Thermodynamics

PHY 215
Thermodynamics and Modern Physics

Spring 2026
MSU

Outline

- Ideal Gas Processes
  - Isochoric
  - Isobaric
  - Isothermal
- Adiabatic Expansion/Compression
- Heat Engines
  - Efficiency

Concept Test - Part I

- A well-insulated container is divided into two sections by a rigid, adiabatic wall. Each section contains a different ideal gas, at different temperatures ($T_{1,2}$) and pressure ($p_{1,2}$). We then remove the partition, and wait some time. This process is

A. Reversible

B. Irreversible ←

C. Can't Tell

Concept Test - Part 2

- A well-insulated container is divided into two sections by a rigid, adiabatic wall. Each section contains a different ideal gas, at different temperatures ($T_{1,2}$) and pressure ($p_{1,2}$). We then remove the partition, and wait some time:

A. The system comes to a common temperature, but a pressure gradient remains.

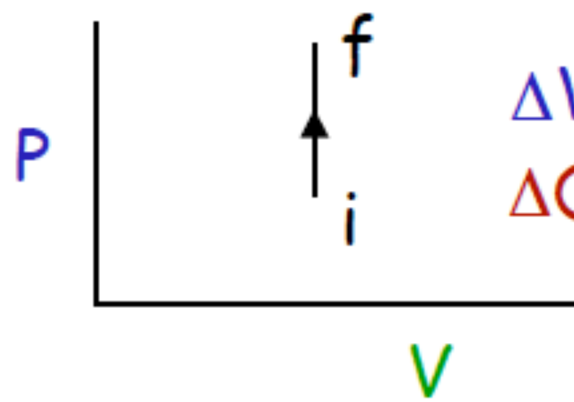
B. The system comes to a common pressure, but a temperature gradient remains.

C. The temperatures and pressures become the arithmetic average of the initial T's and p's.

D. The system arrives at a common T and p, but there is insufficient information to say any more. ←

Ideal Gas Processes

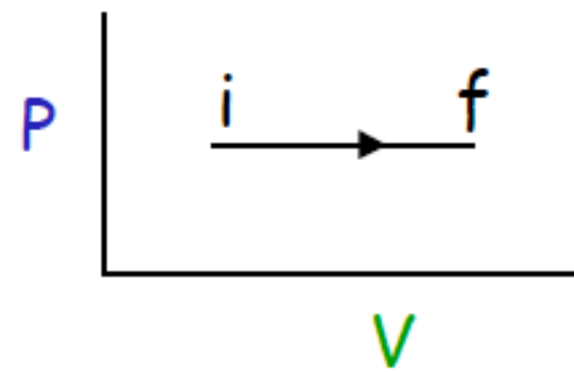
Constant Volume (isochoric)



$\Delta W=0$

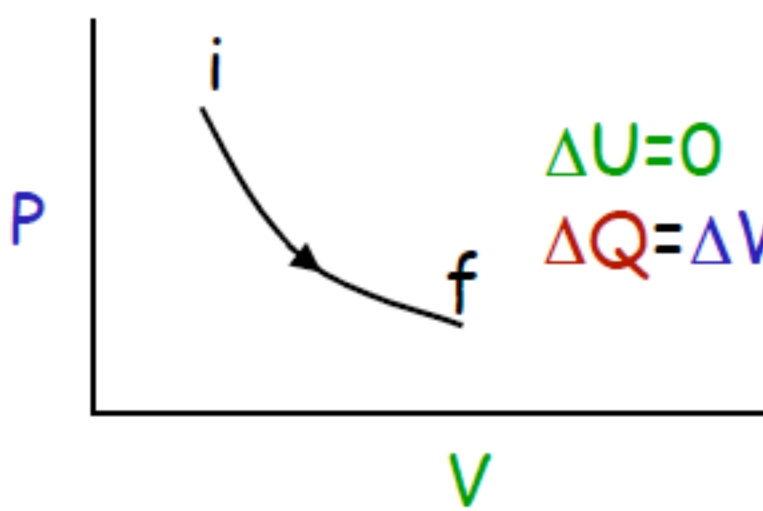
$\Delta Q=\Delta U$

Constant Pressure (isobaric)



