Lecture 30: 2nd Law of Thermodynamics

- Thermodynamic cycles
- 2nd law of Thermodynamics
- Carnot Cycle

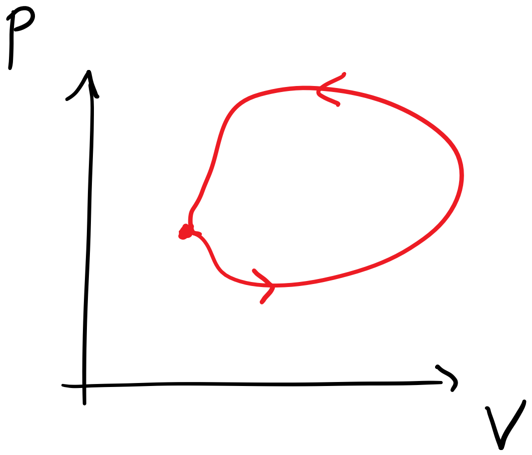
Thermodynamic Cycles

System returns to initial state

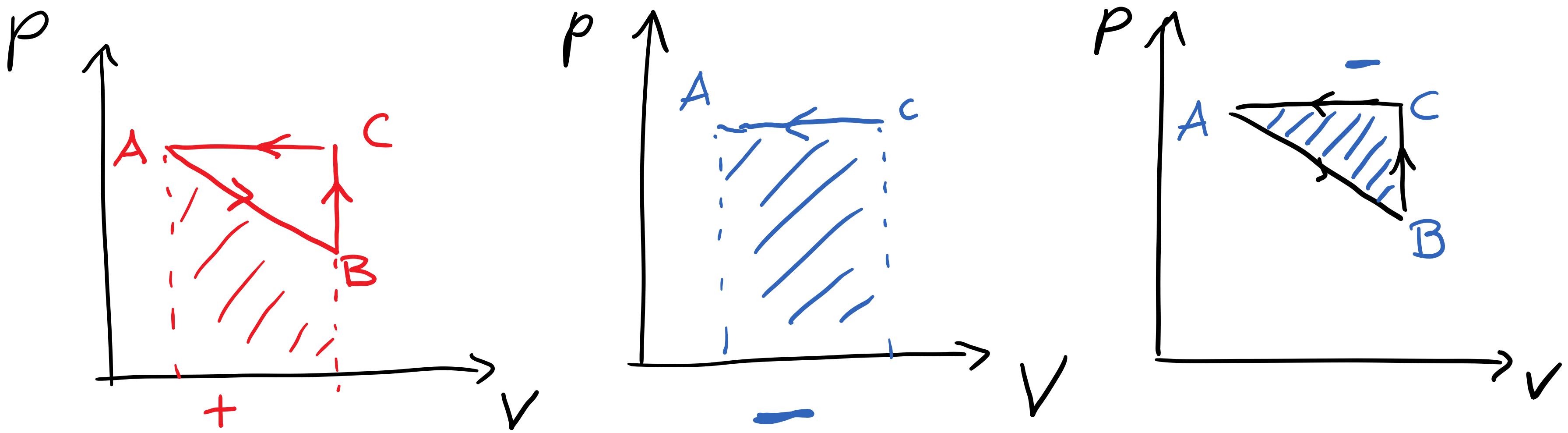
$$U_f = U_i$$

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

$$Q = W$$



Work in cycles



W= area enclosed in the cycle

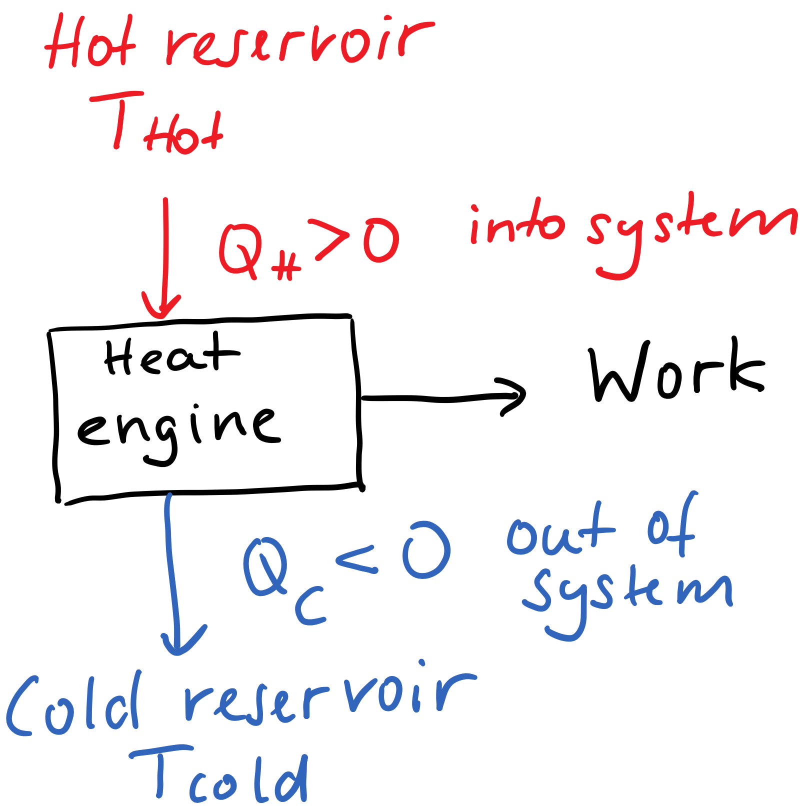
Clockwise: more positive W than negative W

