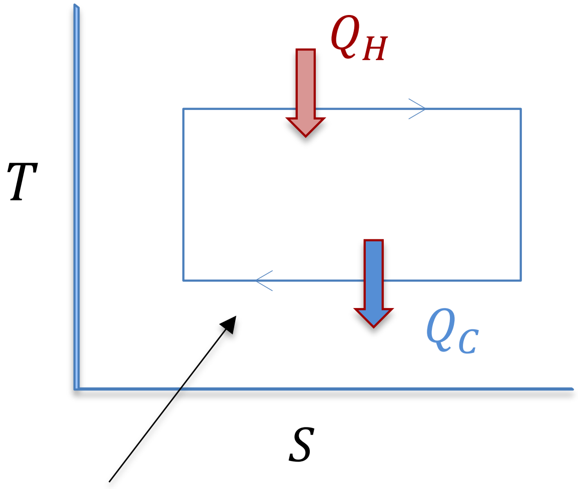
Notes for today

- Continuing Ch. 4.

- Reminder about lecture recording, I can send a recording link if you have to miss.

Carnot cycles recall:

Carnot cycle – does not need to be ideal gas.



Work done = T-S area inside
Done by the gas.

- Reversible; ΔS = 0 heat engine or refrigerator.
- P-V diagram depends on working gas or fluid.
- Carnot cycle most efficient for same T_H & T_C

$$\frac{Q_H}{T_H} = \frac{Q_C}{T_C}$$

$$\varepsilon_e = 1 - \frac{T_C}{T_H}$$

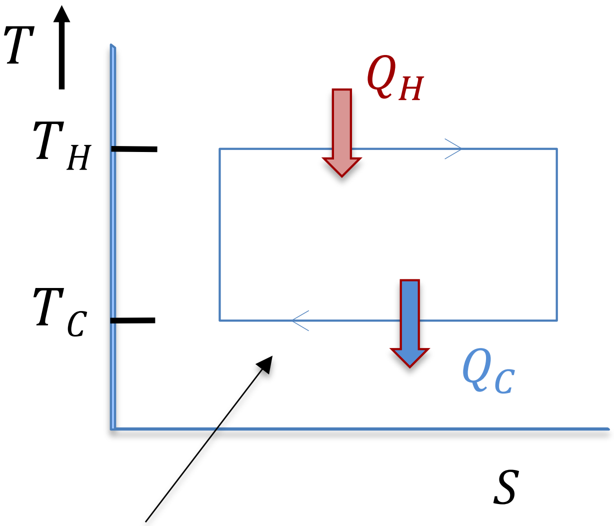
- Heat flow: From & into "heat baths": external reservoir (power plant heat exchanger; combustion of fuel; source of thermal photons, etc.)
- Carnot limit: not 100% efficient (can't have $Q_C = 0$).
- Carnot-cycle power output is essentially zero!

$$\varepsilon_e = \frac{W_{ext}}{Q_H}$$

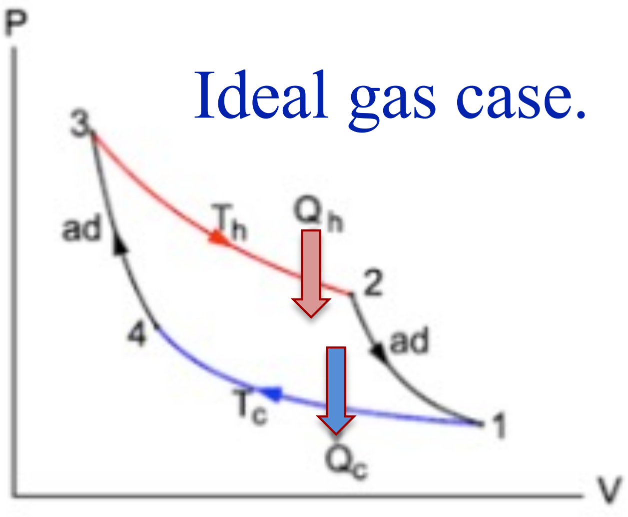
Notation: ε_e now same as text, W_{ext} done by the gas (W_{RWS}). Q_H & $Q_C > 0$

Carnot cycle :

- Reversible; ΔS = 0 heat engine or refrigerator.
- P-V diagram depends on working gas or fluid.
- Carnot cycle most efficient for same T_H & T_C
- Note heat flow across $\Delta T = 0$ needed for $\Delta S = 0$.



