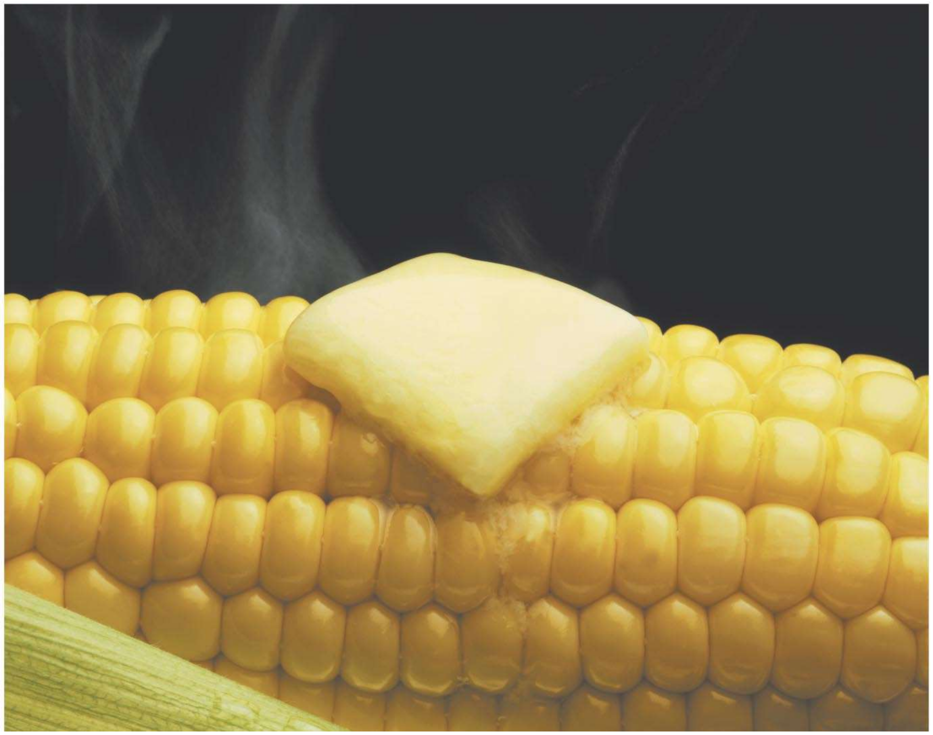
Physics 262/266

George Mason University

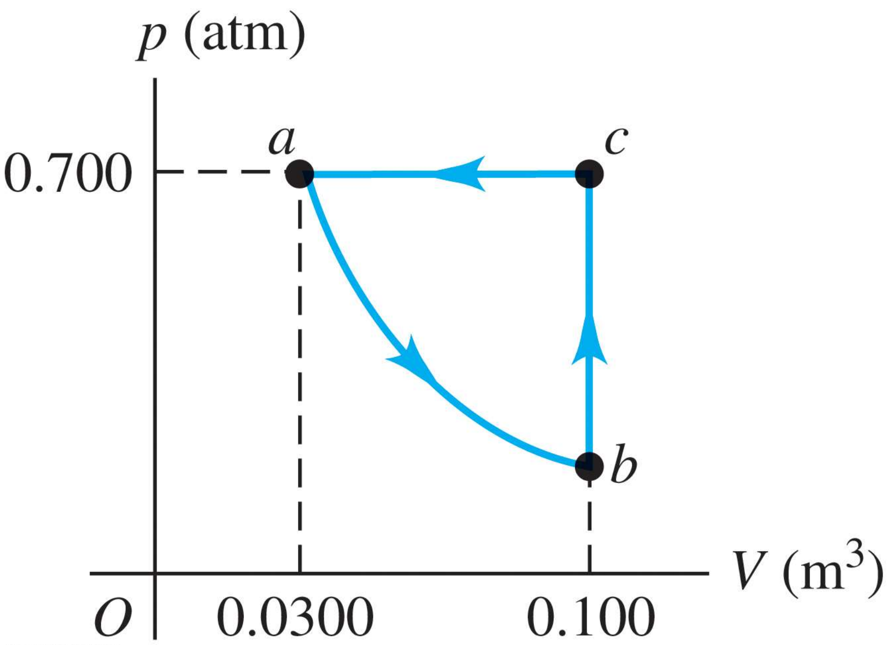
Prof. Paul So

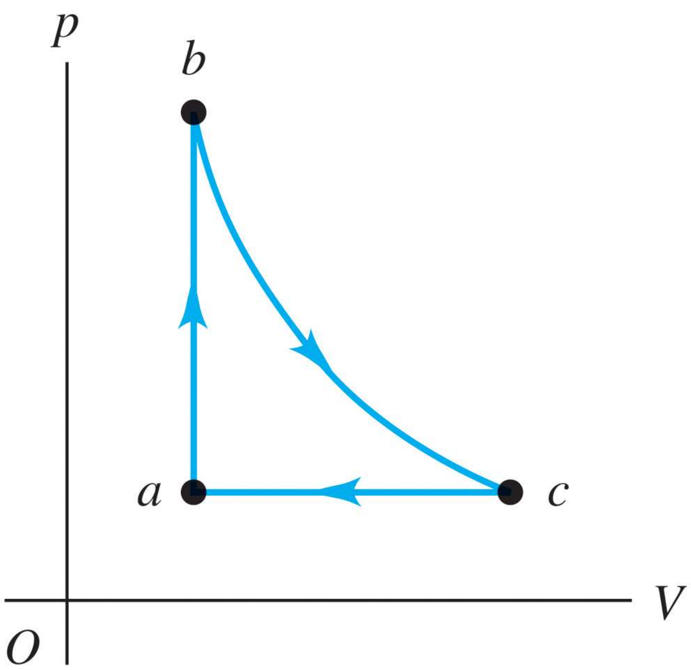
Chapter 20: The 2nd Law of Thermodynamics

- Preferential Direction in Thermodynamic Processes
- Heat Engine and Efficiency
- The 2nd Law of Thermodynamics
- The Carnot Cycle (the most efficient heat engine)
- Entropy
- Entropy and Disorder

