Lecture 9

Heat engines

Pre-reading: §20.2

Review

Second law – when all systems taking part in a process are included, the entropy remains *constant* or *increases*. No process is possible in which the total entropy decreases, when all systems taking part in the process are included

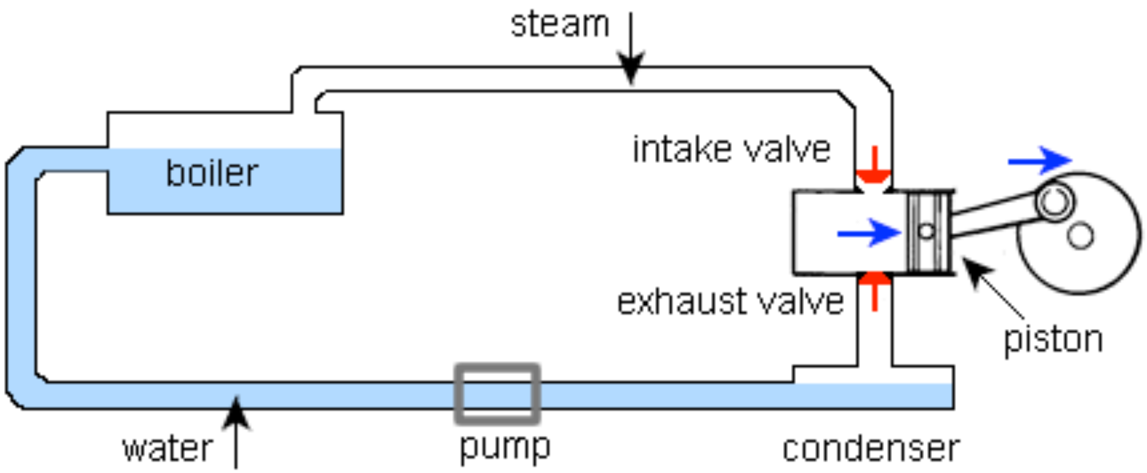
$$\Delta S_{\text{total}} = 0 \quad \text{(reversible process)}$$
$$\Delta s_{\text{total}} > 0 \quad \text{(irreversible process)}$$

