Heat Engines + Refrigerators

Goals: Basic operating principles of engines + refrigerators

Fundamentally limited by entropy

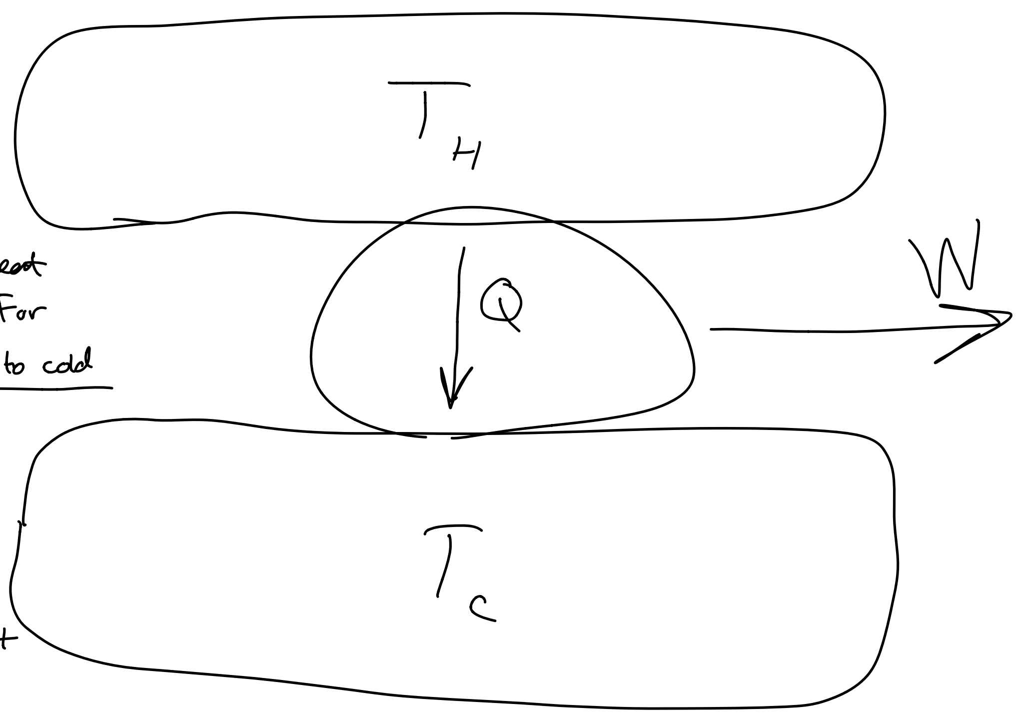
Don't care about actual engines!

Engine: Basic Idea

Want to do some work

Need some energy

Causes heat flow for hot to cold



Capture some of the energy and make it do some work

T_H: hot reservoir

T_C: cold reservoir

reservoir: very large material whose temp is unaffected by heat flow

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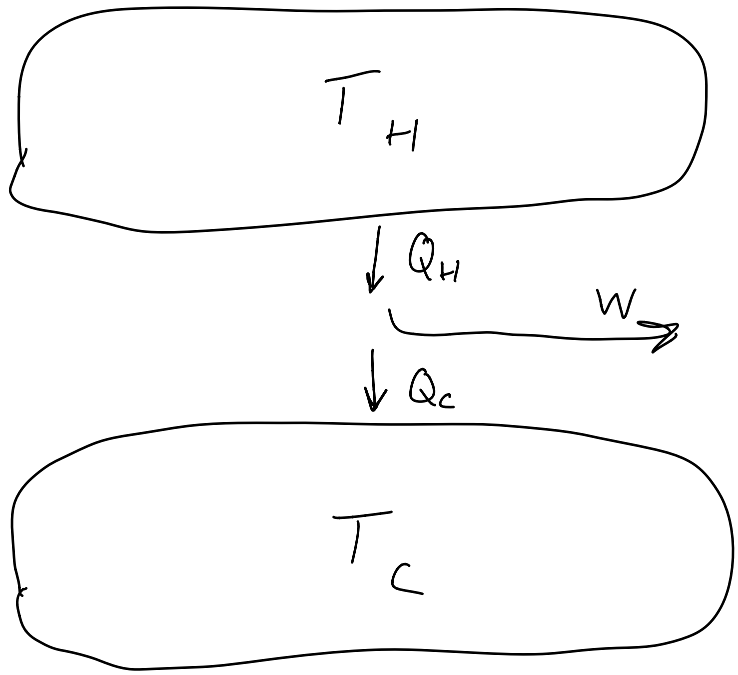
We cannot "use" all of this energy

