$$

Assume an ideal gas.

$A \to B$

isothermal expansion

$P_A V_A = P_B V_B$

$B \to C$

adiabatic expansion

$P_B V_B^{\gamma} = P_C V_C^{\gamma}$

$C \to D$

isothermal compression

$P_C V_C = P_D V_D$

$D \to A$

adiabatic compression

$P_D V_D^{\gamma} = P_A V_A^{\gamma}$

$A \to B$ isothermal expansion

$$\Delta U = \Delta Q - \Delta W = 0$$

$$W_{AB} = Q_{in}$$

$$W_{AB} = \int_A^B P\,dV = \int_A^B \frac{nRT_2}{V}\,dV = nRT_2 \ln\left(\frac{V_B}{V_A}\right) > 0$$

$C \to D$ isothermal contraction

$$W_{CD} = |Q_{out}|$$

$$= \int_C^D P\,dV = \int_C^D \frac{nRT_1}{V}\,dV = nRT_1 \ln\left(\frac{V_D}{V_C}\right) < 0$$

$$= -nRT_1 \ln\left(\frac{V_C}{V_D}\right) > 0$$

$$Q_{out} = nRT_1 \ln\left(\frac{V_C}{V_D}\right) = -W_{CD}$$

$B \to C$ adiabatic expansion

remember

$$W_{BC} = \frac{nR}{\gamma - 1}(T_2 - T_1)$$

and

$$\Delta U = -nC_V(T_2 - T_1) = nC_V(T_1 - T_2)$$

gets cooler

	W (by gas)	Q (added)	ΔU
	$nRT_2 \ln(V_B/V_A)$	$Q_{in} = nRT_2 \ln\left(\frac{V_B}{V_A}\right)$	0
	$\frac{nR}{\gamma-1}(T_2-T_1)$	0	$nC_V(T_1-T_2)$
	$nRT_1 \ln\left(\frac{V_D}{V_C}\right)$	$Q_{\cancel{in}\,out} = nRT_1 \ln\left(\frac{V_D}{V_C}\right)$	0
	$\frac{nR}{\gamma-1}(T_1-T_2)$	0	$nC_V(T_2-T_1)$
net change:	$nR(T_2-T_1)\ln\left(\frac{V_B}{V_A}\right)$	$nR(T_2-T_1)\ln\frac{V_B}{V_A}$	0

D3 show this line

from

$$\frac{Q_{out}}{Q_{in}} = \frac{T_1}{T_2} \frac{\ln(V_C/V_D)}{\ln(V_B/V_A)}$$

and

$$\frac{V_B}{V_A} = \frac{V_C}{V_D}$$ (which you need to show for D_3)

The "Carnot Efficiency" is

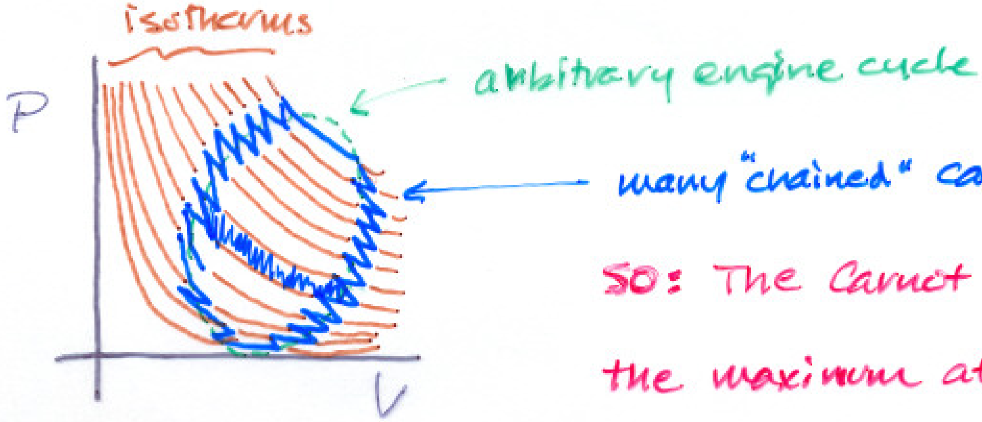
$$\epsilon_c = 1 - \cancel{\frac{Q_{in}}{Q_{out}}} \frac{Q_{out}}{Q_{in}} = 1 - \frac{T_1}{T_2} = 1 - \frac{T_c}{T_H}$$