YF §20.2

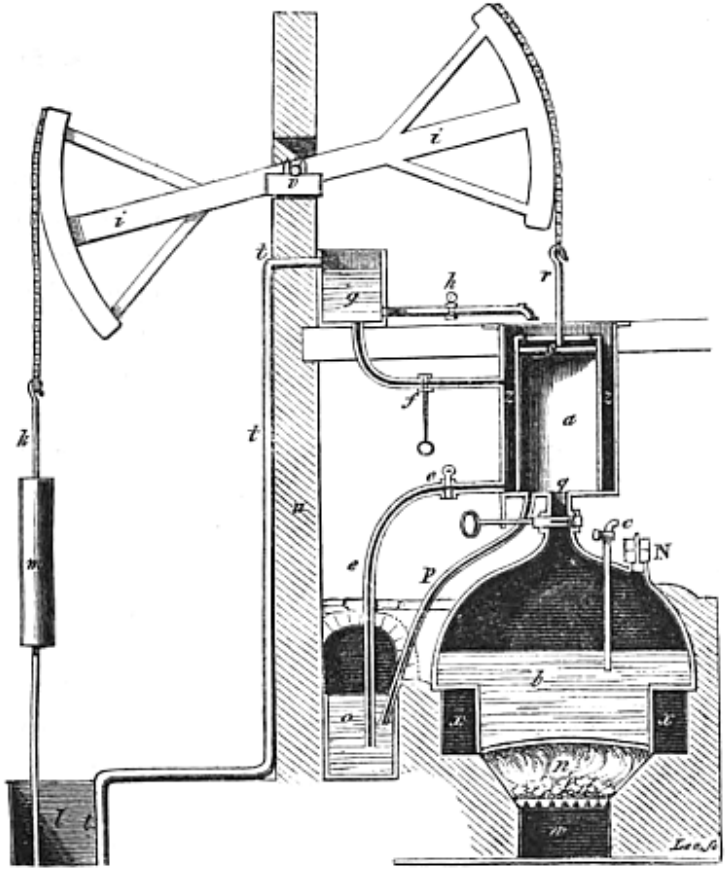
Heat engines

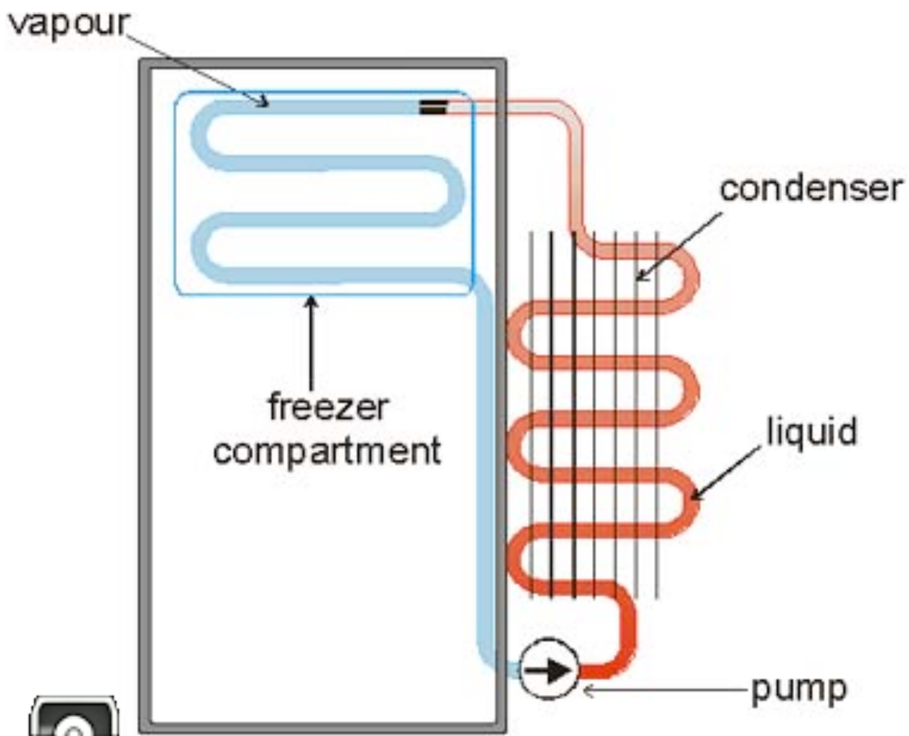
Any device that transforms heat into work or mechanical energy is called a *heat engine*.

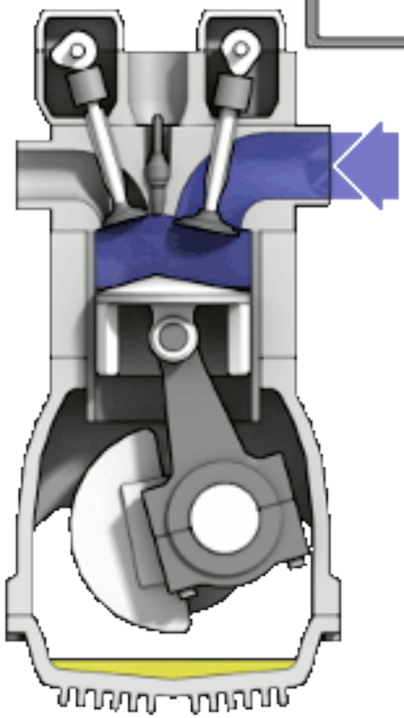
In the simplest kind of engine, the working substance undergoes a cyclic process.



YF §20.2







Thomas Newcomen’s steam engine; an internal combustion engine and a refrigerator

Heat engines

All heat engines absorb heat from a source at high temperature, perform some mechanical work, and discard heat at a lower temperature.

Since the process is cyclic, $U_1 = U_2$, and from the 1st law of thermodynamics we have

$$U_2 - U_1 = 0 = Q - W$$

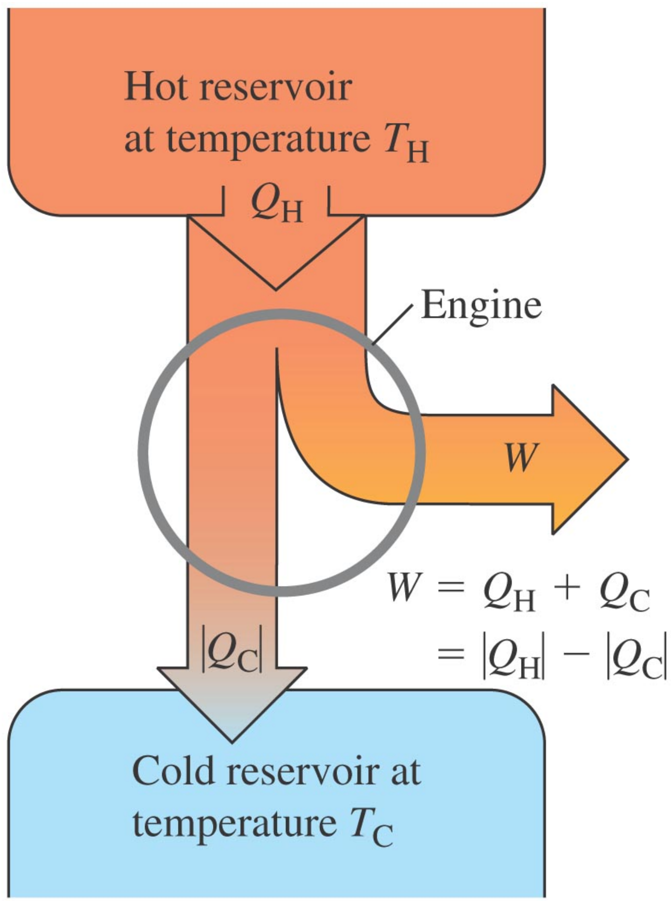
$$\text{so} \quad Q = W$$

i.e. the net heat flowing into the engine equals the net work done by the engine.