$\Delta W=P\Delta V$

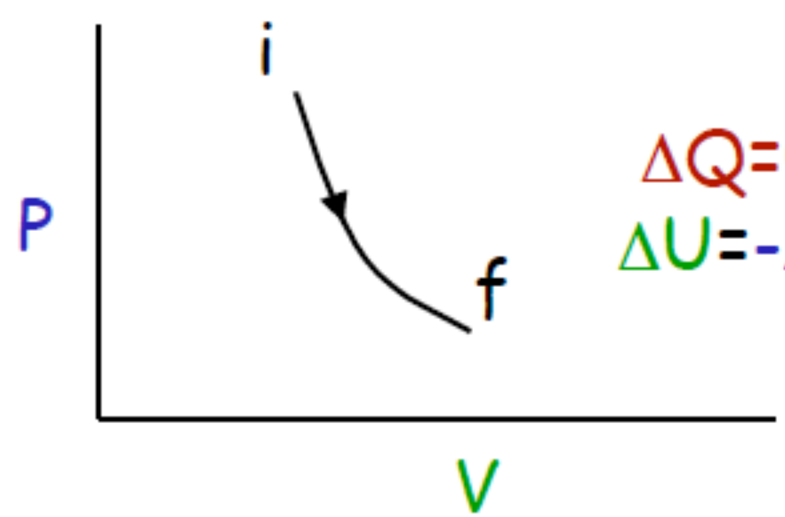
Constant Temp (isothermal)



$\Delta U=0$

$\Delta Q=\Delta W$

Constant Heat (adiabatic)

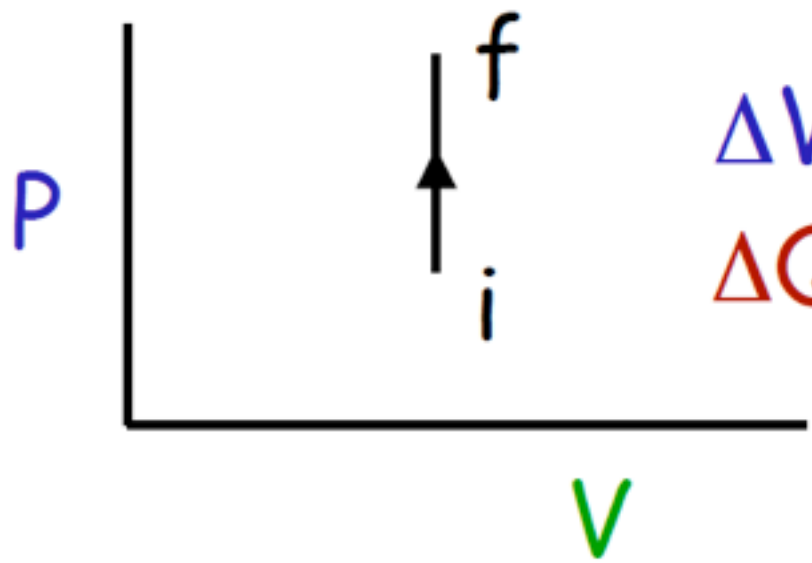


$\Delta Q=0$

$\Delta U=-\Delta W$

Isochoric Process

Constant Volume
(isochoric)



ΔW=0
ΔQ=ΔU

"Equation of State"

$$PV = nRT$$

$$P_f > P_i$$

$$V_f = V_i$$

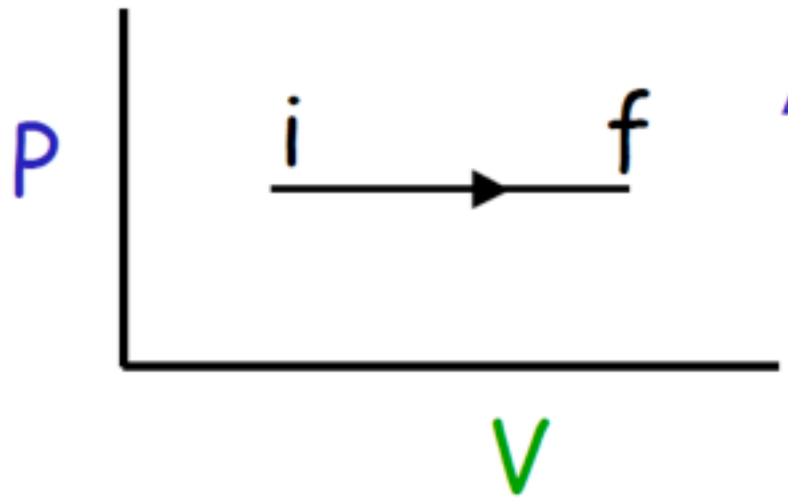
$$\Rightarrow T_f > T_i$$

$$\Delta V = 0 \Rightarrow \Delta W = 0$$

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

Isobaric Process

Constant Pressure
(isobaric)



$\Delta W = P\Delta V > 0$

"Equation of State"

$$PV = nRT$$

$$P_f = P_i$$

$$V_f > V_i$$

$$\Rightarrow T_f > T_i$$

$$U = \frac{nRT}{2} \cdot (\# dof) \Rightarrow \Delta U > 0$$

$$\Delta Q = \Delta U + \Delta W > 0$$

Concept Test

- Which of the following is true?