$$\epsilon_c = 1 - \frac{T_c}{T_H}$$ depends only on temperatures

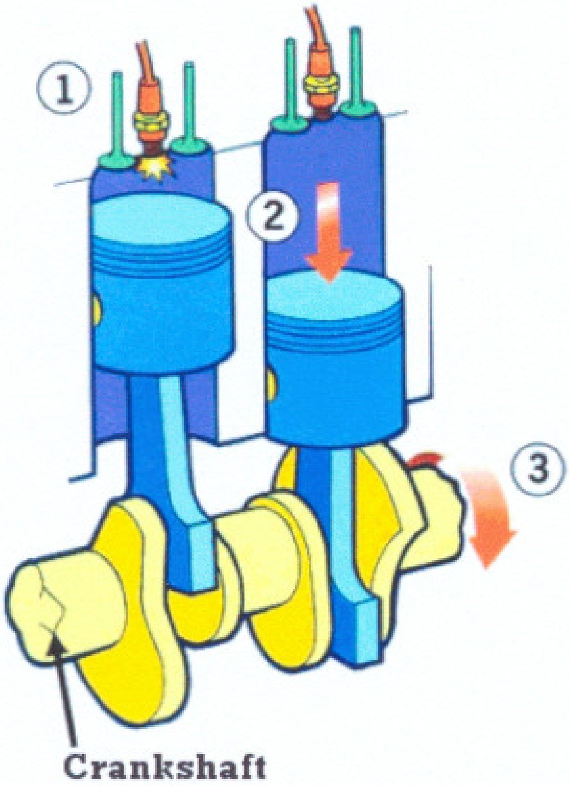
Imagine a bunch of Carnot Engines:

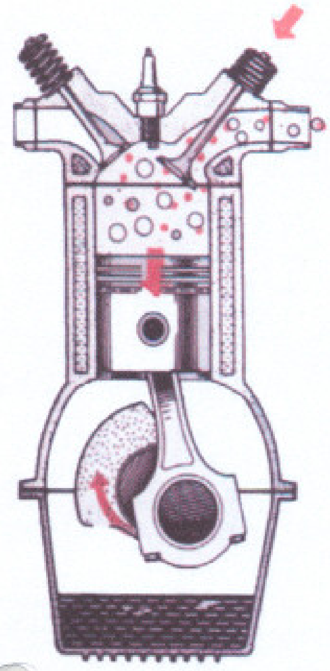
Q_{in} for one $=$ Q_{out} of the previous one...

An arbitrary engine cycle can be thought of as the limit of an infinite number of carnot engines

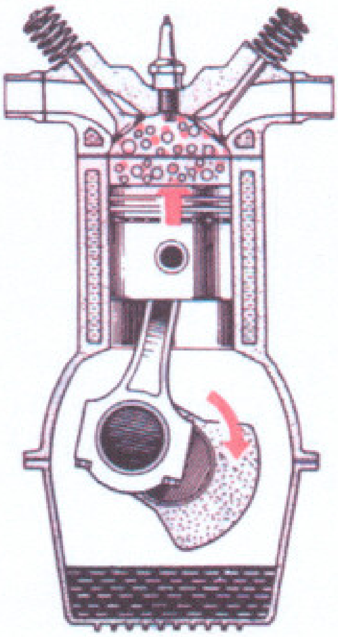


SO: The Carnot efficiency is the maximum attainable... it is an idealization: $\epsilon_{any} < \epsilon_c$