YF §20.2

Heat engines

A heat engine has a hot reservoir at temperature T_H and a cold reservoir at temperature T_C; Q_H flows in from the hot reservoir and Q_C flows out to the cold reservoir.



The *net* heat absorbed per cycle is

$$Q = Q_H + Q_C$$

which is also the work done:

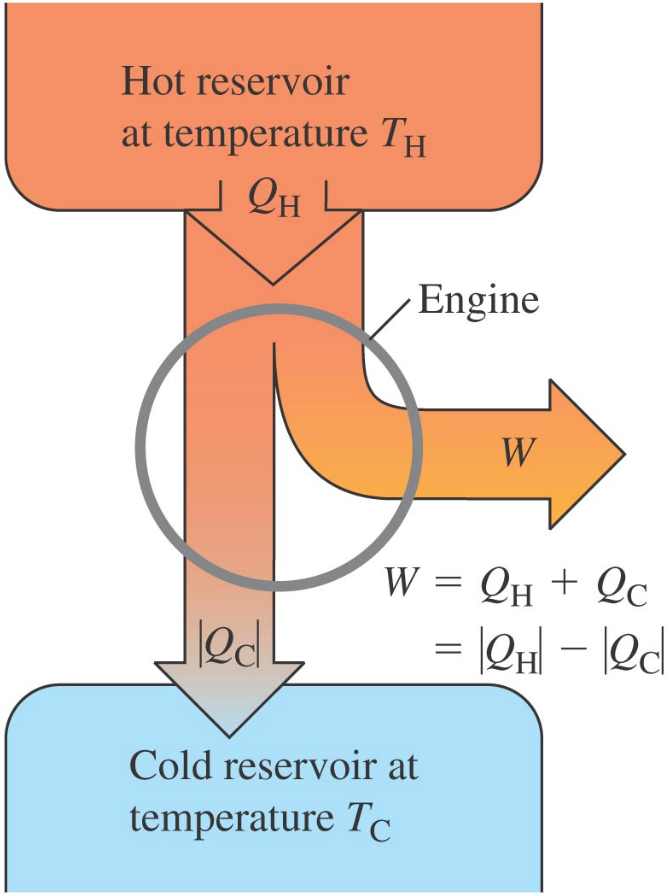
$$W = Q_H + Q_C$$

Efficiency

Ideally we would like to convert *all* Q_H to work; then $W = Q_H$ and $Q_C = 0$.

We define the *efficiency* of the engine as the fraction of the heat input that is converted to work:

$$e = \frac{W}{Q_H} = 1 + \frac{Q_C}{Q_H} = 1 - \left|\frac{Q_C}{Q_H}\right|$$



Problem

A petrol engine takes in 10,000 J of heat and delivers 2000 J of work per cycle. The heat is obtained by burning petrol with heat of combustion $L_c = 5.0 \times 10^4$ J.g^{-1}.

a) What is the efficiency?

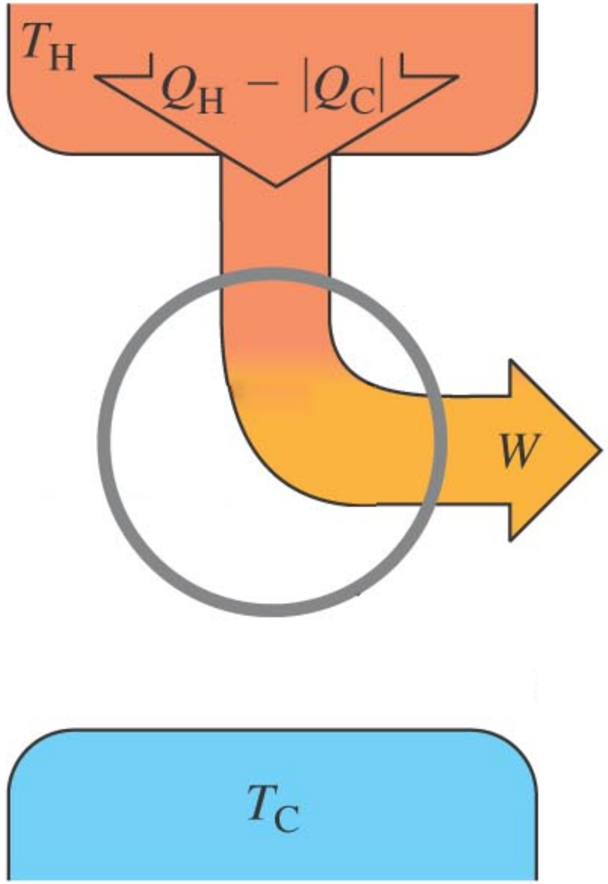
b) How much heat is discarded each cycle?

c) How much petrol is burned each cycle?