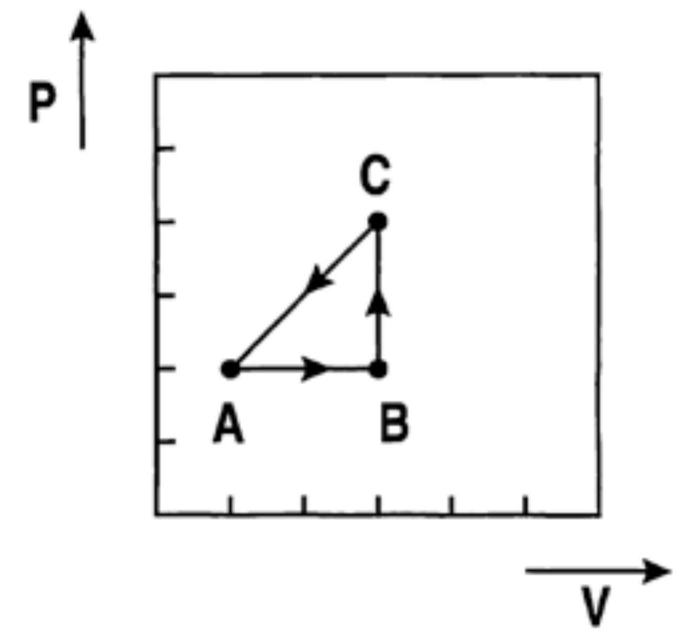
A. $T_A < T_B < T_C$ ←

B. $T_A = T_B < T_C$

C. $T_A < T_B = T_C$

D. $T_A = T_B = T_C$

A system is taken along the indicated path in the P-V plane: A -> B -> C -> A.



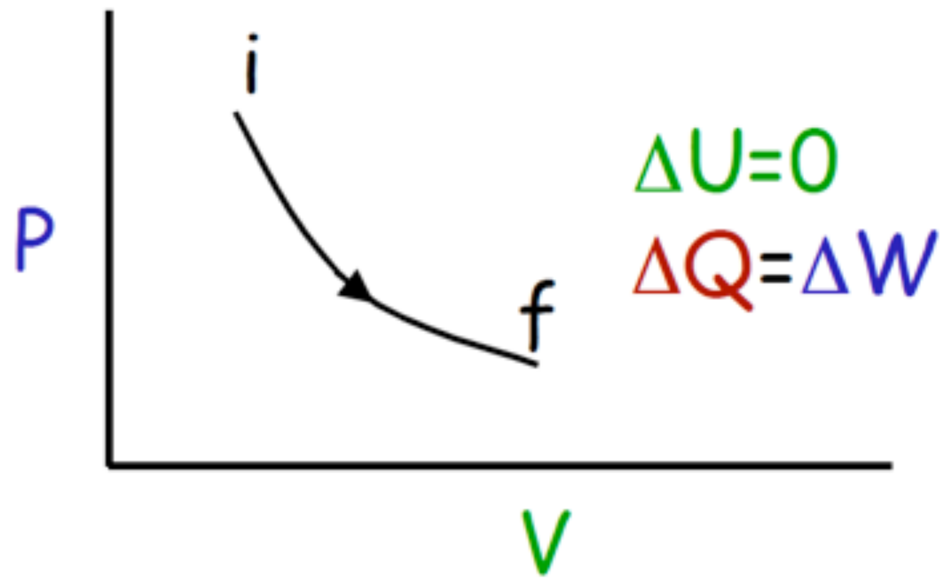
- Is the work done positive (A) or negative (B)?

$$\Delta W = -\frac{1}{2}\Delta P\,\Delta V < 0$$

(Triangular cycle!)

Isothermal Process

Constant Temp
(isothermal)



"Equation of State"