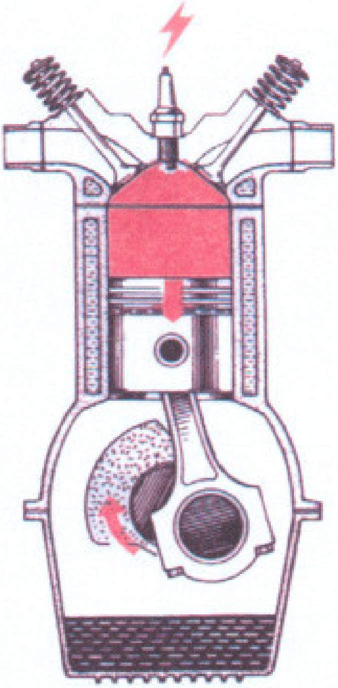

1
2
3
Crankshaft



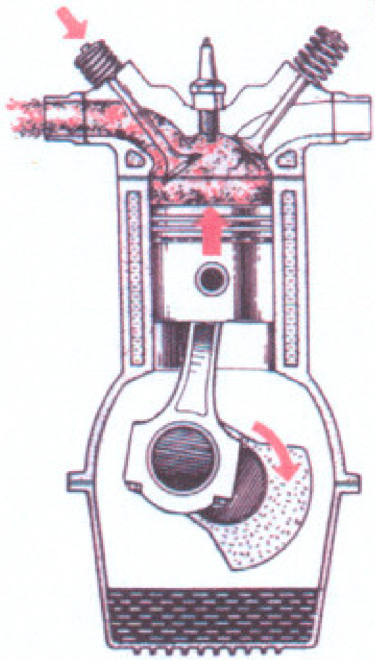
Air intake



Compression

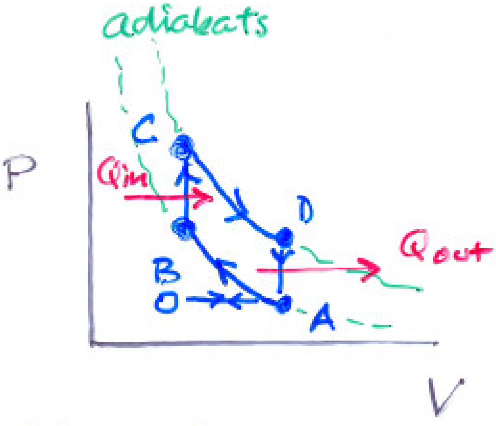


Combustion



Exhaust Emission

REAL ENGINES



"Otto Cycle"

~ an automobile engine

OA – air in at atmospheric pressure

AB – adiabatic compression

BC – Qin represents the heating from a spark plug

CD – adiabatic expansion – work done... turning the crank shaft

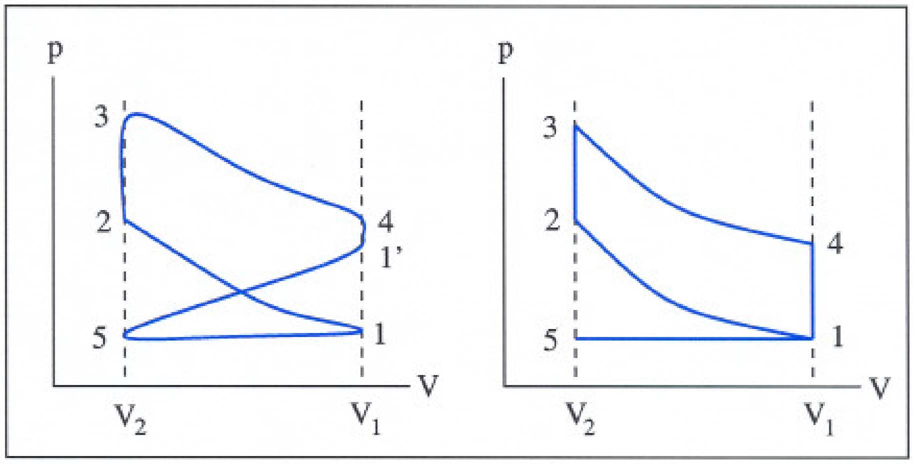
DA – cooling (exhaust stroke, almost)

AO – actual exhaust at atmospheric pressure

$$\epsilon_{otto} = 1 - \frac{1}{\left(V_A/V_B\right)^{\gamma-1}}$$

$$\epsilon_{otto} = 1 - \frac{T_A}{T_D} \qquad \left(\epsilon_c = 1 - \frac{T_A}{T_C} \right)$$