YF §20.2

Efficiency

Can a heat engine ever be 100% efficient in converting heat to mechanical work?



Efficiency

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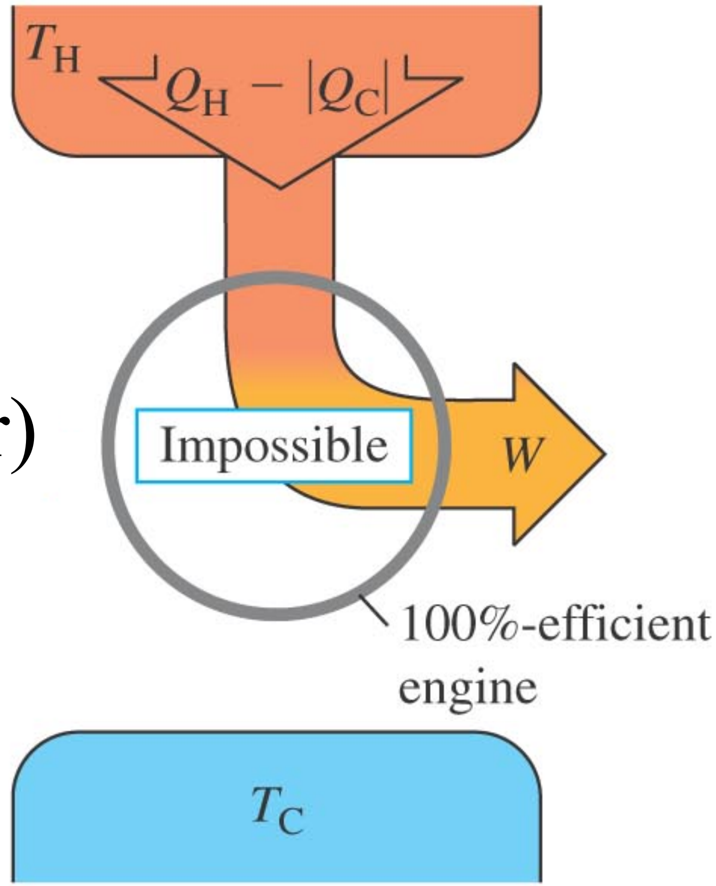


Look at the entropy S:

$\Delta S_{engine} = 0$ (cyclic process)

$\Delta S_{surroundings} = 0$ (no heat transfer)

$\Delta S_{hot\ reservoir} < 0$ (T decrease)

➔ $\Delta S_{total} < 0$ violates 2nd law

➔ ALL heat engines have $e < 1$

2^{nd} law, again

Re-state the 2^{nd} law of thermodynamics (the "engine statement":

It is impossible for any system to undergo a process in which it absorbs heat from a reservoir at a single temperature and converts the heat completely into mechanical work, with the system ending in the same state in which it began.