Work = T-S area inside

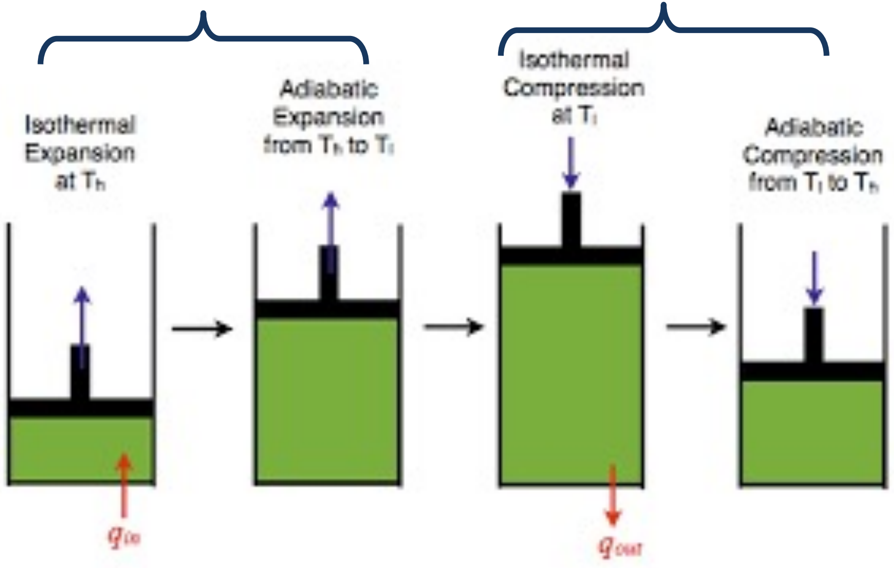


Ideal gas case.

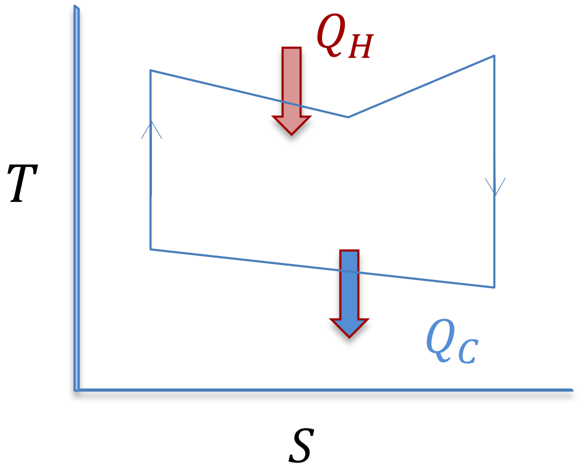
Work = P-V area inside

$W_{ext} > 0$

$W_{ext} < 0$ (reversible work source)



Non-ideal cycle:



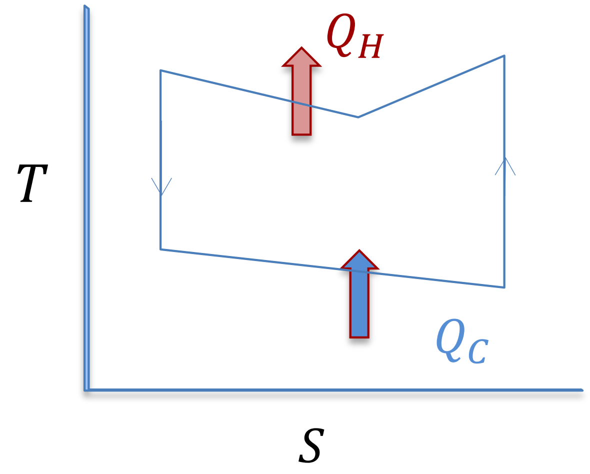
General cycle run as heat engine:

(1) Non-ideal heat flow: T_H reservoir must exceed working temperature for Q_H flow, Similarly T_C lower than working temperature.
(Reversed for refrigerator.)

