Engines convert (some) Heat to Work

Second Law of thermodynamics

CLAUSIUS: Heat can't flow from colder to hotter
KELVIN/PLANCK: Cannot convert ALL heat to work
CARNOT: Best possible heat engine between T_1 and T_2 is...

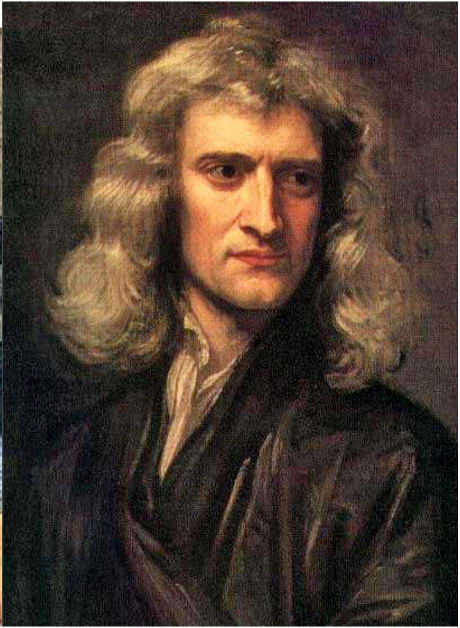
- a) Reversible
- b) Has all heat transfer at exactly T_1 and T_2.
- i.e. Reversible isothermal/adiabatic Carnot cycle

Carnot cycle is not generally useful: isothermal = slow, so very low power

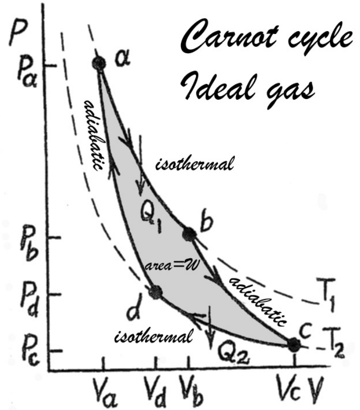
Engines

(Finn: 4.7, 4.8, 4.9, 4.10)

- Carnot Efficiency
- Thermodynamic temperature scale.
- Carnot devices.
- A (nearly) real engine.



Carnot Engine efficiency



- Carnot efficiency is independent of working substance.
- Heat flows (Q_1 and Q_2) are determined solely by the reservoir temperatures (T_1 and T_2).
- Can define a temperature scale based on thermodynamic principles.

Is it consistent with ideal gas scale?

... consider ideal gas as a working substance.

Heat flow and work done in a Ideal gas Carnot cycle

- Isothermal expansion "ab":
  Ideal gas $U = U(T)$; First Law gives $dU = 0 = đq - PdV \implies$,

$$q_{ab} = \int_{Va}^{Vb} PdV = nRT_1 \int_{Va}^{Vb} \frac{dV}{V} = nRT_1 \ln(\frac{V_b}{V_a}), \text{ which is positive.}$$

- Similarly, isothermal compression "cd":

$$q_{cd} = \int_{Vc}^{Vd} PdV = nRT_2 \int_{Vc}^{Vd} \frac{dV}{V} = nRT_2 \ln(\frac{V_d}{V_c}), \text{ which is negative.}$$

Heat flows using "engine" sign convention. $Q_1 = q_{ab}$; $Q_2 = -q_{cd}$.

$$\frac{Q_2}{Q_1} = \frac{nRT_2 \ln(V_c/V_d)}{nRT_1 \ln(V_b/V_a)} = \frac{T_2}{T_1} \frac{\ln(V_c/V_d)}{\ln(V_b/V_a)}$$

$$\frac{Q_2}{Q_1} = \frac{nRT_2 \ln(V_c/V_d)}{nRT_1 \ln(V_b/V_a)} = \frac{T_2}{T_1}\frac{\ln(V_c/V_d)}{\ln(V_b/V_a)}$$

- Adiabats

$$T_1 V_b^{\gamma-1} = T_2 V_c^{\gamma-1} \quad \text{and} \quad T_1 V_a^{\gamma-1} = T_2 V_d^{\gamma-1}$$

