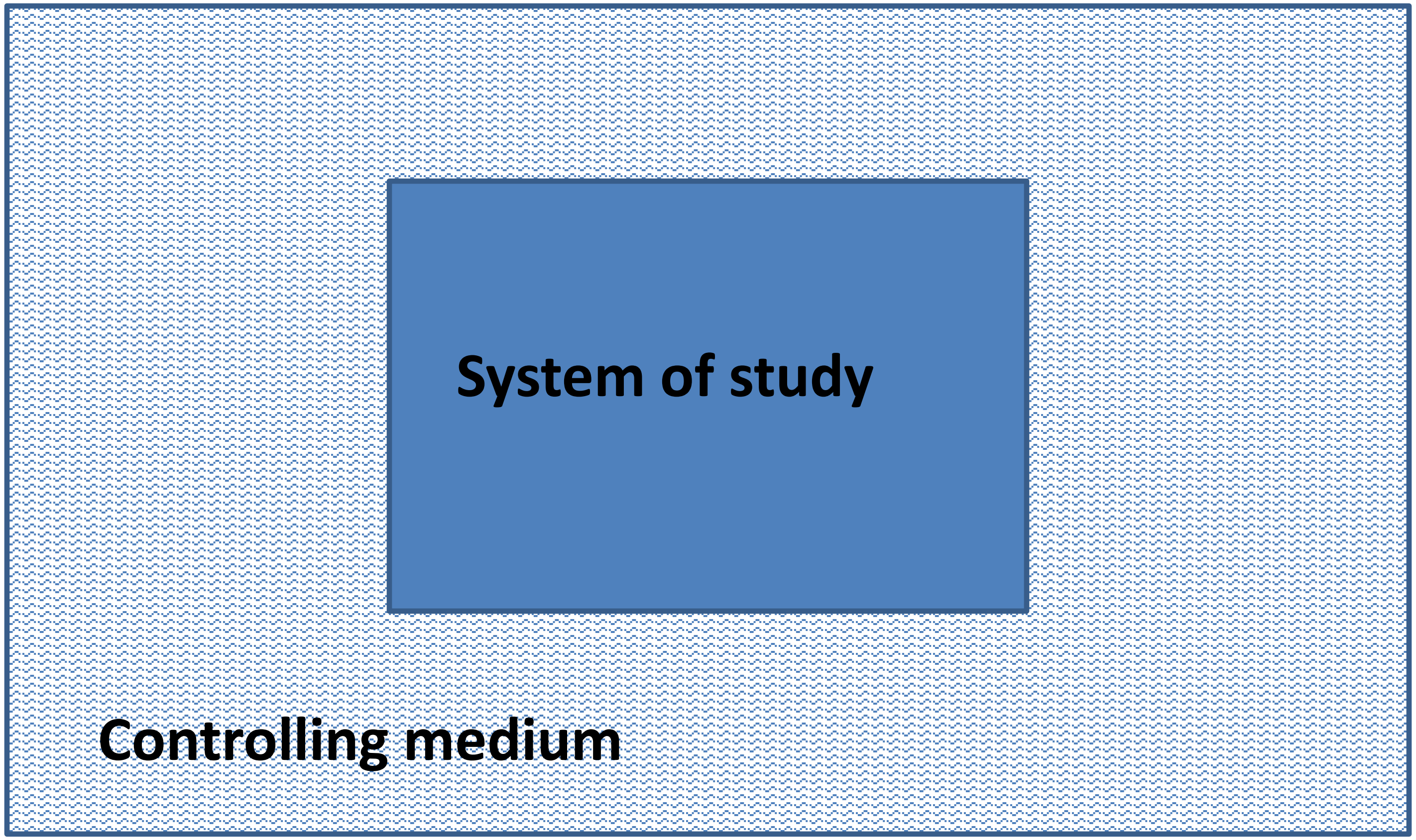
PHY 341/641
Thermodynamics and Statistical Physics