Is $\Delta S = 0$ in this case if these are quasistatic, "infinitely slow" processes?

Non-ideal cycle:

refrigerator



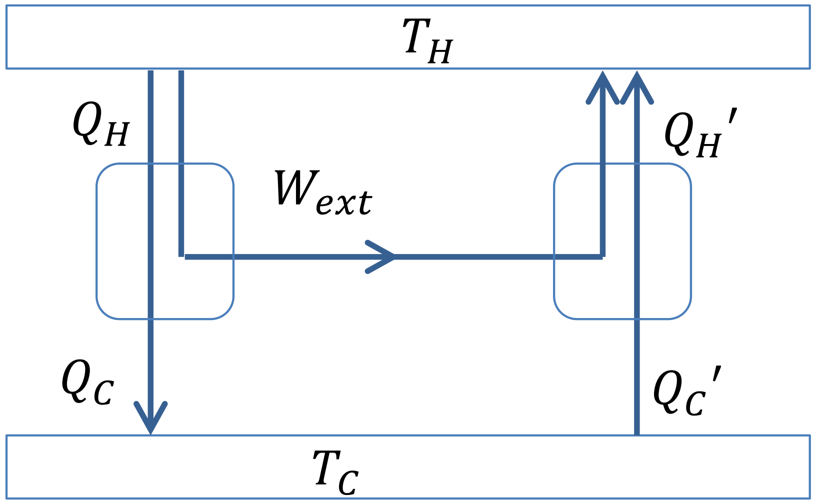
General cycle

(1) Non-ideal heat flow: T_H reservoir must exceed working temperature for Q_H flow, Similarly T_C lower than working temperature.
(Reversed for refrigerator.)

$$\Longrightarrow total\ \Delta S \neq 0$$

(2) sudden or dissipative processes also increase overall entropy without turning heat into work; maximum work theorem will see later.

Carnot cycle maximum engine efficiency:



- Carnot refrigerator; can engine have *greater* efficiency?
- Assume same amount of work per cycle, can show 2nd law is violated (heat flows from cold to hot with no external input)
- Carnot cycle results $\varepsilon_e = 1 - \frac{T_C}{T_H}\,;\ \frac{Q_H}{T_H} = \frac{Q_C}{T_C}$
- Note "endoreversible" maximizes power not efficiency (simple heat-flow cases) I won't show, $\varepsilon_e = 1 - \sqrt{\frac{T_C}{T_H}}$

Efficiencies:

$e = \frac{520}{810} = 64\%$

Carnot

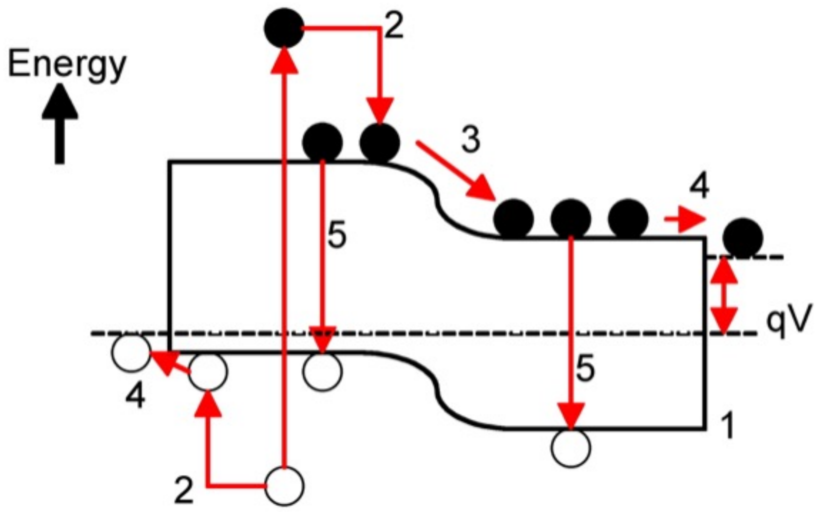
- Steam turbine (electric power plant) $\varepsilon_e \approx 45\%$. $T_H \leq 540^o C$.