$$PV = nRT$$

$$P_f < P_i$$

$$V_f > V_i$$

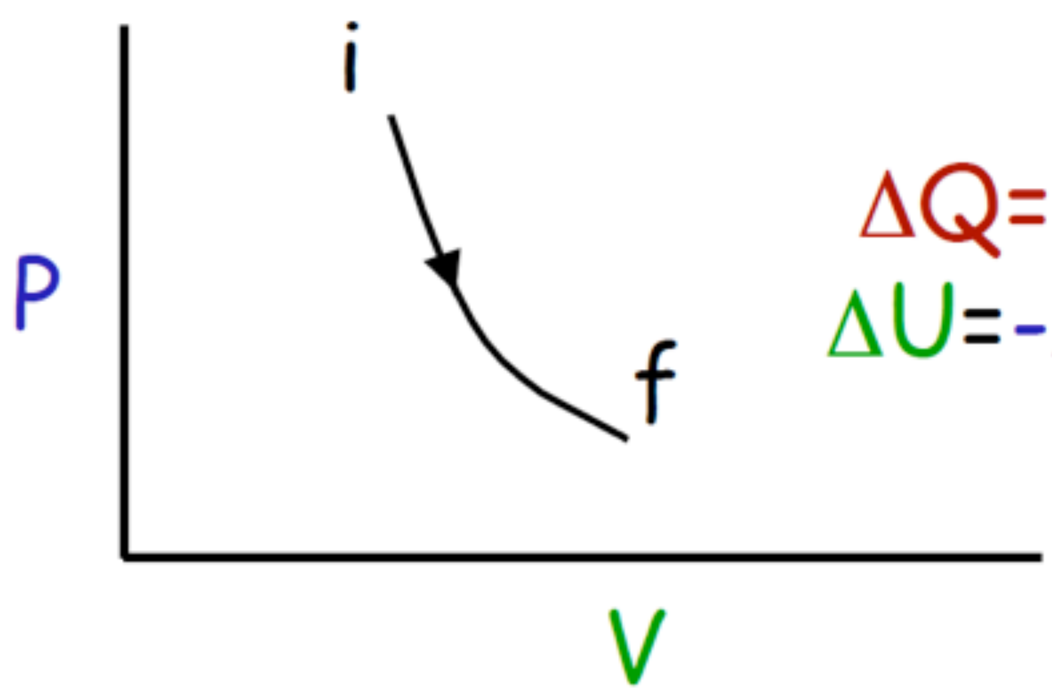
$$T_f = T_i$$

$$U = \frac{nRT}{2} \cdot (\# dof) \Rightarrow \Delta U = 0$$

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

Adiabatic Process I

Constant Heat
(adiabatic)



$\Delta Q=0$

$\Delta U=-\Delta W$

$$PV^{\gamma} = const$$

$$\gamma = \frac{C_p}{C_V} > 1$$

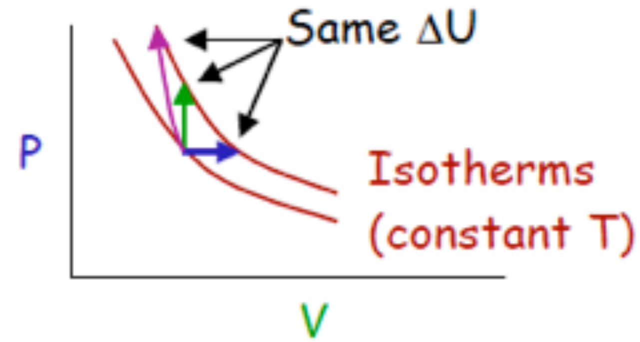
Adiabatic Process 2

Proof of PV^{γ}=constant

(for adiabatic process)

1) Adiabatic: $dQ = 0 = dU + dW$
$= dU + PdV$

2) U only depends on T:



$dU = n\,C_V\,dT$ (derived for constant volume, but true in general)

3) Ideal gas: $T = PV/(nR)$
$dT = [(dP)V + P(dV)]/(nR)$

Plug into 2): $dU = (C_V/R)[VdP + PdV]$

Plug into 1): $0 = (C_V/R)[VdP + PdV] + PdV$

Rearrange:

$(dP/P) = -\,(C_V+R)/C_V\,(dV/V)$
$= -\,\gamma\,(dV/V)$

where $\gamma = (C_V+R)/C_V = C_P/C_V > 1$

Integrate both sides:

$\ln(P) = -\,\gamma\,\ln(V) + \text{constant}$

or

$\ln(PV^{\gamma}) = \text{constant}$

or

$PV^{\gamma} = \text{constant}$

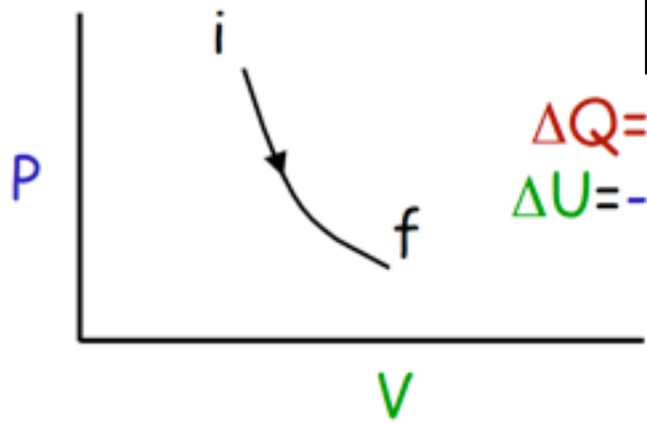
QED

Concept Test

Constant Heat (adiabatic)