Gasoline engine (Otto cycle) [tln65]



Four-stroke Otto cycle (left)

1-2: compression stroke
2-3-4: power stroke (spark plug ignites at 2)
4-1'-5: exhaust stroke (exhaust valve opens at 4)
5-1: intake stroke (intake valve opens at 5)

Idealized Otto cycle (right)

1-2: adiabatic compression of air-fuel mixture ($S = \text{const}$)
2-3: explosion of air-fuel mixture ($V = \text{const}$)
3-4: adiabatic expansion of exhaust gas ($S = \text{const}$)
4-1: isochoric release of exhaust gas ($V = \text{const}$).
1-5-1: intake stroke (thermodynamically ignored)

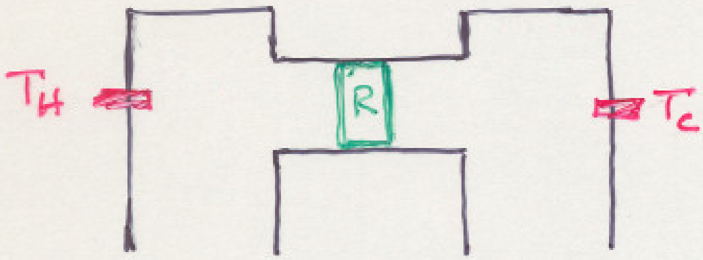
Parameter: $K \doteq V_1/V_2$ (compression ratio).

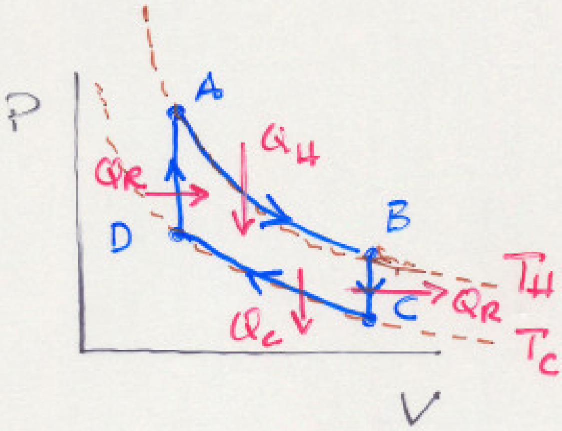
The compression ratio K must not be chosen too large to prevent the air-fuel mixture from igniting spontaneously, i.e. prematurely.

STIRLING ENGINE

real-live, near-Carnot engine concept

Robert Stirling ~1816



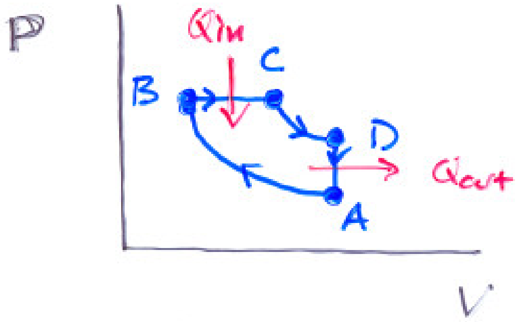


AB - isothermal expansion
L - down → power
Q_H in

BC - isochoric !
R - ~~up~~ down   L. ~~down~~ up !
Q_R - out

CD - isothermal compress.
R - up
Q_C - out

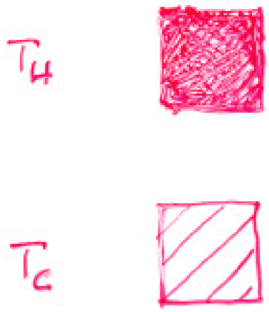
DA - isochoric
L - down   R - up
Q_R - in



Diesel Cycle

ENTROPY

Suppose we have two objects at different temperatures

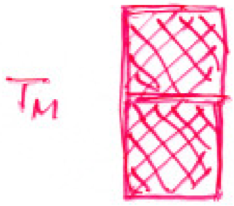


this configuration is useful
- could run an engine between them and get W out.
- could warm anything $T_A < T_H$

without transfering heat in or out — put them together.

