THE SECOND LAW OF THERMODYNAMICS

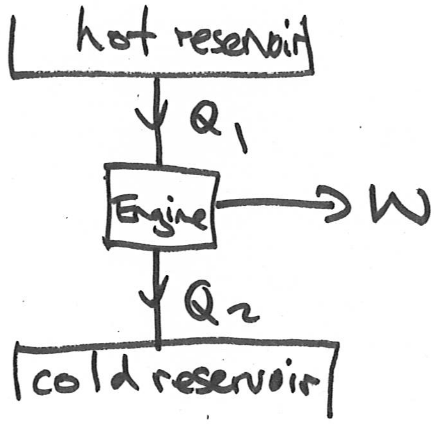
The 1st law taught us we can't create energy.

When trying to make efficient steam engines physicists also learnt they can't turn ambient heat energy into work....

HEAT ENGINES

Machines that do something powered by a heat source are generally complicated.... but Carnot realized he could idealize them

- take Q_1 from hot reservoir
- dump Q_2 to cold
- perform work W



This is "one cycle" after which engine has returned exactly to it's starting point - it's not storing any new internal energy.

$$\Rightarrow \qquad W = Q_1 - Q_2$$

We'll see it's impossible for an engine to be 100% efficient - you must have a cold reservoir or the engine will melt!

→ steam trains vent into atmosphere

→ power stations have cooling stacks

Efficiency

$$\eta = \frac{\text{useful energy}}{\text{expended energy}}$$

$$\eta_{\text{heat engine}} = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - Q_2/Q_1$$

$\eta = 1$ would be all Q_1 used to do work ($Q_2 = 0$)

Statements Of The Second Law

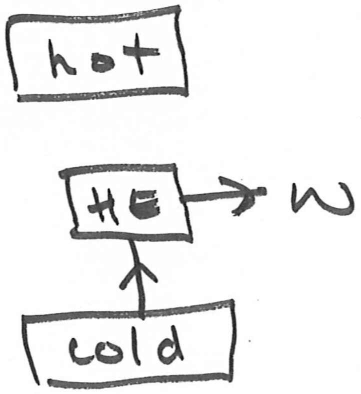
Clausius: "It is impossible to construct a device that, operating in a cycle, produces no other effect than the transfer of heat from a colder to a hotter body"

eg pour hot water into cold cup – the water doesn't heat up.

Kelvin Planck: "It is impossible to construct a device, operating in a cycle, that produces no effect other than the extraction of heat from a single body & the performance of an equal amount of work"

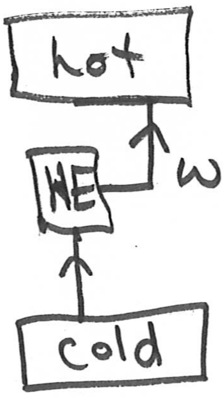
The two statements are really the same

eg



Forbidden by Kelvin Planck.

It stops you doing the work on hot to violate Clausius

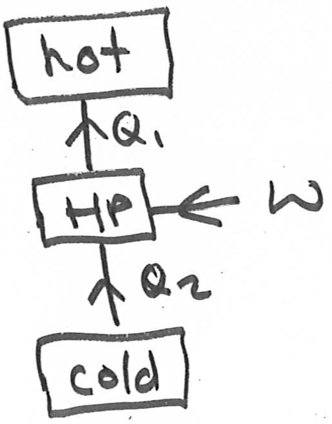


Perpetual Motion Machines Of Second Kind: these run purely off the environment's thermal energy. They are impossible by the second law!

Stress: the second law is an add on to energy conservation we didn't spot in the kinetic model of gases - in a bit we will return & see what we missed.

HEAT PUMPS

The second law does allow us to heat a house from the cold ground outside...



... but we have to put energy in to achieve it

$$Q_1 = Q_2 + W$$

$$\eta_{HP} = \frac{Q_1}{W} = \frac{1}{\eta_{HE}}$$

$$\eta_{HP} = \frac{Q_2 + W}{W} > 1$$

You can also view this as a refrigerator making the cold fridge colder - the extracted energy is dumped into the hot room.