$$W_{net} > 0$$

Counter-clockwise: more negative W than positive W

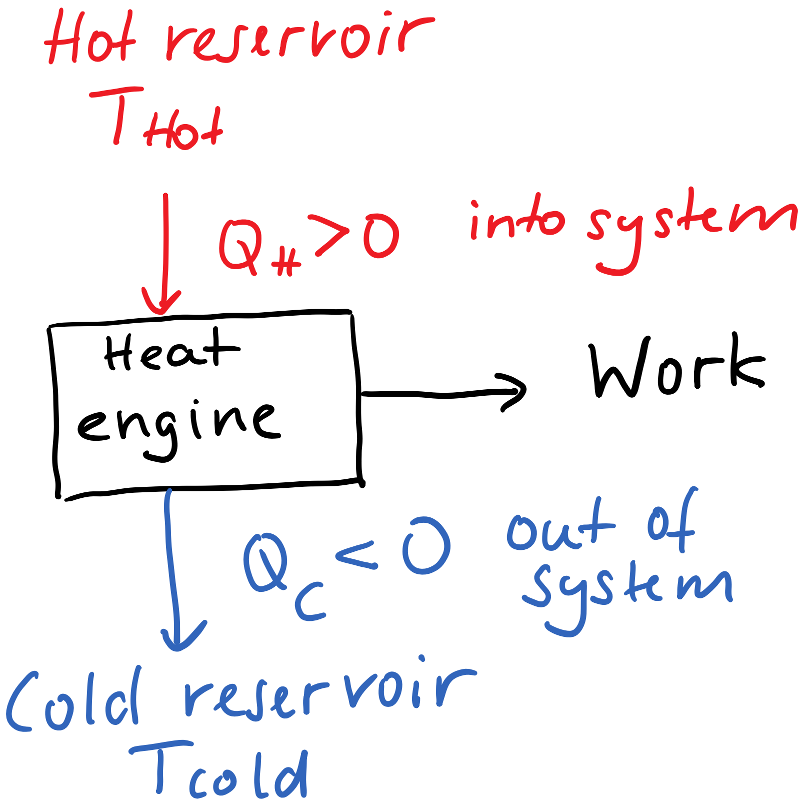
$$W_{net} < 0$$

Heat engine



$$Q_{net} = Q_H + Q_C$$
$$= Q_H - |Q_C|$$

Efficiency



$$e = \frac{W_{out}}{Q_H} = \frac{Q_{net}}{Q_H}$$

cycle $W = Q$

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

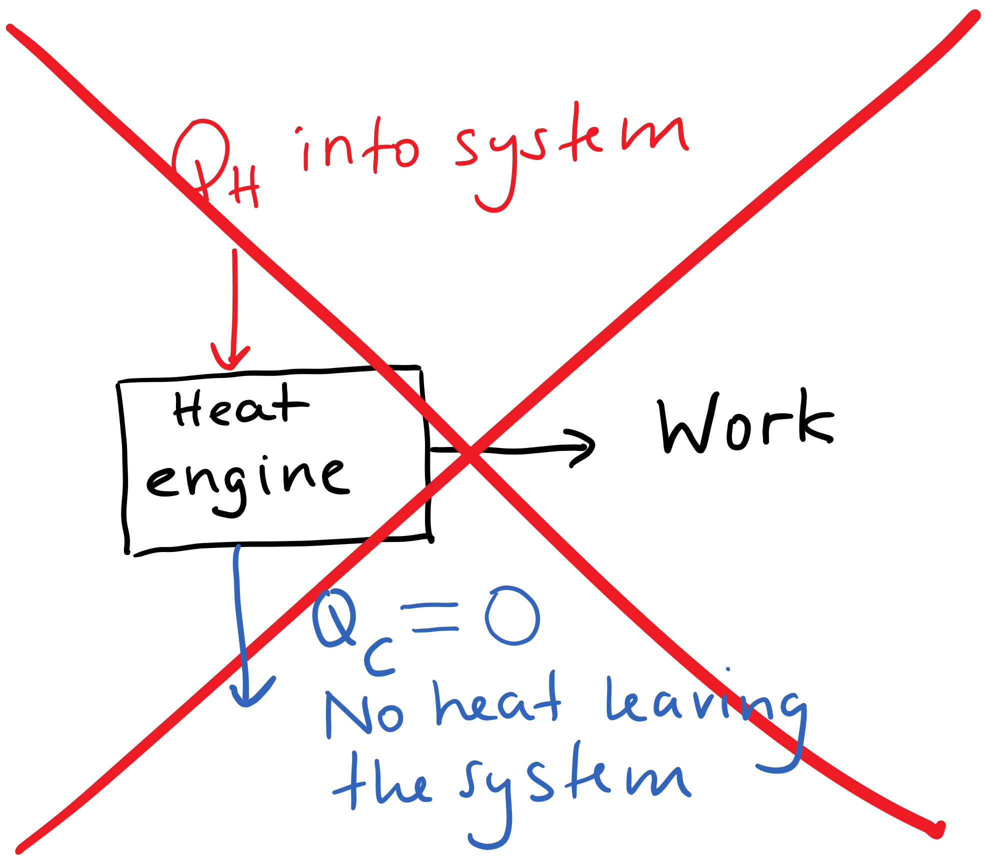
$$e = 1 - \frac{|Q_C|}{Q_H}$$

2^{nd} Law of Thermodynamics

Clausius:
Heat flows naturally from a hot object to a cold object; heat will not flow spontaneously from a cold object to a hot object.

Kelvin-Planck:
No device is possible whose sole effect is to transform a given amount of heat completely into work.

impossible to construct perpetual motion machine of 2^{nd} kind

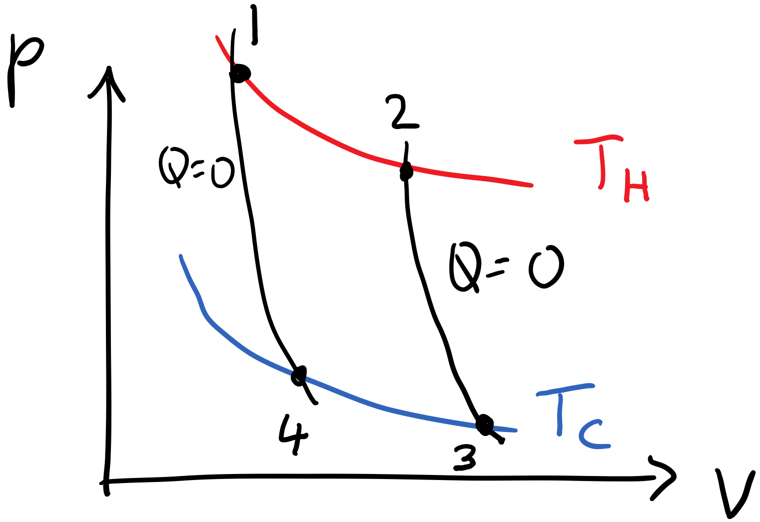


Forbidden by 2^{nd} Law

$$e = 1 - \frac{|Q_C|}{Q_H}$$

$e = 1$ impossible

Carnot Cycle



1-2 isothermal expansion
2-3 adiabatic expansion
3-4 isothermal compression
4-1 adiabatic compression