Lecture 3

1. Introduction to thermodynamics (Chapter 2)
   a. Definition of “the system”
   b. Thermodynamic variables (T, P, V, N, …)
2. First law of thermodynamics -- the sign of work
   a. Some examples for ideal gas systems
   b. Some cyclic processes
   c. Efficiency of process

Macroscopic viewpoint – thermodynamics

(start reading Chapter 2)



Thermodynamic process -- WORK

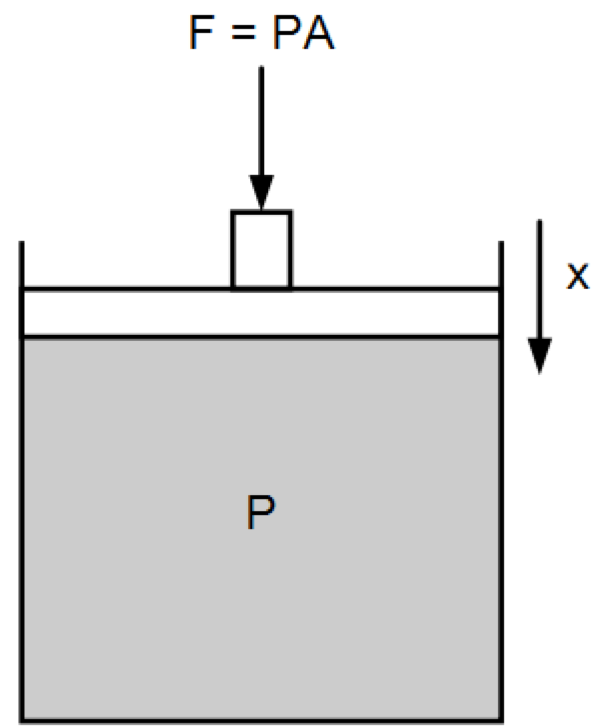
various sign conventions !!!#$#!!!

Sign convention in your text -- work ON the system;

system expands $\Rightarrow W < 0$:

$$dW = -Fdx = -PAdx = -PdV$$

$$W_{1\to 2} = -\int_{V_1}^{V_2} P(T,V)dV$$



Work sign conventions in various text books:

$$dW = \pm PdV$$

Work done BY the system (+)

Work done ON the system (–)

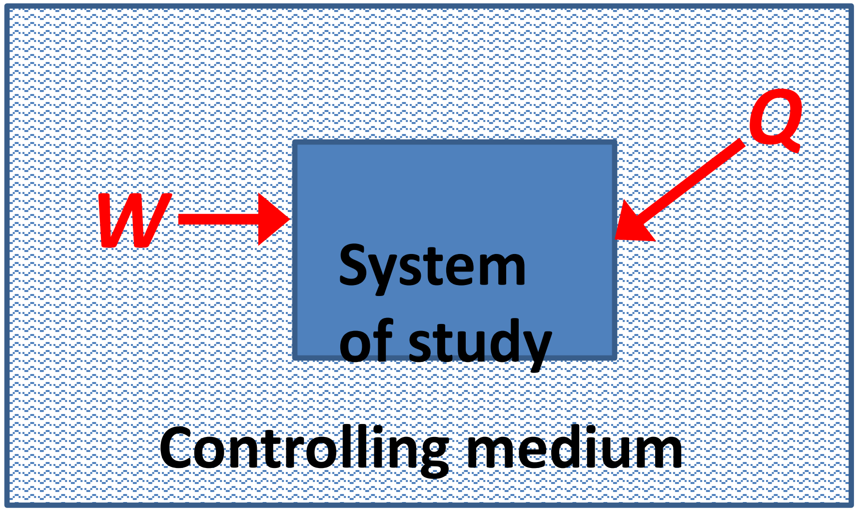
Textbook	Sign
Gould & Tobochnik, *Statistical and Thermal Physics* (2010)	–
Kittel & Kroemer, *Thermal Physics* (1980)	–/+
Serway & Jewitt, *Physics* (8^{th} Ed.) (2010)	–
Serway & Beichner, *Physics* (5^{th} Ed.) (2000)	+
Baierlein, *Thermal Physics* (1999)	+
Callen, *Thermodynamics* (1985)	–
Bailyn, *A Survey of Thermodynamics* (1994)	+
Fermi, *Thermodynamics* (1936)	+