So $V_b/V_a = V_c/V_d \implies \ln(V_b/V_a) = \ln(V_c/V_d)$. Substitution of this result in the formula above gives

$$\frac{Q_2}{Q_1} = \frac{T_2}{T_1}$$

- Conclusion

Defining **thermodynamic temperature** T_{th} via

$$\boxed{\frac{T_{th2}}{T_{th1}} = \frac{Q_2}{Q_1}}$$

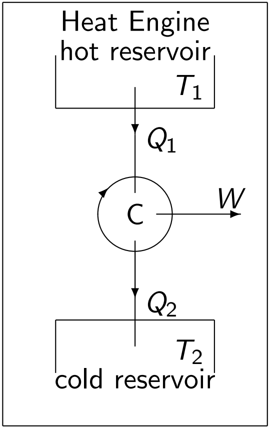
makes the thermodynamic temperature scale the same as the ideal gas temperature scale. Henceforth we denote temperatures on both scales by T, measured in kelvin.

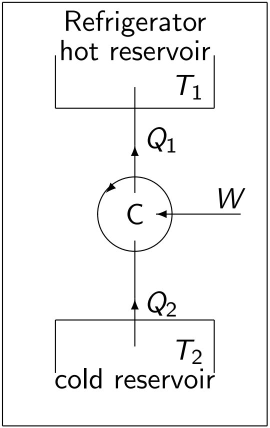
Efficiency for engines, refrigerators and heat pumps

Can define ideal efficiency via of the temperatures of the reservoirs. Efficiency is always *defined* by (what you want out)/(what you put in). So

- For an *Engine* you put heat in and get work out.
- For a *Refrigerator*, put work in, take heat out (from the cold region).
- For a *Heat Pump* put work in, get heat out (into the warm region).

There's no d in: refri *đ*gerator





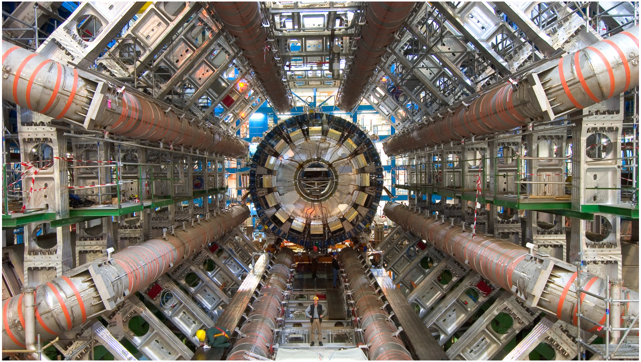
Engine, efficiency $\eta = 1 - \frac{Q_2}{Q_1}$

Refrigerator, coefficient of performance $\eta^R = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2}$

Heat pump efficiency: $\eta^{HP} = \frac{Q_1}{W} = \frac{Q_1}{Q_1 - Q_2}$

Carnot only: $\eta_C = 1 - \frac{T_2}{T_1}$; $\eta_C^{HP} = \frac{T_1}{T_1 - T_2}$ $\eta_C^R = \frac{T_2}{T_1 - T_2}$

World's biggest Fridge Magnet?



CERN uses about 1/3rd as much energy as Geneva. Of which..
LHC cryogenics 27.5 MW
LHC experiments 22 MW

infinitely efficient?

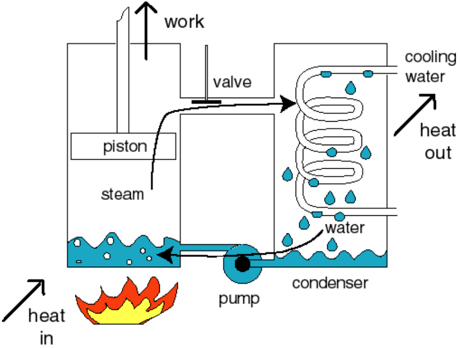
Heat Pump and Refrigerator: same device, different purpose.
Refrigerator, coefficient of performance η^R:

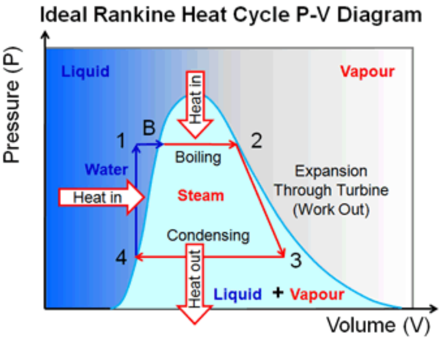
$$\eta^R = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2} \qquad \eta_C^R = \frac{T_2}{T_1 - T_2}$$

Heat pump, heat pump efficiency η^{HP}:

$$\eta^{HP} = \frac{Q_1}{W} = \frac{Q_1}{Q_1 - Q_2} \qquad \eta_C^{HP} = \frac{T_1}{T_1 - T_2}$$

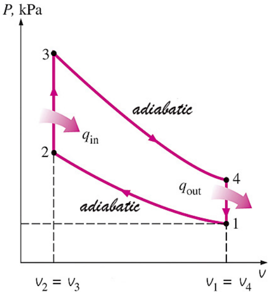
QUESTION : Explain (using the engineering definition of the efficiency of a heat pump) why heat pumps are best used to produce domestic **background** heating.



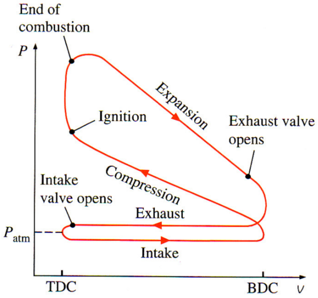


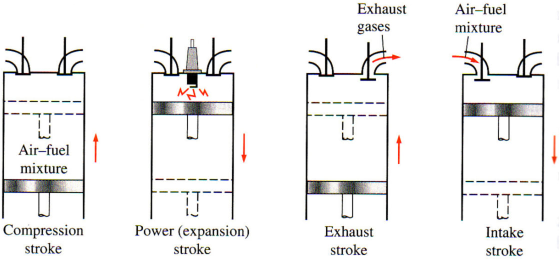
Steam engine works with a liquid+vapour mixture, which combines big volume expansion (steam) and easy to pump/heat (water)

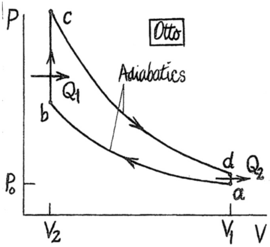
The Otto cycle: a "nearly real" engine



- Simplified two-stroke petrol engine.
- Assume single working substance with "external" heating
- Two adiabats and two isochores.
- Heat exchange takes place in the isochoric processes (i.e. not isothermal)







1. a – b: reversible adiabatic compression (Piston moves in)

$$T_a V_1^{\gamma-1} = T_b V_2^{\gamma-1}$$

2. b – c: heat added (actually, combustion) at constant volume.

$$Q_1 = C_V(T_c - T_b)$$

3. c – d: reversible adiabatic expansion (the "power stroke": piston moves out)

$$T_d V_1^{\gamma-1} = T_c V_2^{\gamma-1}$$

4. d – a: heat rejected (actually exhaust) at constant volume.