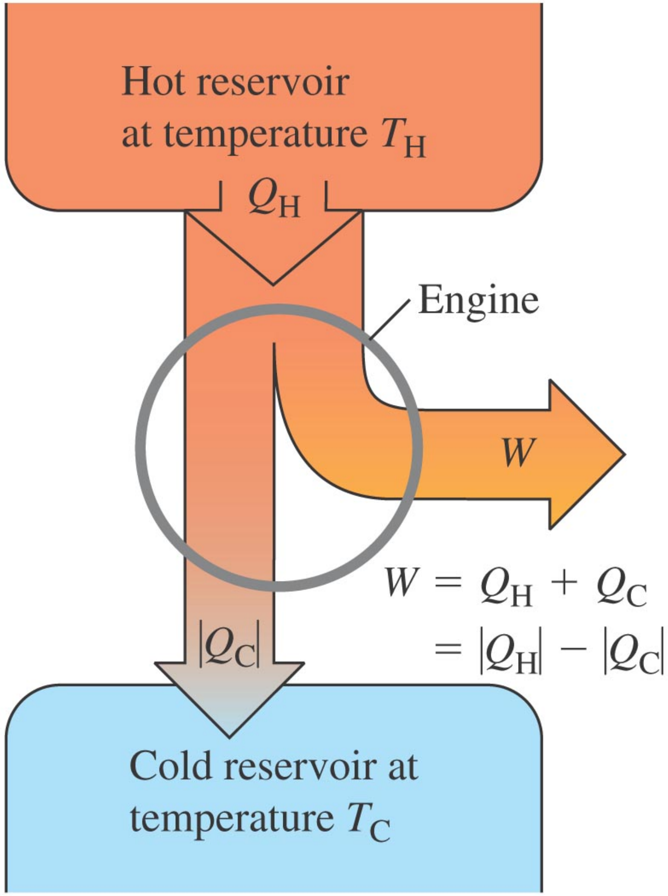
Entropy of a heat engine

$$\Delta S_{\text{hot reservoir}} = -|Q_H|/T_H$$

$$\Delta S_{\text{cold reservoir}} = +|Q_C|/T_C$$

$$\Delta S_{\text{engine}} = 0 \quad \text{(cyclic process)}$$

$$\Delta S_{\text{surroundings}} = 0 \quad \text{(no heat transfer)}$$



So $\Delta S_{\text{total}} = -|Q_H|/T_H + |Q_C|/T_C$

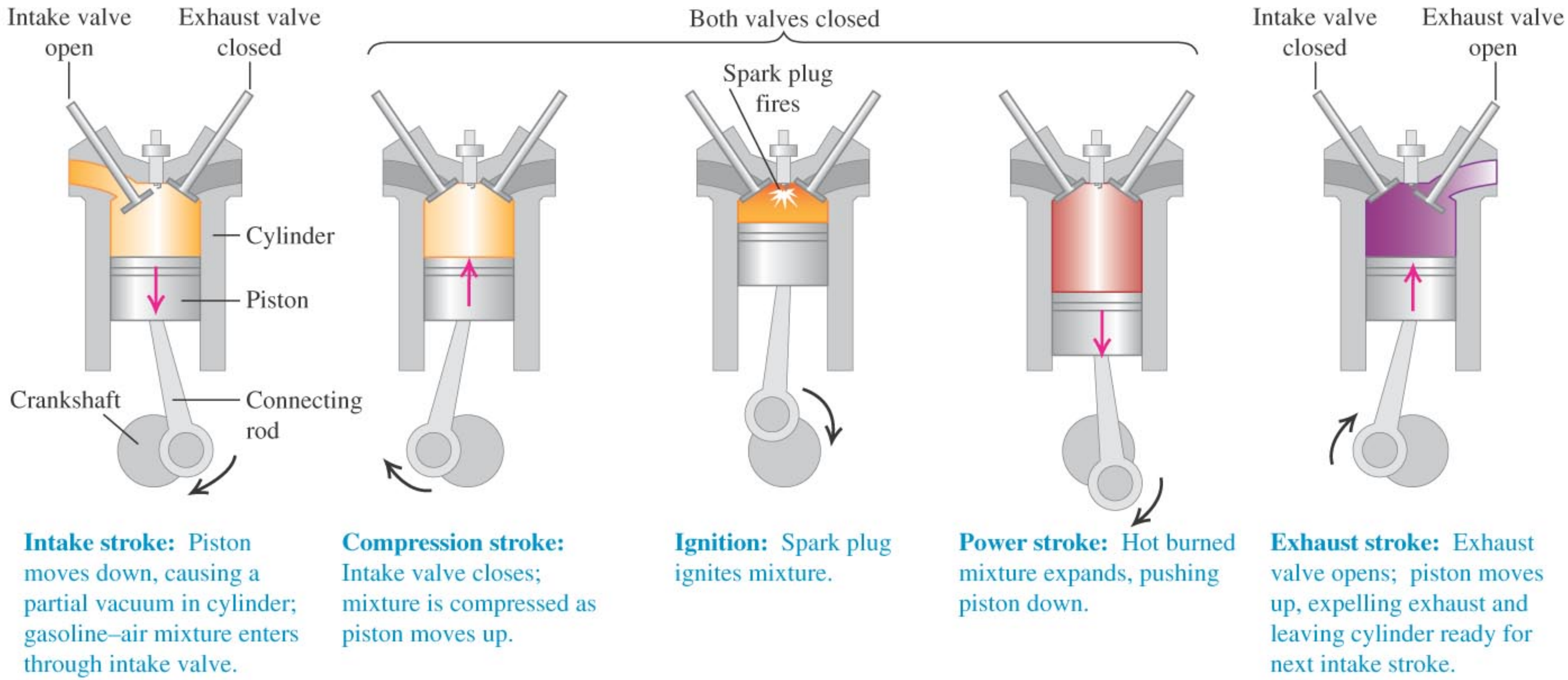
Useful work can only be done if

$$\Delta S_{\text{total}} > 0$$

➔ $$|Q_H|/T_H \leq |Q_C|/T_C$$

Example: The Otto cycle

An internal combustion engine, like the engine in your car, is a heat engine.



Example: The Otto cycle

The *Otto cycle* is an idealised model of this engine.