First law of thermodynamics

$$U_2 - U_1 \equiv \Delta U = Q + W$$

$$Q \equiv \text{ heat added TO the system}$$

$$W \equiv \text{ work done ON the system}$$



$$\text{First law:} \qquad dU = dQ + dW$$

$$dW = -PdV$$

Examples of heat and work performed by ideal gas

$$PV = NkT \quad (k \equiv k_B \quad \text{Boltzmann constant})$$

$$U = \frac{k}{\gamma - 1} NT = \frac{PV}{\gamma - 1} \quad (\gamma = C_P / C_V)$$

Various ideal gas processes (assuming *N* constant)

Process	Variables	Q	W	ΔU
Constant V	$V_1, P_1, T_1 \rightarrow V_1, P_2, T_2$	$\frac{(P_2 - P_1)V_1}{\gamma - 1}$	0	$\frac{(P_2 - P_1)V_1}{\gamma - 1}$
Constant P	$V_1, P_1, T_1 \rightarrow V_2, P_1, T_2$	$\frac{\gamma P_1(V_2 - V_1)}{\gamma - 1}$	$-P_1(V_2 - V_1)$	$\frac{P_1(V_2 - V_1)}{\gamma - 1}$
Constant T	$V_1, P_1, T_1 \rightarrow V_2, P_2, T_1$	$P_1 V_1 \ln\left(\frac{V_2}{V_1}\right)$	$-P_1 V_1 \ln\left(\frac{V_2}{V_1}\right)$	0
Q = 0	$V_1, P_1, T_1 \rightarrow V_2, P_2, T_2$	0	$-\frac{P_1 V_1}{\gamma - 1}\left(1 - \left(\frac{V_1}{V_2}\right)^{\gamma - 1}\right)$	$-\frac{P_1 V_1}{\gamma - 1}\left(1 - \left(\frac{V_1}{V_2}\right)^{\gamma - 1}\right)$