$$PV^{\gamma} = const$$

$$\gamma = \frac{C_p}{C_V} > 1$$

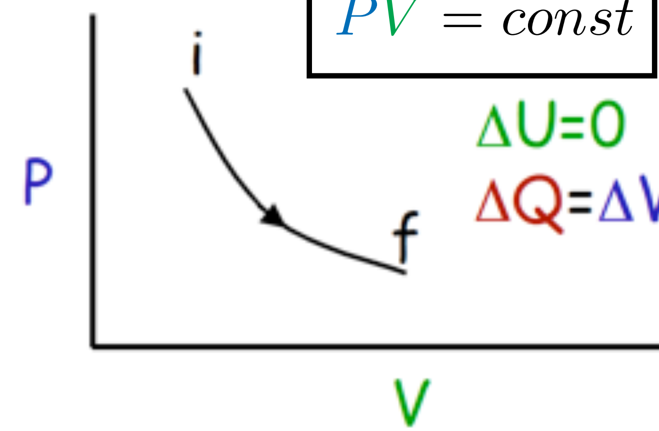


ΔQ=0
ΔU=-ΔW

Constant Temp (isothermal)

PV=nRT

$$PV = const$$



ΔU=0
ΔQ=ΔW

- The adiabatic (left) and isothermal (right) processes above, start at the *same* temperature and pressure, and end at the same *volume*. The final temperature for the adiabatic process is

  A. *lower than* ←

  B. *equal to*

  C. *greater than*

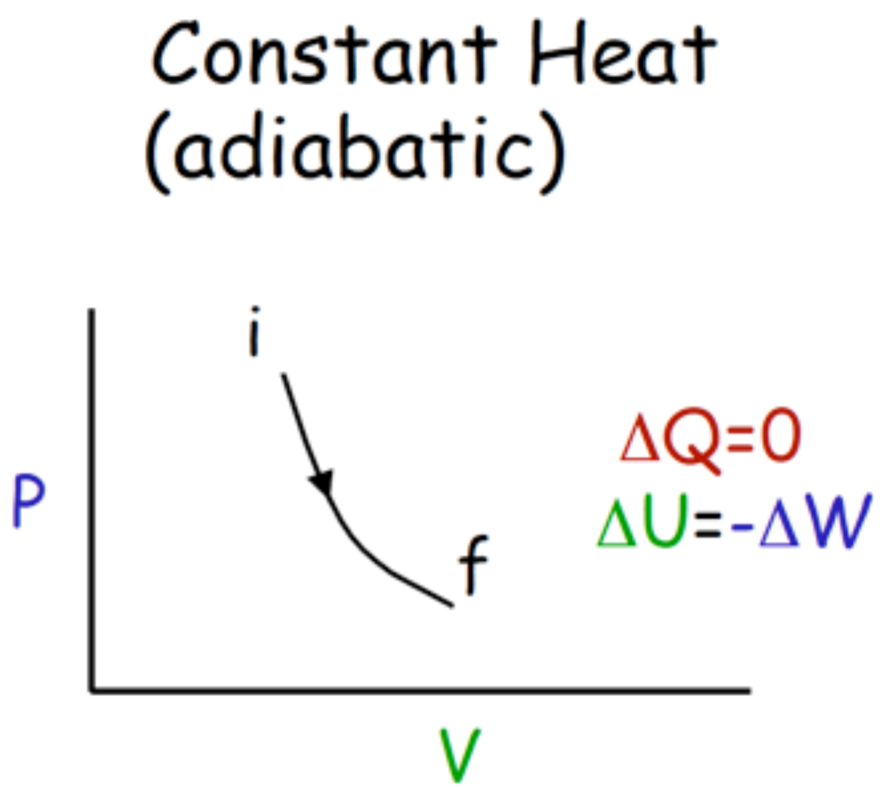
  the isothermal process.