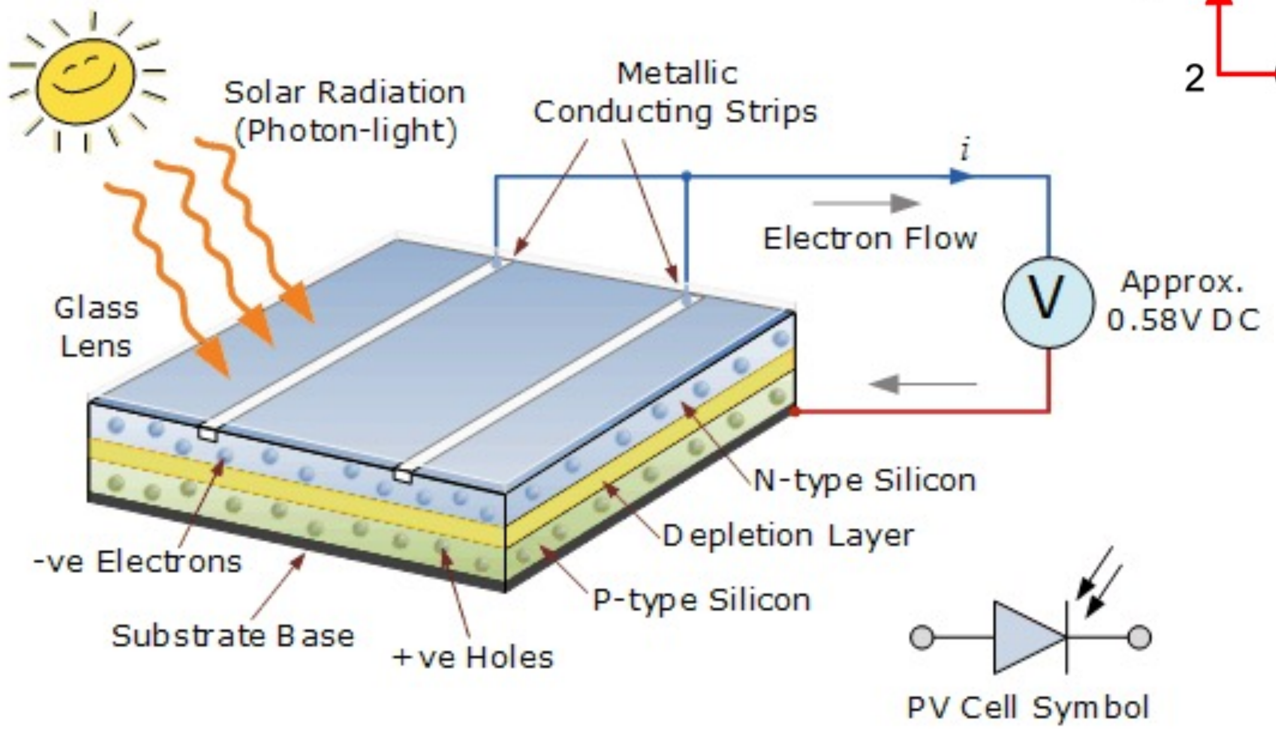
  60% achieved with “combined cycle”

  $e = \frac{780}{1090} = 72\%$

- Gasoline engine (car) $\varepsilon_e \approx 30\%$ (to 50%). $T_H \approx 800^o C$ fuel burning.
- Hydroelectric plant 95% (electric motors/ regenerative breaking)
- Solar power: photovolatic cell based on conversion of photons, ultimately a heat engine (e_{max} = 95% Carnot limit)

$$dU = \underset{\overset{\uparrow}{\text{Heat}}}{TdS} \underbrace{- PdV + \mu dN + IdB}_{\text{Work}}$$