Entropy of Hot reservoir decreases as heat leaves

$$dU = T\,dS \longrightarrow dS = \frac{dU}{T} = \frac{Q}{T}$$

- There must be some "waste heat"



$$Q_H = W + Q_c$$

Efficiency: $\dfrac{W}{Q_H} = \epsilon$

$$\epsilon = \frac{Q_H - Q_c}{Q_H} = 1 - \frac{Q_c}{Q_H}$$

Neglecting any ΔS from work done:

$$\Delta S = -\frac{Q_H}{T_H} + \frac{Q_c}{T_c}$$

2^{nd} Law: $\Delta S \geq 0$

$$-\frac{Q_H}{T_H} + \frac{Q_c}{T_c} \geq 0$$

$$\Rightarrow \quad \frac{Q_c}{T_c} \geq \frac{Q_h}{T_h}$$

$$\frac{Q_c}{Q_h} \geq \frac{T_c}{T_h}$$

$$\epsilon = 1 - \frac{Q_c}{Q_h}$$

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

Ex: $T_h = 500\,K$

$T_c = 300\,K$

$$\epsilon = 1 - 0.6 = 0.4$$

40% of spontaneous heat flow is usable for work

1) Conservation of energy : $\epsilon \leq 1$

$\epsilon = \frac{W}{Q_h}$ Can't get <u>more</u> out than you put in

2) Second law

$\epsilon \leq 1 - \frac{T_c}{T_h}$;

If $T_c = 0$ and/or $T_h = \infty$, $\epsilon = 1$

But this is impossible!

- How to cool something down to 0 K ?

Need to remove energy from it

Energy flows from hotter to colder

To cool down to 0 K, we need something <u>colder</u> than 0 K

+ $T < \infty$

First Law: Can't get out than you put in

Second Law: Must get less out than you put in

Can only approach $\epsilon = 1 - \frac{T_c}{T_h}$ if the rest of the engine creates minimal (0) entropy

- A theoretical engine cycle which creates no entropy is the Carnot Cycle

- Consider an Engine which uses a gas as the working material

The engine cycle consists of several steps

1) Transfer heat Q_h from the hot reservoir to the gas

$$\Delta S = \frac{-Q_h}{T_h} + \frac{Q_h}{T_{gas}}$$

$\Delta S = 0$ if $T_h = T_{gas}$, but then no heat flows

Want T_{gas} to be just smaller than T_h

- Need to prevent T_{gas} from increasing as heat enters it

Let it expand isothermally

First step in cycle

isothermal expansion at hot temp

When the "wasted" heat leaves the gas

To minimize entropy when Q_c leaves the gas for the cold reservoir, want T_{gas} to be close to, but just above, T_c

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as heat leaves gas, temp decreases

unless we compress it

isothermal compression at low temp

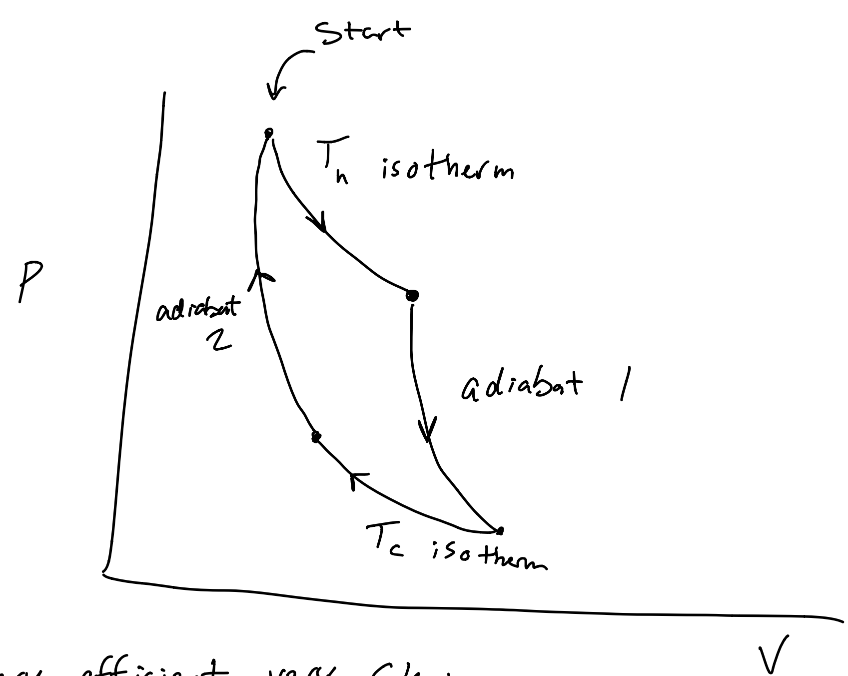
How do we get the gas from hot to cold?

- Don't want any heat exchange

  Adiabatic expansion

The Carnot Cycle

1) Isothermal expansion near T_h
2) Adiabatic expansion from T_h to T_c
3) Isothermal compression near T_c
4) Adiabatic compression to get back up to T_h



very efficient, very slow