Ideal Gas Adiabatic Process:

$$TV^{\gamma-1} = const$$

$$P^{(1-\gamma)/\gamma}T = const$$

Work done during an Adiabatic Process



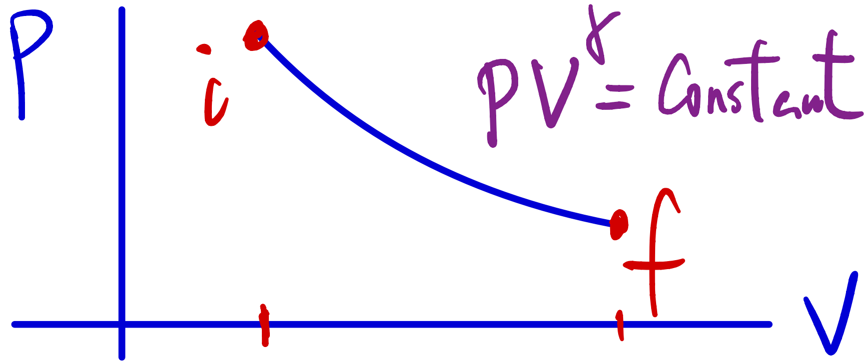
$$\Delta U = \frac{nR\Delta T}{2} \cdot (\# \, dof) = nC_V \Delta T$$

$$PV = nRT$$

$$\Delta T = \frac{\Delta(PV)}{nR}$$

$$\begin{aligned} \Delta W &= -nC_V \Delta T = -nC_V (T_f - T_i) \\ &= -\frac{C_V}{R} \Delta(PV) = \frac{1}{\gamma - 1} (P_i V_i - P_f V_f) \end{aligned}$$

Alternative method:



$PV^{\gamma} = \text{Constant} \equiv C$

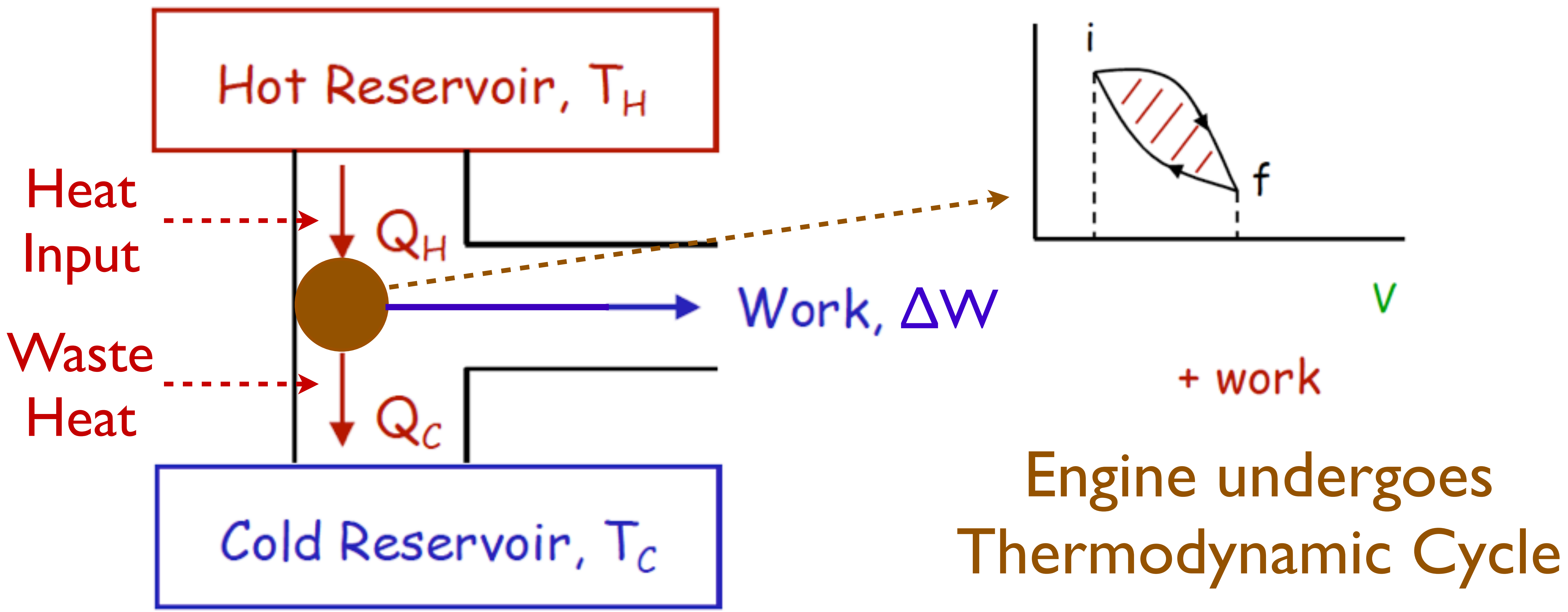
$$W = \int_{V_i}^{V_f} P\,dV = \int \frac{C}{V^{\gamma}}\,dV = \frac{1}{1-\gamma}\left(\frac{C}{V_f^{\gamma-1}} - \frac{C}{V_i^{\gamma-1}}\right)$$