Processes *bc* and *ad* are constant volume, so

$$Q_H = nC_V(T_c - T_b) > 0$$

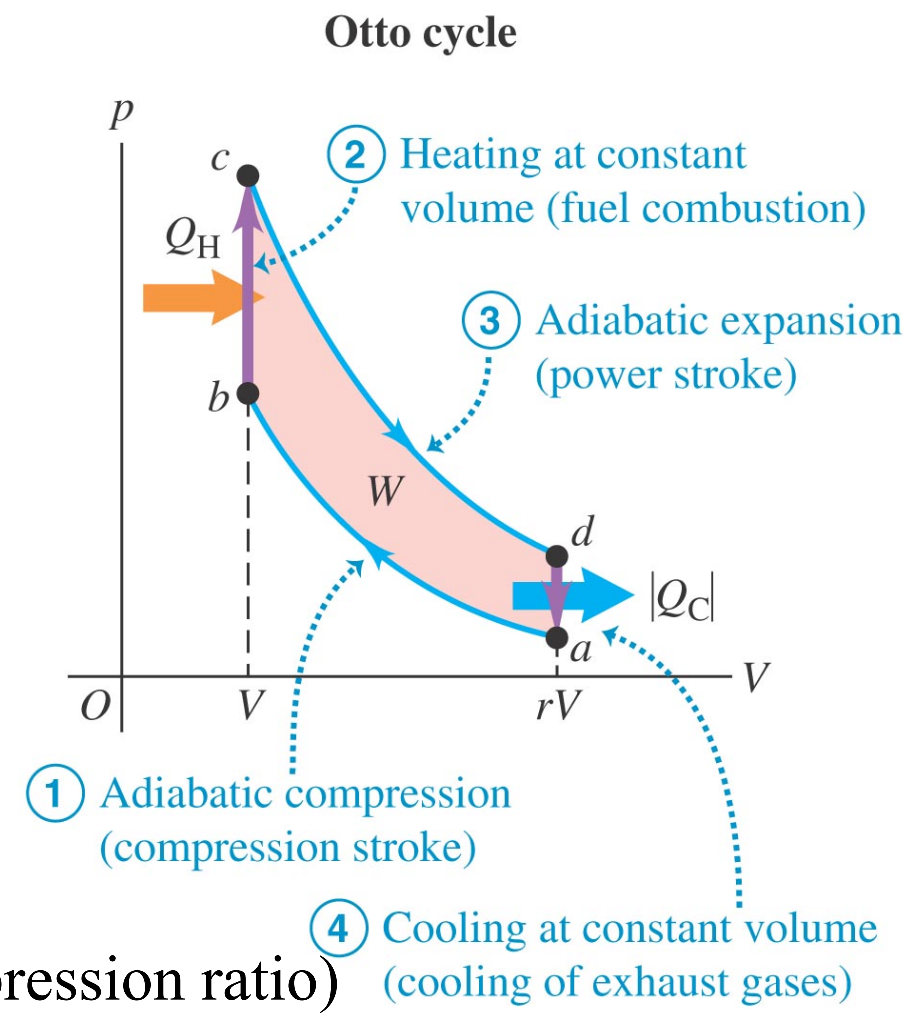
$$Q_C = nC_V(T_a - T_d) < 0$$

Processes *ab* and *cd* are adiabatic, so

$$T_a(rV)^{\gamma-1} = T_b V^{\gamma-1}$$

$$T_d(rV)^{\gamma-1} = T_c V^{\gamma-1}$$

(r is the compression ratio)