Let them come to equilibrium -- T_M

$T_M > T_C$
right?
$T_M < T_H$

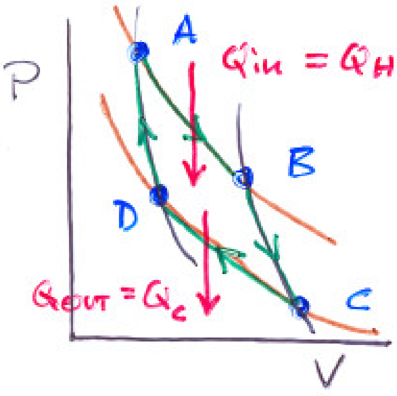


- total energy is the same
- no work was done on it

But, this configuration is somehow less useful -- "lower quality" energy

- can't run an engine
- can't warm anything $T_A > T_M$

Remember the Carnot Cycle...



we found

$$\frac{Q_{out}}{Q_{in}} = \frac{T_C}{T_H} = \frac{Q_C}{Q_H}$$

rearrange

$$\frac{Q_C}{T_C} = \frac{Q_H}{T_H}$$

$$0 = \frac{Q_H}{T_H} - \frac{Q_C}{T_C}$$ for the <u>whole</u> <u>cycle</u>

Something called $\frac{Q}{T}$ appears to not change in the cycle. This is called ENTROPY

$$\Delta S = \frac{\Delta Q}{T} \Rightarrow$$ $\Delta S = 0$ for closed, complete cycle

or... think lots of infinitesimal Carnot cycles to make one arbitrary cycle:

$$\Delta S = \oint \frac{dQ}{T} = 0$$ for an arbitrary, closed system

symbolize for whole cycle

What's an obvious characteristic of a cycle?

reversibility

$\Delta S = \frac{\Delta Q}{T}$ was for the isothermal stages of the Carnot cycle.

* $\Delta S = \frac{\Delta Q}{T}$ for any isothermal REVERSIBLE process

* $\oint \frac{dQ}{dT} = 0$ for any complete reversible cycle

The entropy of the universe is unaffected by any reversible process

Look closely at some arbitrary path from

$i \to f \quad \Rightarrow \quad T_i V_i \longrightarrow T_f V_f$

reversible, ideal gas

1st: $\quad dQ = dU + dW$

$$dW = PdV$$

$$dU = nc_V dT$$

$$P = \frac{nRT}{V}$$

so:

$$dQ = nC_V dT + nRT\frac{dV}{V}$$

$$\frac{dQ}{T} = nC_V\frac{dT}{T} + nR\frac{dV}{V} \qquad i \to f \Rightarrow$$

$$\int_{Q_i}^{Q_f}\frac{dQ}{T} = nC_V\int_{T_i}^{T_f}\frac{dT}{T} + nR\int_{V_i}^{V_f}\frac{dV}{V}$$

$$\Delta S = nC_V \ln\left(T_f/T_i\right) + nR\ln\left(V_f/V_i\right)$$

nothing said about the path ...

ΔS is dependent only on initial state and the final state $\Rightarrow$ a State Function

State Functions: P, V, S

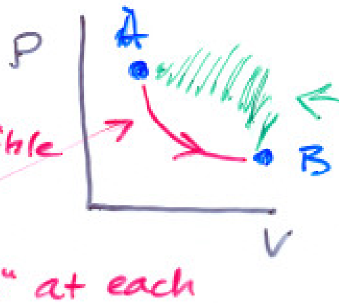
REMEMBER MY "ARROW OF TIME" DISCUSSION?

let's consider an IRREVERSIBLE process...

can consider entropy changes now since we find that S is a state function

WHAT'S AN IRREVERSIBLE PROCESS?

- In a reversible process, one can describe each step as having a definite thermodynamic state
- an irreversible process has a well defined thermodynamic state only at the beginning and the end



for whole system

reversible transition

irreversible transition

"quasi-static" at each point → P & V same everywhere in system

P & V will vary all over the SYSTEM throughout.