$$= \frac{1}{1-\gamma}\left(\frac{P_f V_f^{\gamma}}{V_f^{\gamma-1}} - \frac{P_i V_i^{\gamma}}{V_i^{\gamma-1}}\right)$$

$$= \frac{1}{1-\gamma}\left(P_f V_f - P_i V_i\right)$$

$$= \frac{1}{\gamma-1}\left(P_i V_i - P_f V_f\right)$$

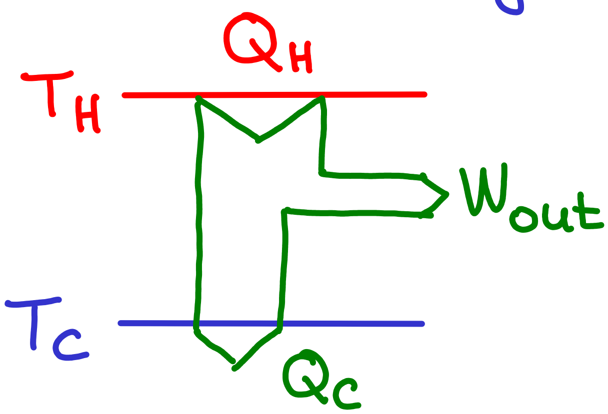
Heat Engine: Heat to Work



Efficiency=Work done/Heat Input

$$\eta = \frac{\Delta W}{Q_H}$$

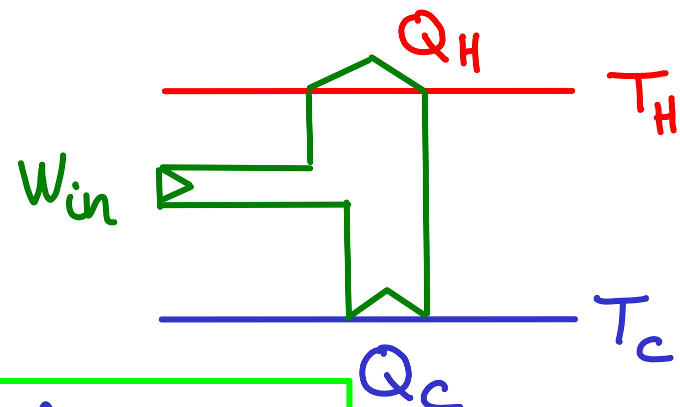
Heat-engines, heat-pumps



heat-engine

efficiency: $\eta = \dfrac{W_{out}}{Q_H}$

$0 \leq \eta < 1$



refrigerator ; heat-pump

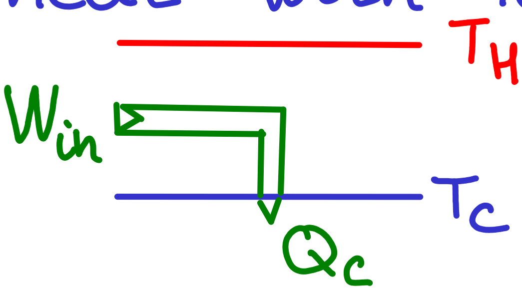
coefficient of performance

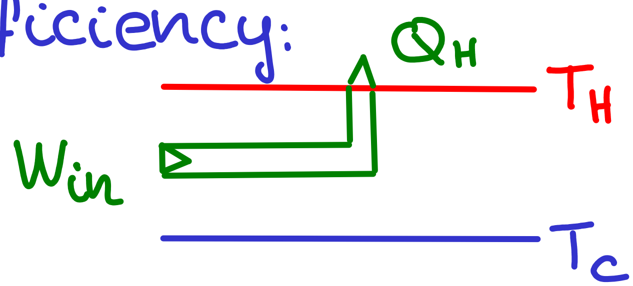
$\kappa = \dfrac{Q_C}{W_{in}}$

$\kappa = \dfrac{Q_H}{W_{in}}$

$0 \leq \kappa < \infty$

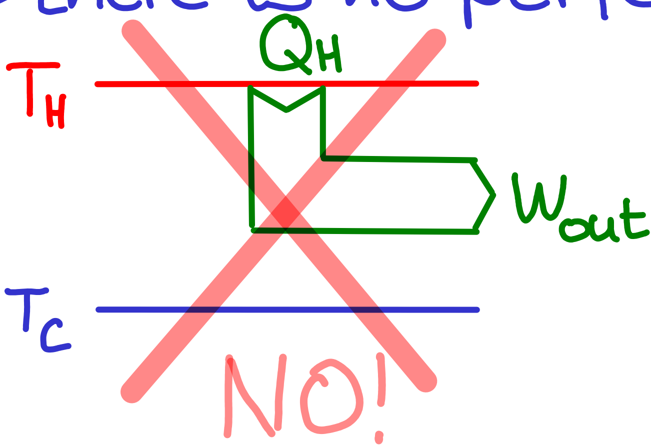
Mechanical work can be converted to heat with 100% efficiency:

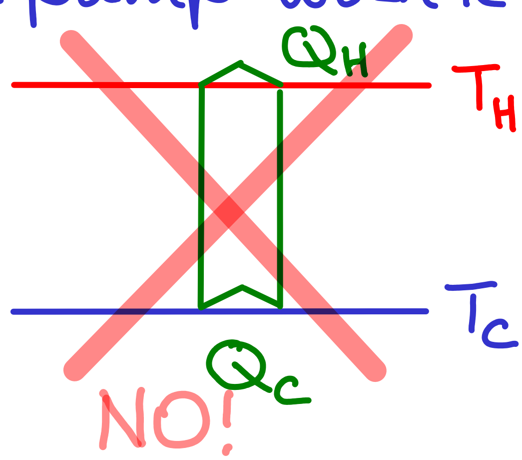




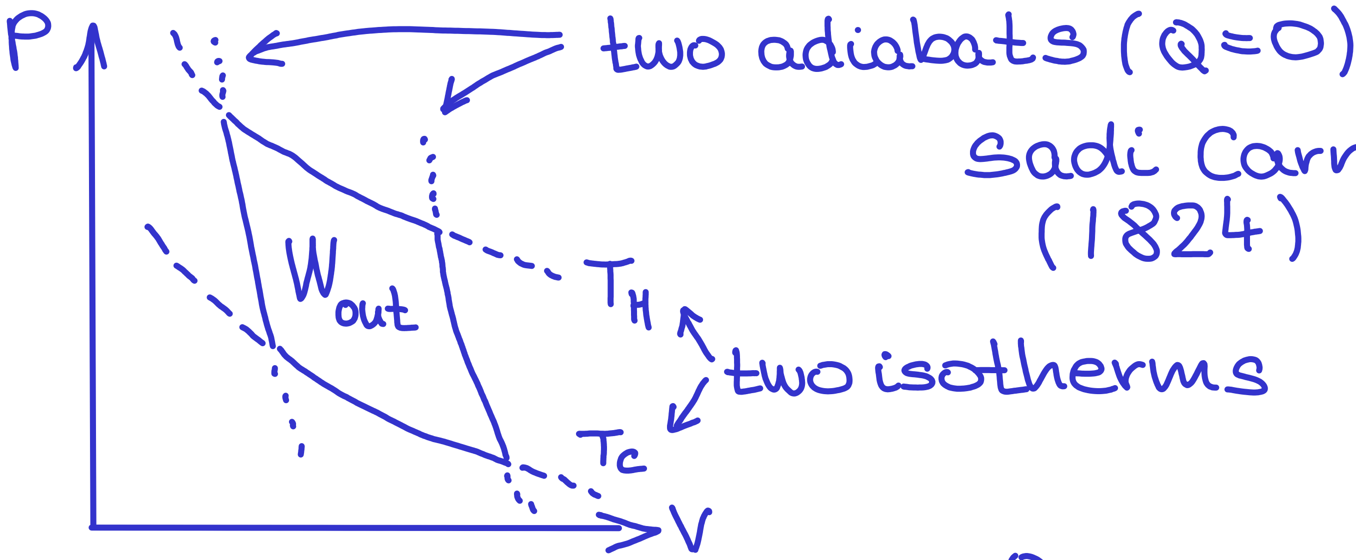
2nd law with engines/pumps:

- there is no perfect heat engine with $\eta = 1$
- there is no perfect heat pump with $\kappa = \infty$





The Carnot-cycle



Sadi Carnot (1824)

Definition: $\eta = \frac{W_{out}}{Q_H} = \frac{Q_H - Q_c}{Q_H}$

Carnot: $\boxed{\eta_{Carnot} = \frac{T_H - T_c}{T_H}}$ $\boxed{K_{Carnot} = \frac{T_c}{T_H - T_c}}$

<u>Second law</u>: no heat engine operating between heat reservoirs with temperatures T_H and T_c can exceed the Carnot efficiency. (And no heat pump can exceed the Carnot coefficient of performance.)

<u>Note</u>: you cannot outperform the Carnot engine.

Summary

- Ideal Gas Processes can be
  - Isochoric - no ΔW
  - Isobaric (constant p)
  - Isothermal - no ΔU
- Adiabatic Expansion/Compression
  - No ΔQ
- Heat Engines transform heat into work
  - Efficiency: work done over heat *input*

$$PV^{\gamma} = const$$

$$\gamma = \frac{C_p}{C_V} > 1$$