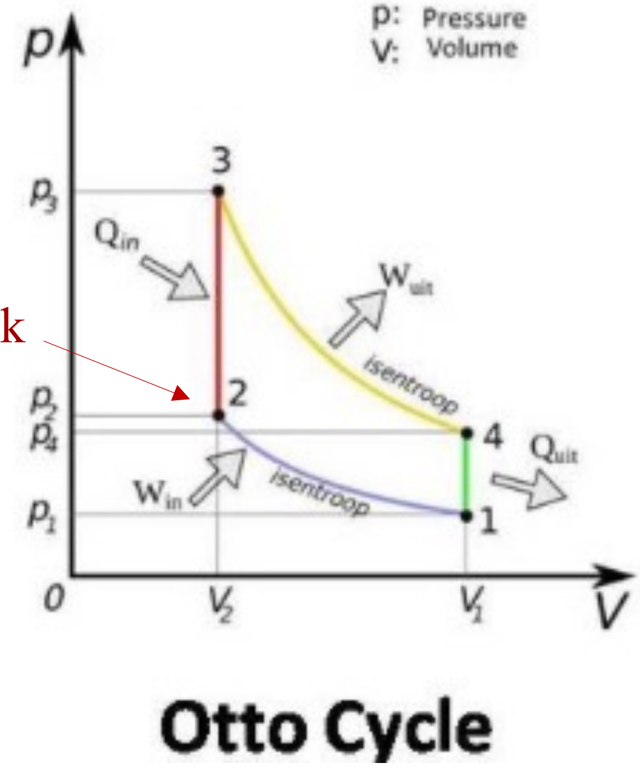




Electrical work this case, similar to chemical work.

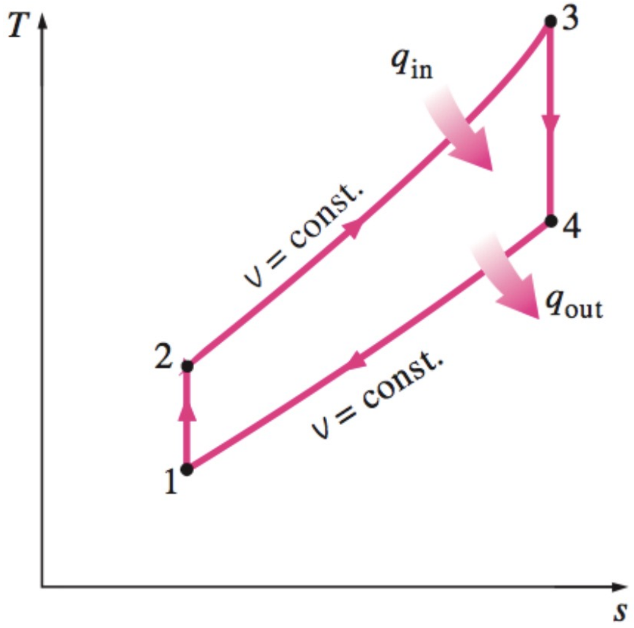
Solar cell (equivalent to a heat engine)

Real cycles:

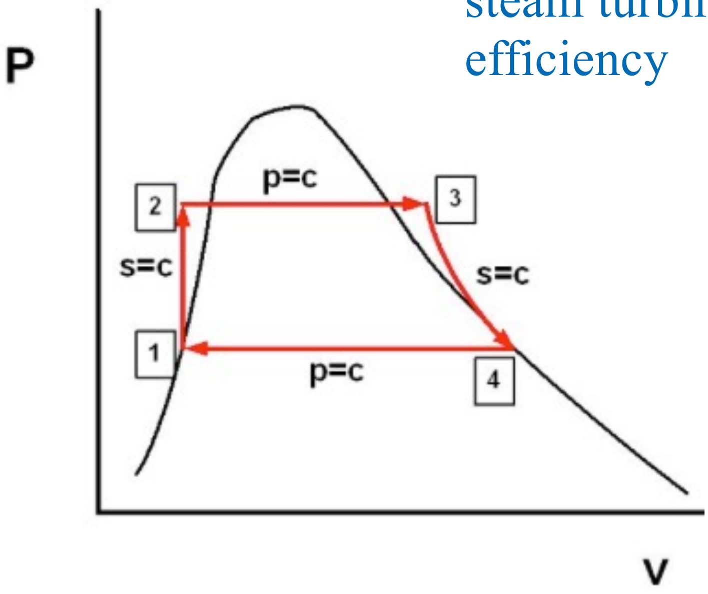


spark

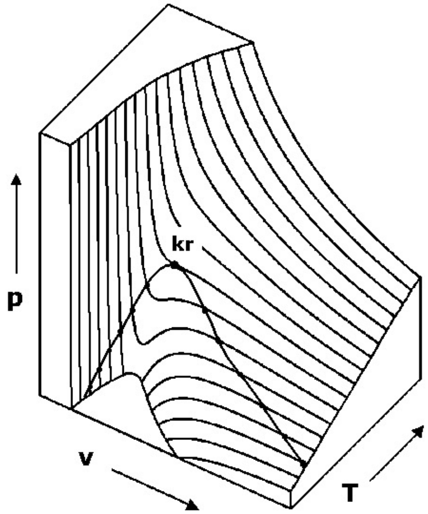
Gasoline engine



Real cycles:

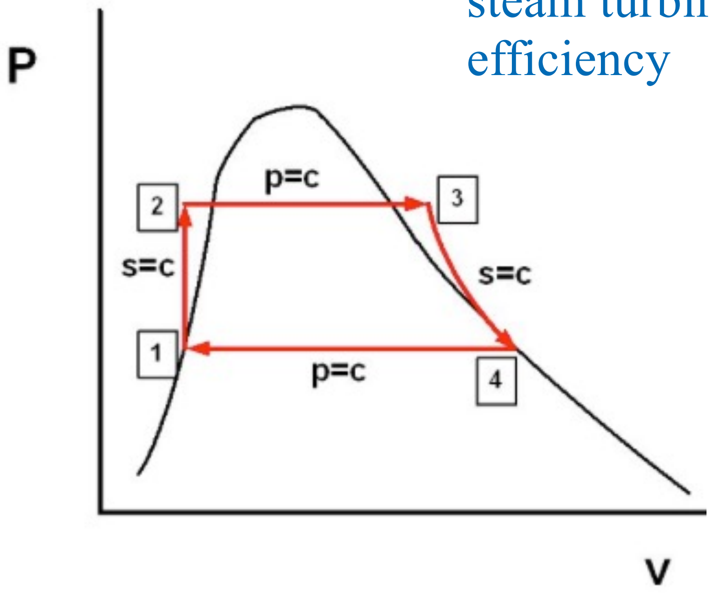


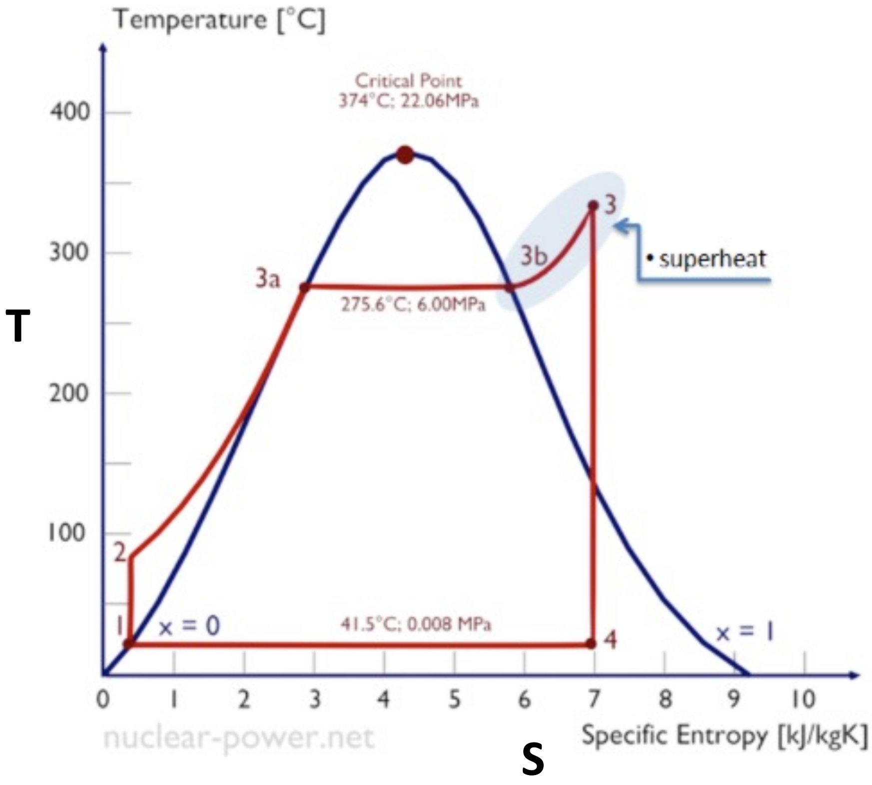
Rankine (power plant steam turbine)- high efficiency