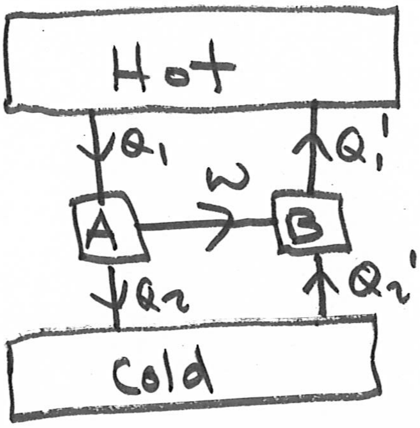
Now you would say $\eta_R = \frac{Q_2}{W}$

Reversible Heat Engines Are Most Efficient

Remember a reversible engine is one where we can reverse the energy flow arrows.

Consider

A is some non-reversible heat engine

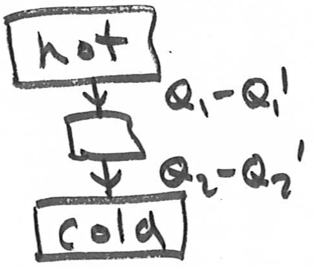


B is a reversible heat engine running as a heat pump powered by A...

$$\eta_A = \frac{W}{Q_1} \qquad \eta_{B_{HP}} = \frac{Q_1'}{W} \quad \Rightarrow \quad \eta_B = \frac{W}{Q_1'}$$

if we ran backwards

For the whole system



Clausius' statement of the 2nd law forbids cold to flow to hot

$$\Rightarrow \quad Q_1 - Q_1' \geqslant 0$$

$$Q_1 \geqslant Q_1'$$

So $\dfrac{W}{Q_1} \leq \dfrac{W}{Q_1'}$

$$\Rightarrow \quad \eta_A \leq \eta_B$$

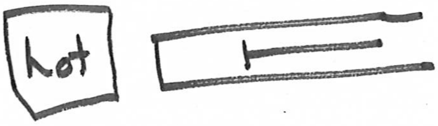
There is no heat engine better than the reversible engine B!

$\boxed{\text{CARNOT'S THEOREM}}$

Can we build (or at least imagine) a reversible heat engine – yes it follows Carnot's cycle

THE CARNOT CYCLE

Take a volume of ideal gas in thermal $\equiv$'m with the hot reservoir

① 

$A \to B$: expand isothermally doing W_1 work & absorbing Q_1 heat.

$T =$ const $\quad \Delta U = 0$

$\Rightarrow W_1 = Q_1$

② 

$B \to C$: isolate & expand adiabatically to the temperature of the cold reservoir.

Expands doing work W_2

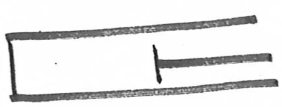
$Q = 0 \Rightarrow \Delta U_2 = -W_2$

③ 

$C \to D$: in contact with cold reservoir isothermally compress. Do work W_3 on the gas

$T =$ const $\Rightarrow \Delta U = 0$

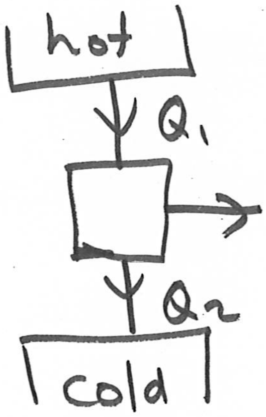
$W_3 = Q_2$

④ 

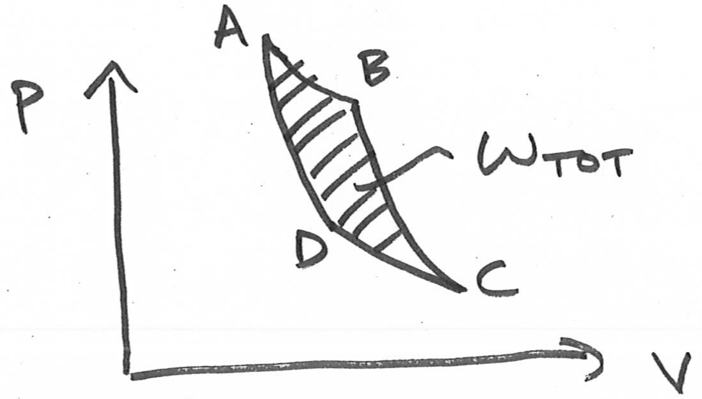
$D \to A$: isolate & compress adiabatically until at hot reservoirs temperature.

Do work W_4 on gas

$Q = 0 \Rightarrow \Delta U_4 = W_4$



$$W_1 + W_2 - W_3 - W_4 = W_{TOT}$$



We have completed one cycle.

In principle everything can be reversed.