Example: The Otto cycle

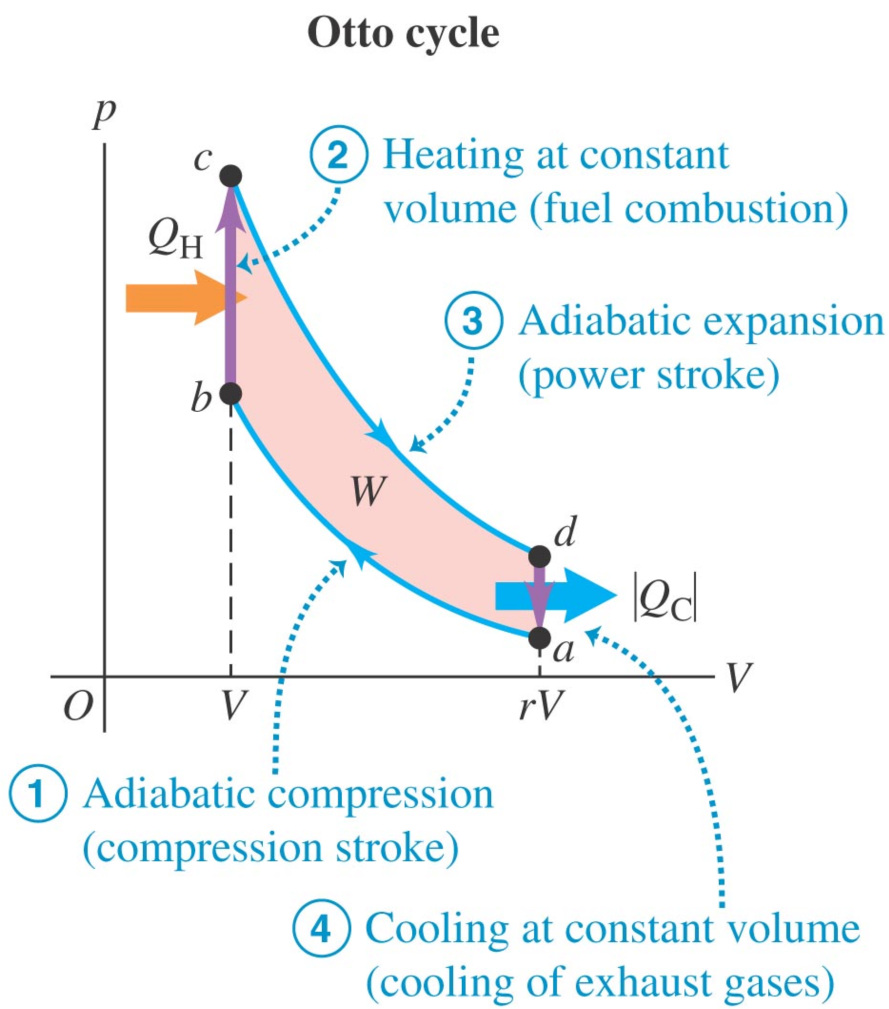
So the efficiency of the engine is

$$e = \frac{Q_H + Q_C}{Q_H}$$

$$= \frac{T_c - T_b + T_a - T_d}{T_c - T_b}$$

$$= 1 - \frac{1}{r^{\gamma - 1}}$$

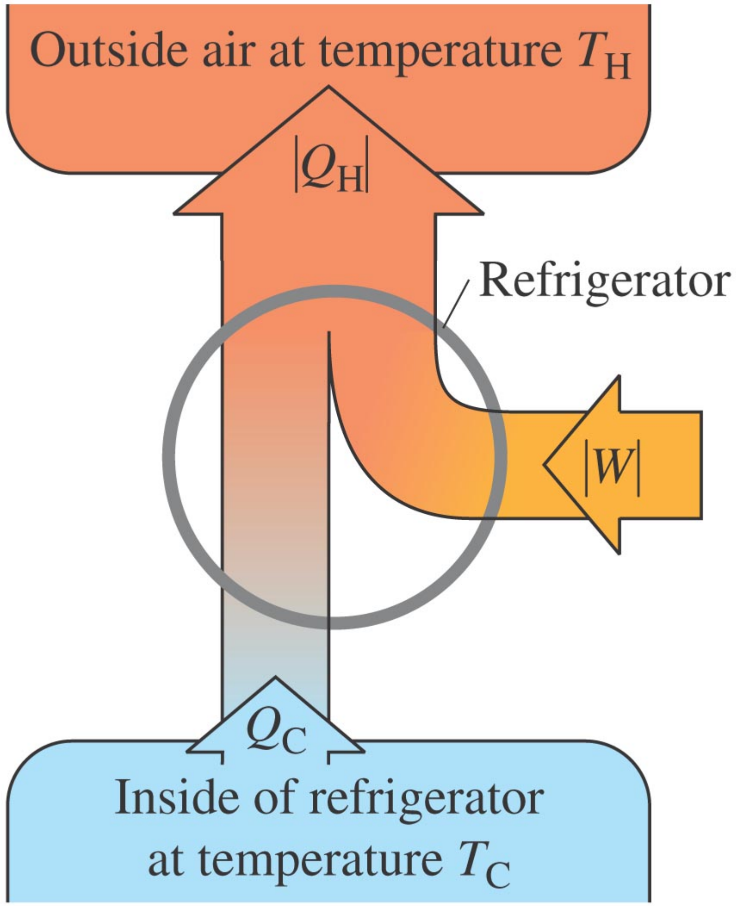
where r is the compression ratio. For $r = 8$ and $\gamma = 1.4$, we get $e = 0.56$.



The refrigerator

A refrigerator is a heat engine operating in reverse.

It takes heat from a cold place and gives it off at a warmer place; it requires a net *input* of mechanical work.