Some details of the adiabatic case: Q = 0

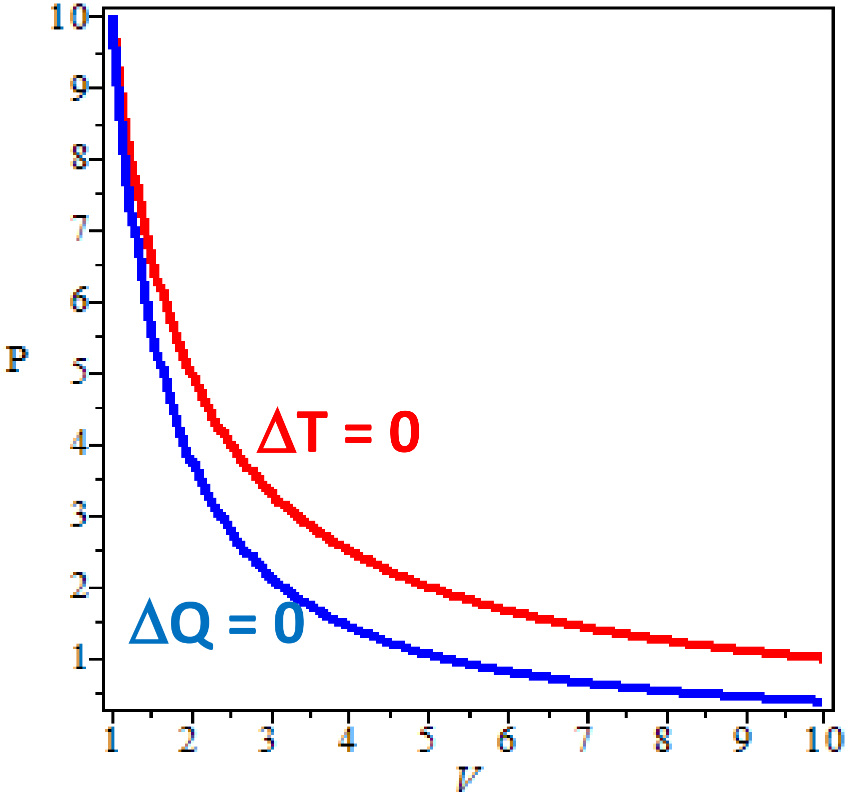
$$dU = dW$$

$$\frac{d(PV)}{\gamma - 1} = -PdV$$

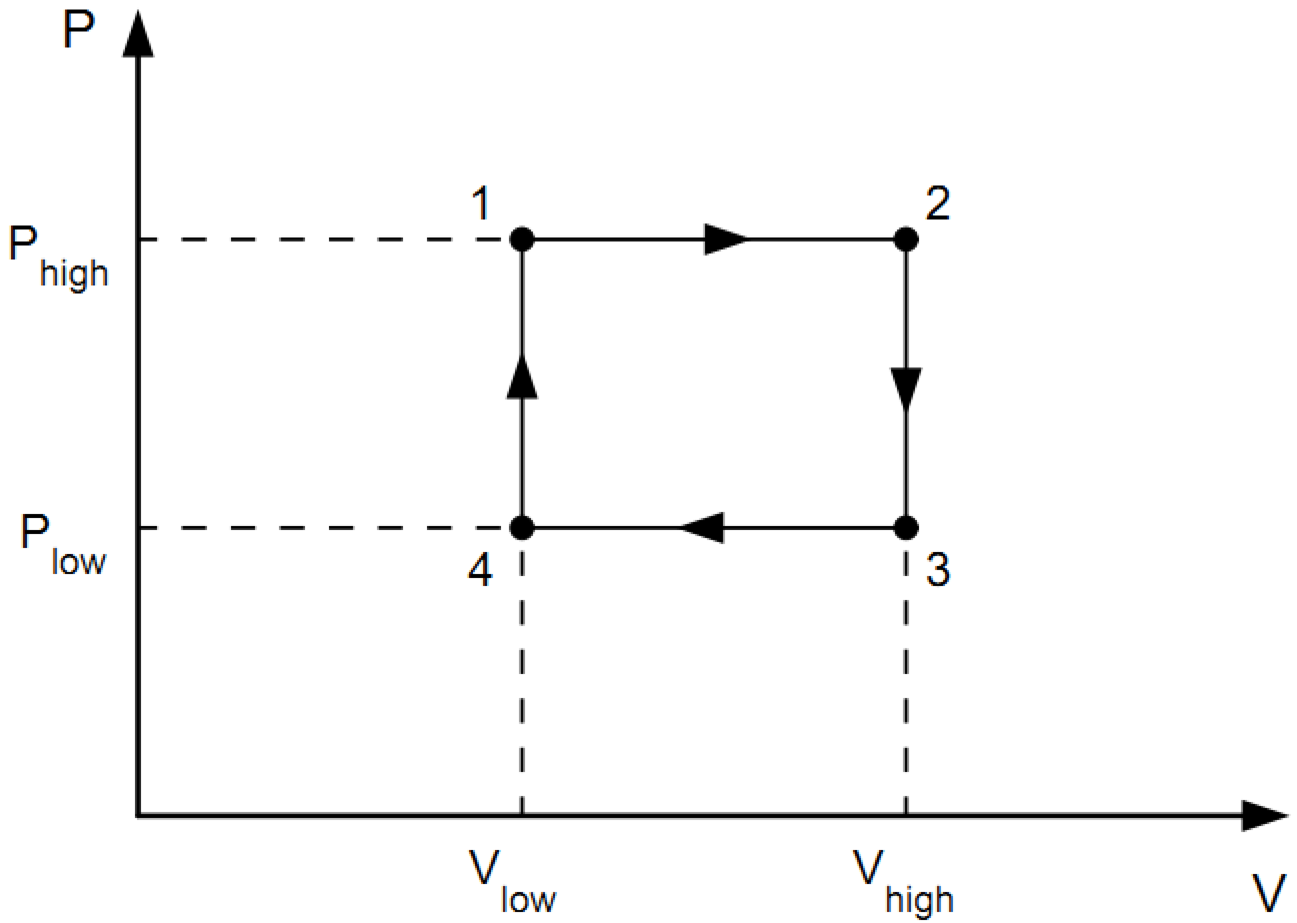
$$PdV\left(\frac{1}{\gamma - 1} + 1\right) + VdP\left(\frac{1}{\gamma - 1}\right) = 0$$