$$Q_2 = C_V(T_d - T_a)$$

Otto efficiency

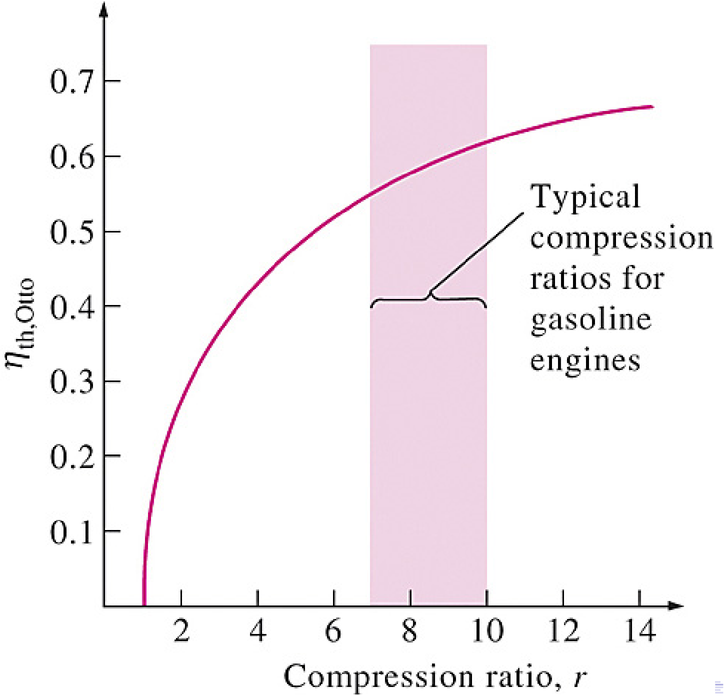
The efficiency η for the engine has to be specified in terms of Q_1 and Q_2. From (4) and (2):

$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_d - T_a}{T_c - T_b}$$

To get more insight into the factors controlling efficiency use (1) and (3) to give:

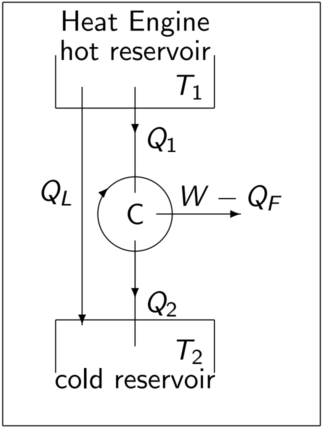
$$\eta = 1 - \left(\frac{V_2}{V_1}\right)^{\gamma - 1} = 1 - \frac{1}{r_c^{\gamma - 1}}$$

where $r_c = V_1/V_2$ is called the compression ratio. If r_c is ~ 5, $\eta \sim 50\%$. Other considerations mean real engines are well below this.
Four-stroke engines have exhaust and intake stages between *da* and *ab*.


0.7
0.6
0.5
0.4
0.3
0.2
0.1
$\eta_{th,Otto}$
Typical compression ratios for gasoline engines
2
4
6
8
10
12
14
Compression ratio, r

Losses of heat and Friction

Real engines are always imperfect.



Lossy engine,

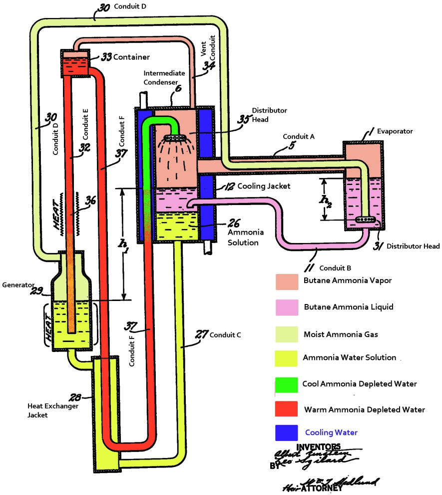
$W \to W - Q_F$ Frictional loss
$Q_1 \to Q_1 + Q_L$ Heat loss

Kelvin-Planck: $Q_F > 0$
Clausius $Q_L > 0$

$\eta = \frac{W - Q_F}{Q_1 + Q_L} < \frac{W}{Q_1}$

Efficiency is always reduced.

Patent for the patent clerk



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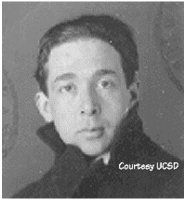

Einstein and Szilard patent a fridge.
No moving parts.
No work input.
Butane as working fluid.
Ammonia/water mixture pump.
Energy supplied as heat to
Ammonia/water

https://www.youtube.com/watch?v=oU6KyH8HAAI
http://www.bbc.co.uk/newsbeat/article/37306334/this-invention-by-a-british-student-could-save-millions-of-lives-across-the-world