Real cycles:

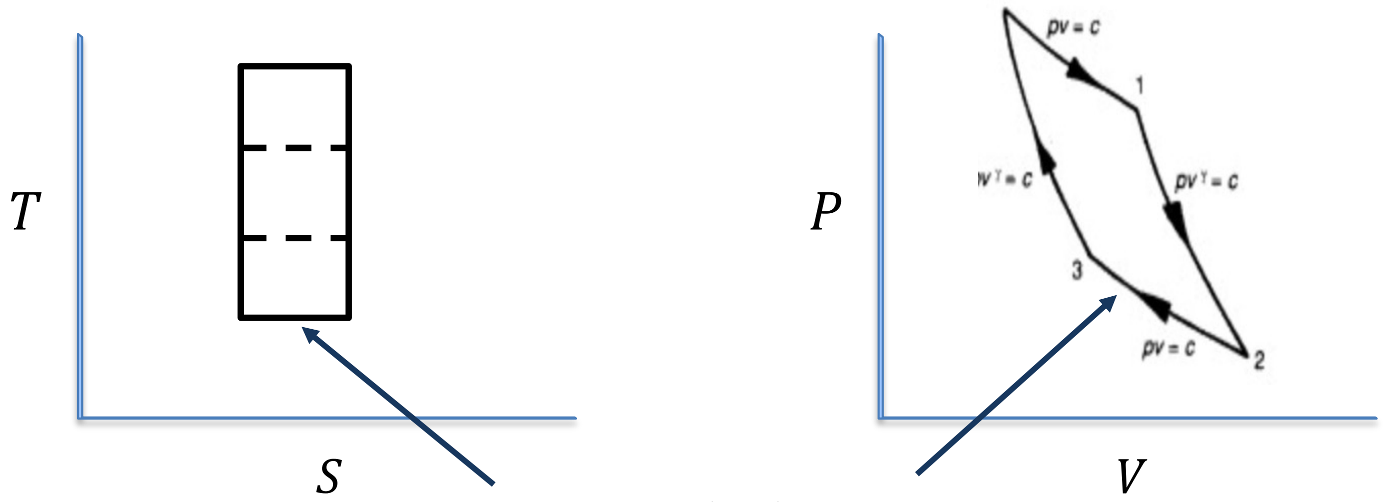
Rankine (power plant steam turbine)- high efficiency





- Heat involved is <u>Latent heat</u> (vaporization)
- Traditional refrigerator or heat pump: cycle a bit different, also has latent heat process ≈ isotherm.

Temperature scales:



Known standard temperature
(e.g. water triple point)

- Carnot result $\frac{Q_H}{T_H} = \frac{Q_C}{T_C}$ formal means to define temperature scale independent of working substance.
- Basis for SI temperature scale up to 2019
- Newest SI definition: Uses Boltzmann factor $e^{-\Delta E/kT}$ to define temperature scale (no fixed points in new definition).