$$\frac{dV}{V}\gamma + \frac{dP}{P} = 0 \qquad \Rightarrow PV^{\gamma} = P_1 V_1^{\gamma}$$

Ideal gas expansions



Work performed during a cyclic process:



$$W_{net} = -\left(P_{high} - P_{low}\right)\left(V_{high} - V_{low}\right)$$

Efficiency of cyclic processes:

The notions of work and heat can be used for practical devices

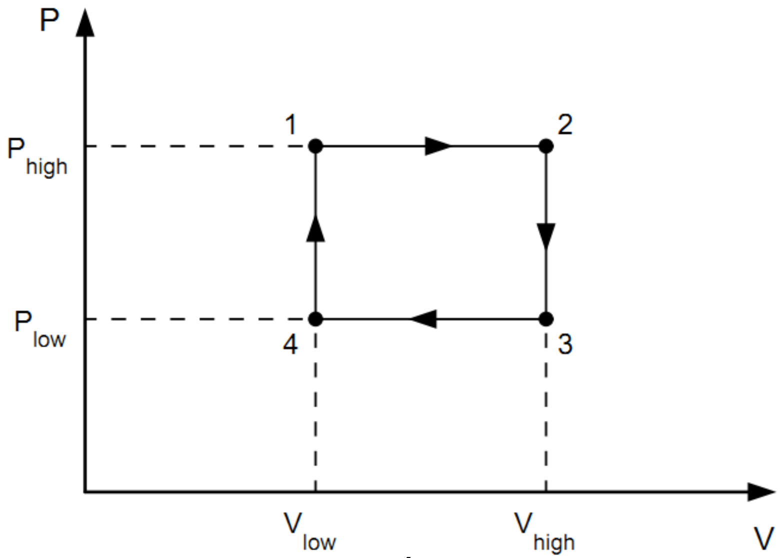
Example: Internal combustion engine

Otto cycle:

http://www.howstuffworks.com/engine1.htm

General measure of process efficiency (assuming no frictional losses; "completely reversible processes"):

$$\varepsilon = \frac{\text{output}}{\text{input}} = \frac{\text{work done by system}}{\text{heat input to system}} = \frac{-W_{total}}{Q_{input}}$$



$$\varepsilon = \frac{-W_{total}}{Q_{input}}$$

$$W_{total} = -\left(P_{high} - P_{low}\right)\left(V_{high} - V_{low}\right)$$

$$Q_{input} = Q_{12} + Q_{41}$$

$$\varepsilon = \frac{\left(P_{high} - P_{low}\right)\left(V_{high} - V_{low}\right)}{\frac{\gamma}{\gamma - 1}\left(P_{high}\left(V_{high} - V_{low}\right)\right) + \frac{1}{\gamma - 1}\left(V_{low}\left(P_{high} - P_{low}\right)\right)}$$