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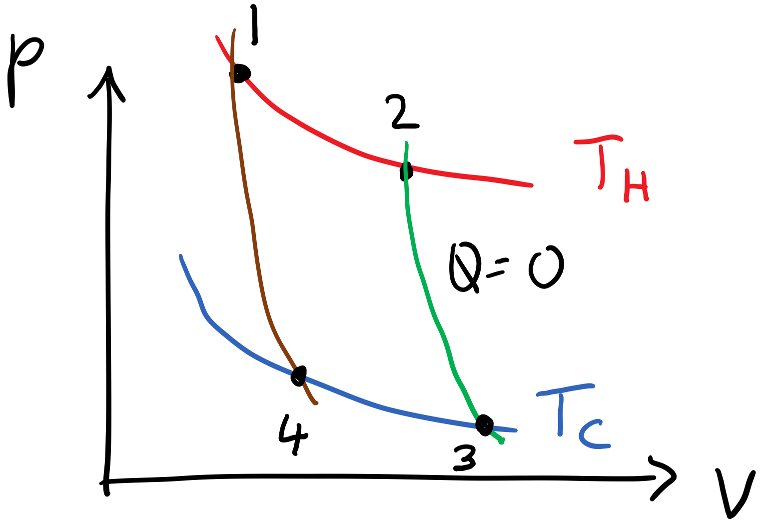
Carnot Cycle



1-2 isothermal expansion

$\Delta U = 0$

$Q = W = \int p\,dV = \int \frac{nRT}{V}\,dV$

$Q = nRT_H \ln \frac{V_2}{V_1}$ >0 in

2-3 adiabatic expansion

$Q = 0$

$\Delta U = -W \quad W = -nc_v(T_C - T_H)$

3-4 isothermal compression

$\Delta U = 0 \quad Q = W = nRT_C \ln \frac{V_4}{V_3}$ <0 out

4-1 adiabatic compression

$Q = 0 \quad \Delta U = -W \quad W = -nc_v(T_H - T_C)$

Efficiency of Carnot Cycle

1-2 isothermal expansion $W = Q = nRT_H \ln \frac{V_2}{V_1} > 0$

2-3 adiabatic expansion $Q = 0, \; W = -nc_v(T_c - T_H)$

3-4 isothermal compression $Q = W = nRT_c \ln \frac{V_4}{V_3} < 0$

4-1 adiabatic compression $Q = 0 \quad W = -nc_v(T_H - T_c)$

$$e = \frac{W_{net}}{Q_{in}} = \frac{nRT_H \ln \frac{V_2}{V_1} + nRT_c \ln \frac{V_4}{V_3}}{nRT_H \ln \frac{V_2}{V_1}} = 1 - \frac{T_c}{T_H} \frac{\ln \frac{V_3}{V_4}}{\ln \frac{V_2}{V_1}}$$

with $T \cdot V^{\gamma-1} = \text{const}$ on adiabatic + some math $\longrightarrow$

$$e_{Carnot} = 1 - \frac{T_c}{T_H}$$

Carnot Cycle has maximum efficiency

Heat transfer during isothermal process reversible
No heat transfer during process that involves temperature change

→ Carnot cycle is reversible

If more efficient engine existed:
Couple hypothetical engine with reverse Carnot engine
Transforms amount of heat completely into work
Violates 2nd Law

→ More efficient engine can not exist

$$e_{Carnot} = 1 - \frac{T_C}{T_H}$$

Maximum efficiency of any cycle operating between T_C and T_H