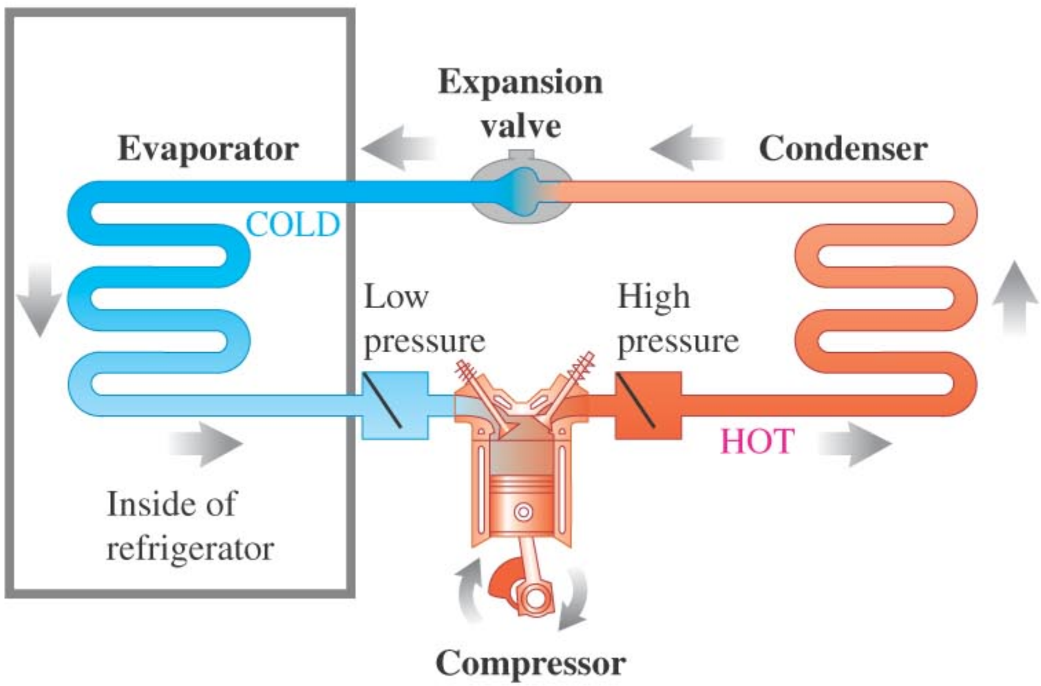


For a fridge, Q_C is positive but Q_H and W are negative.

$$|Q_H| = |Q_C| + |W|$$

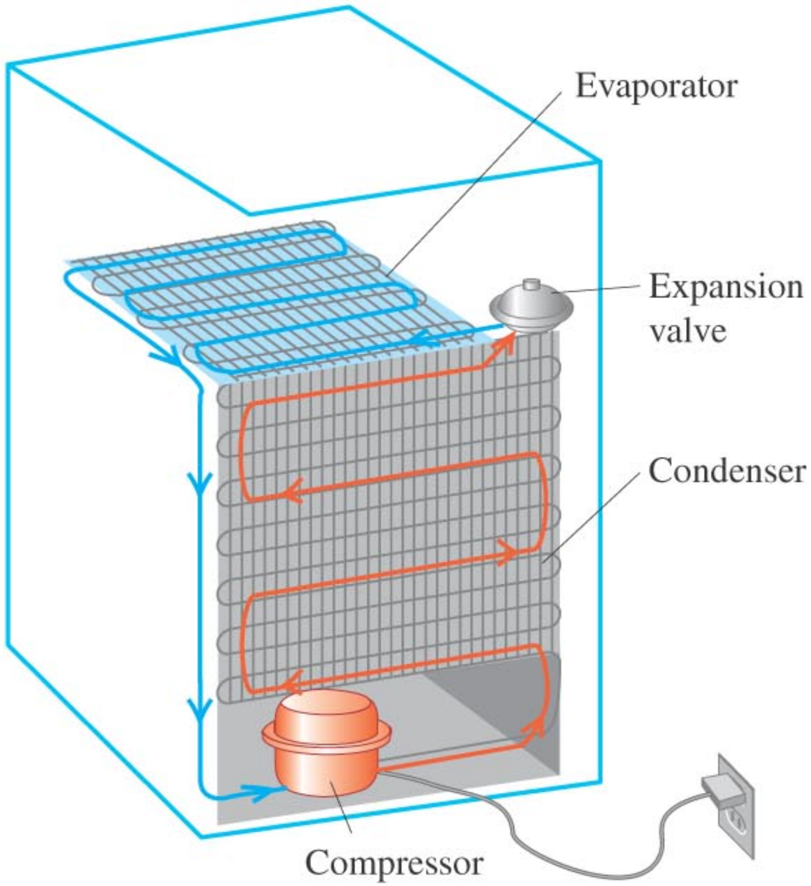
YF §20.4

(a)



Expansion
valve
Evaporator
Condenser
COLD
Low
pressure
High
pressure
HOT
Inside of
refrigerator
Compressor

(b)



Evaporator
Expansion
valve
Condenser
Compressor

Next lecture

The Carnot cycle

Read: YF §20.6