Analysis of an ideal heat engine

Nicholas Carnot (French Engineer) 1834

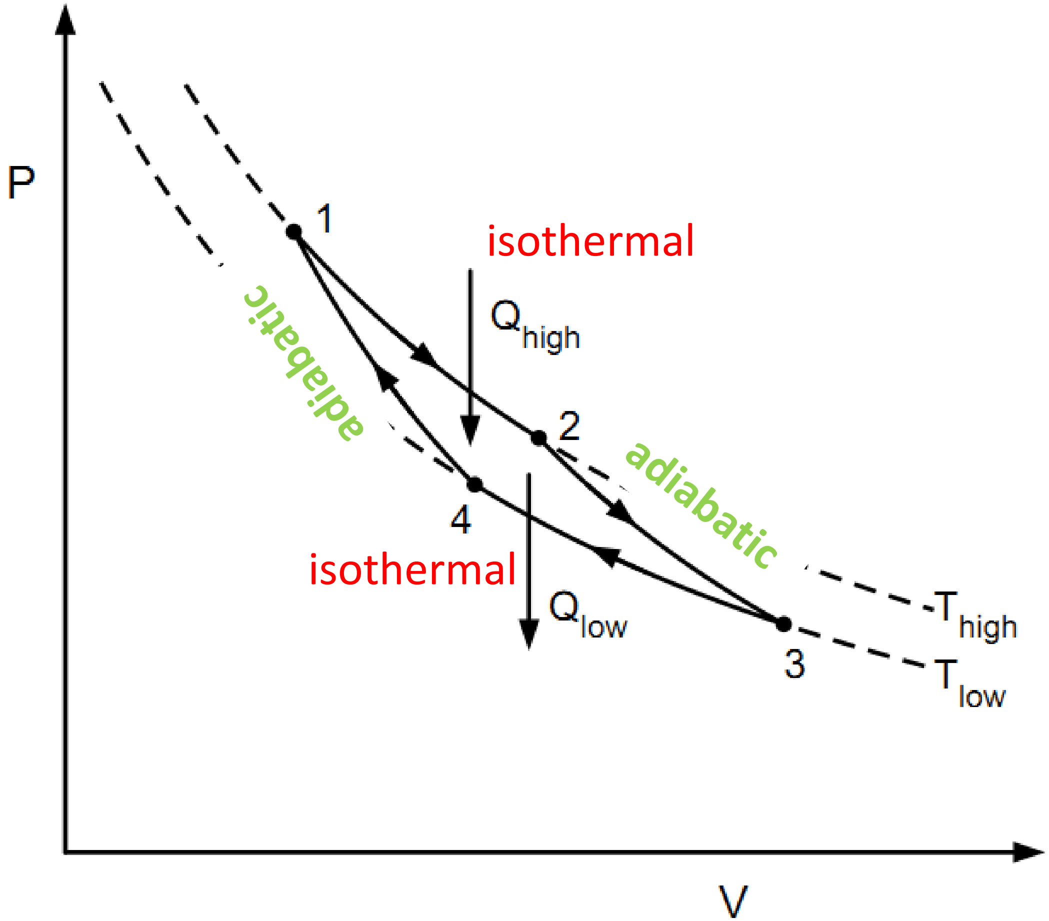
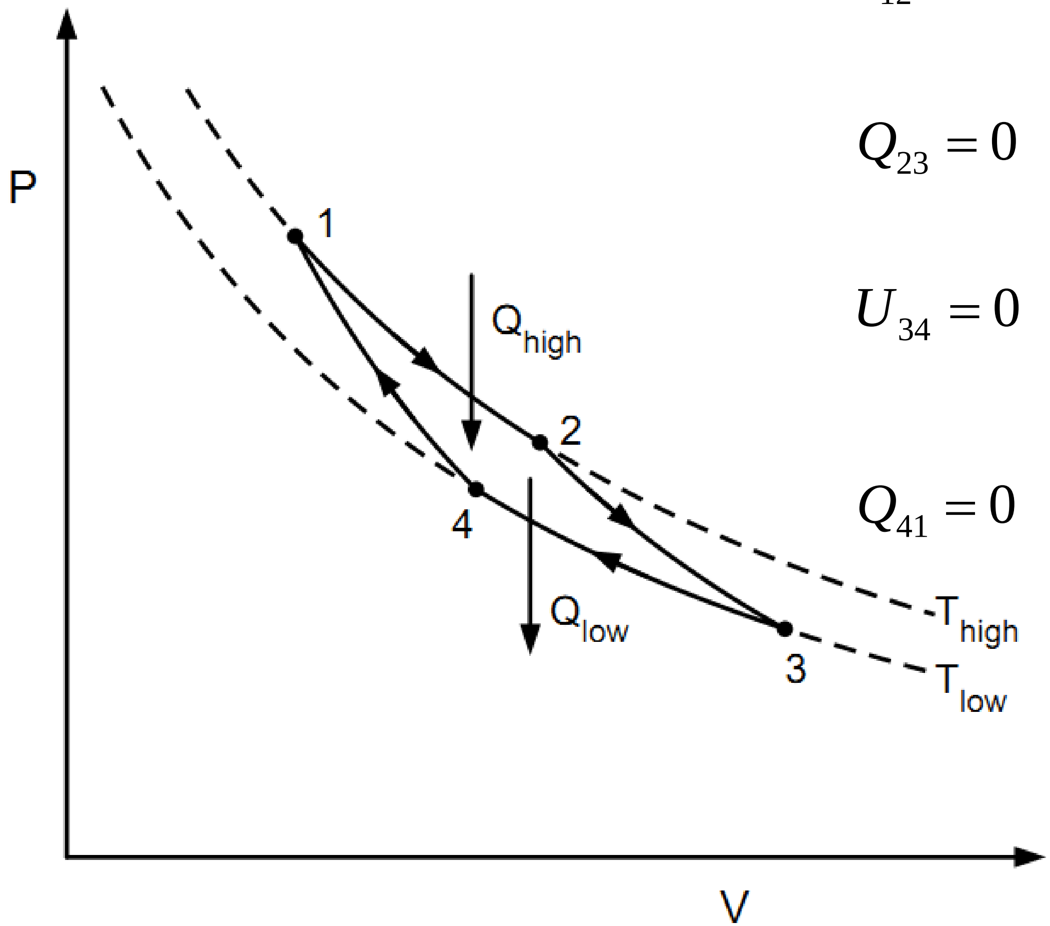


Figure 2.9: The four steps of the Carnot cycle.

Analysis of Carnot cycle for ideal gas system



$$U_{12} = 0 \qquad \Rightarrow Q_{12} = -W_{12} = NkT_{high} \ln \frac{V_2}{V_1}$$

$$Q_{23} = 0 \qquad \Rightarrow U_{23} = W_{23} = \frac{Nk\left(T_{low} - T_{high}\right)}{\gamma - 1}$$

$$U_{34} = 0 \qquad \Rightarrow Q_{34} = -W_{34} = NkT_{low} \ln \frac{V_4}{V_3}$$

$$Q_{41} = 0 \qquad \Rightarrow U_{41} = W_{41} = \frac{Nk\left(T_{high} - T_{low}\right)}{\gamma - 1}$$

$$\varepsilon = \frac{-W_{total}}{Q_{input}} = \frac{-W_{12} - W_{34}}{Q_{12}}$$

$$= 1 + \frac{NkT_{low} \ln\left(V_4/V_3\right)}{NkT_{high} \ln\left(V_2/V_1\right)}$$

$$= 1 - \frac{T_{low}}{T_{high}}$$