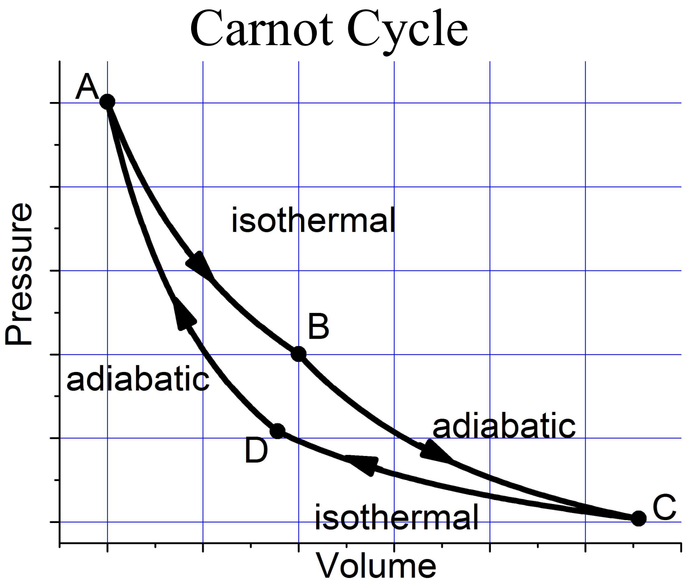


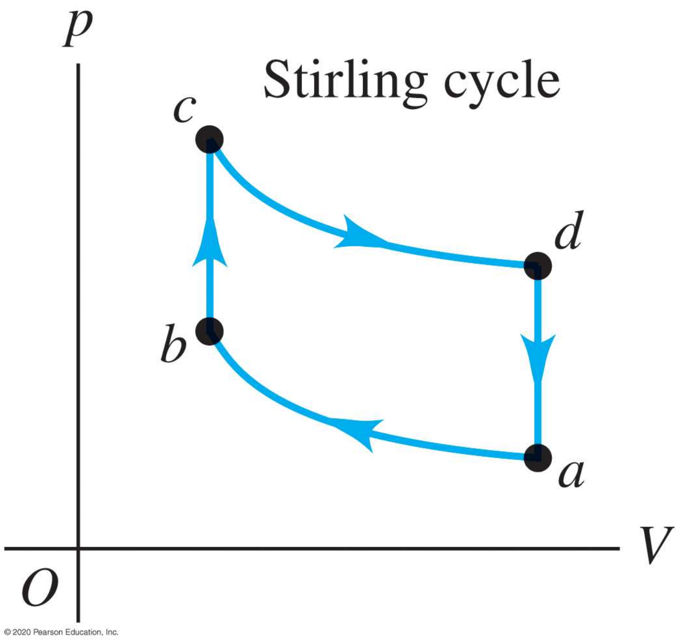
Heat Engines

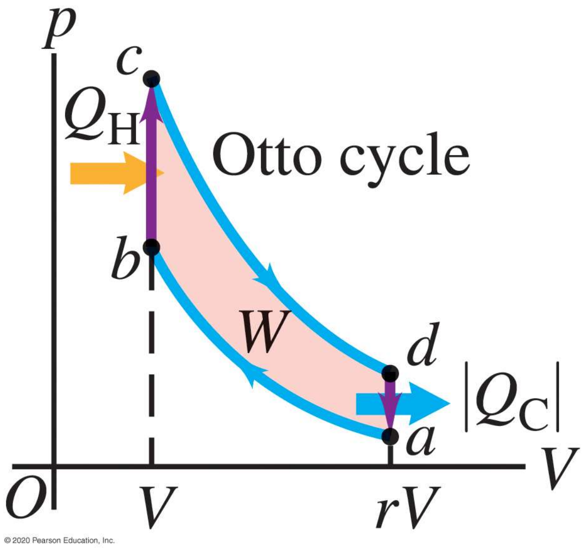




Heat Engines

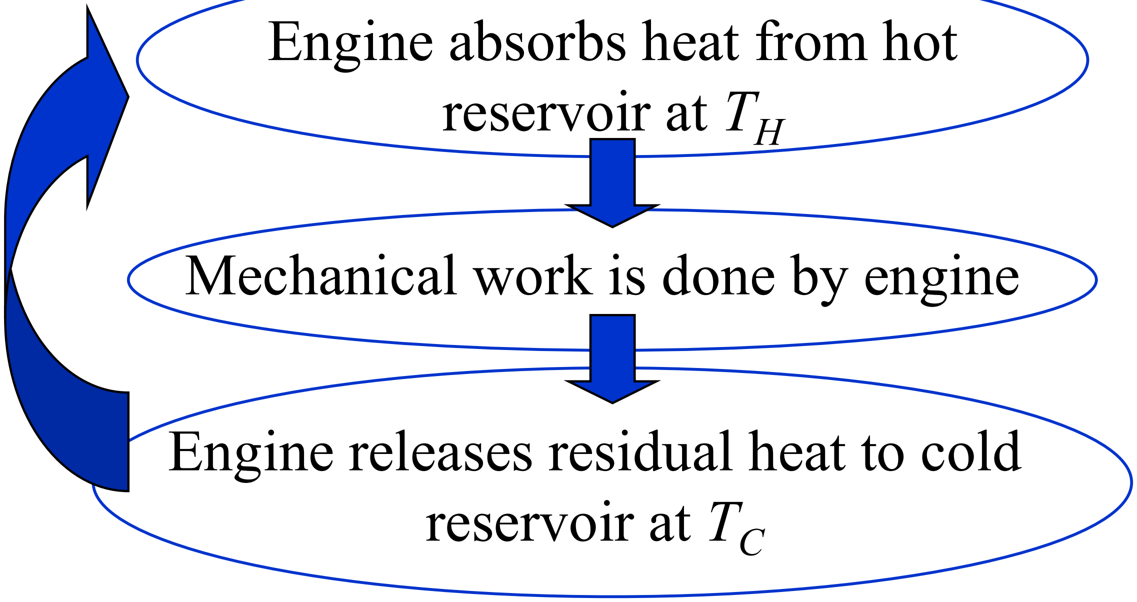






Heat Engines

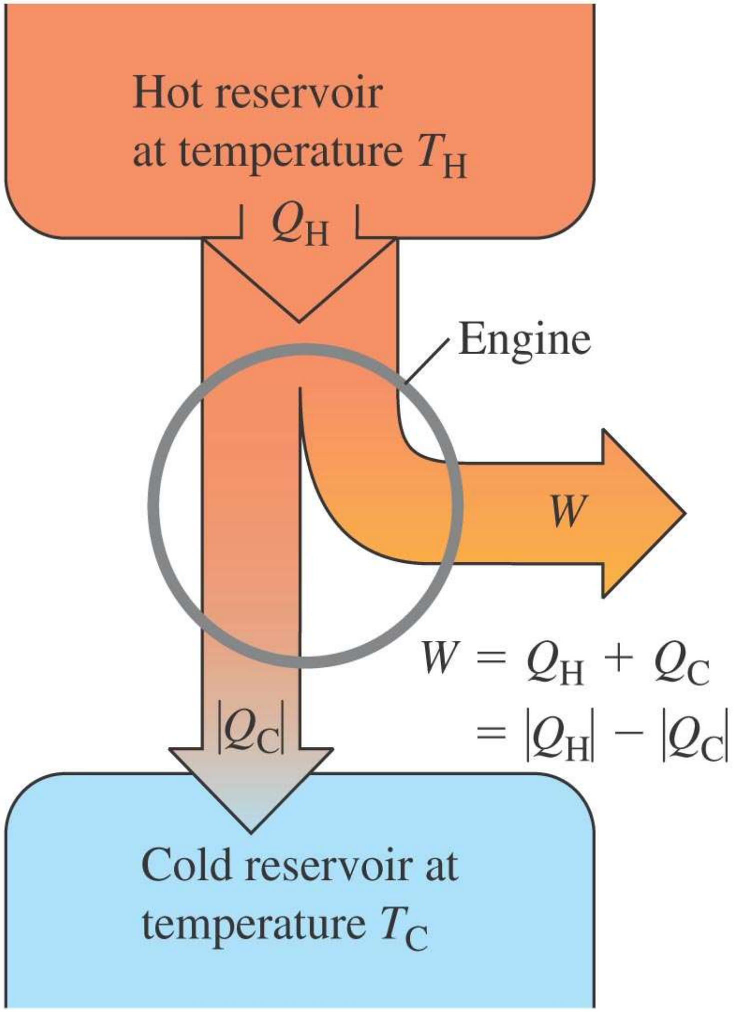
- Definition: A device that converts a given amount of *heat* into *mechanical energy*.
- All heat engines carry some *working substance* thru a *cyclic process*:



Engine absorbs heat from hot reservoir at T_H

Mechanical work is done by engine

Engine releases residual heat to cold reservoir at T_C



Efficiency for a Heat Engine

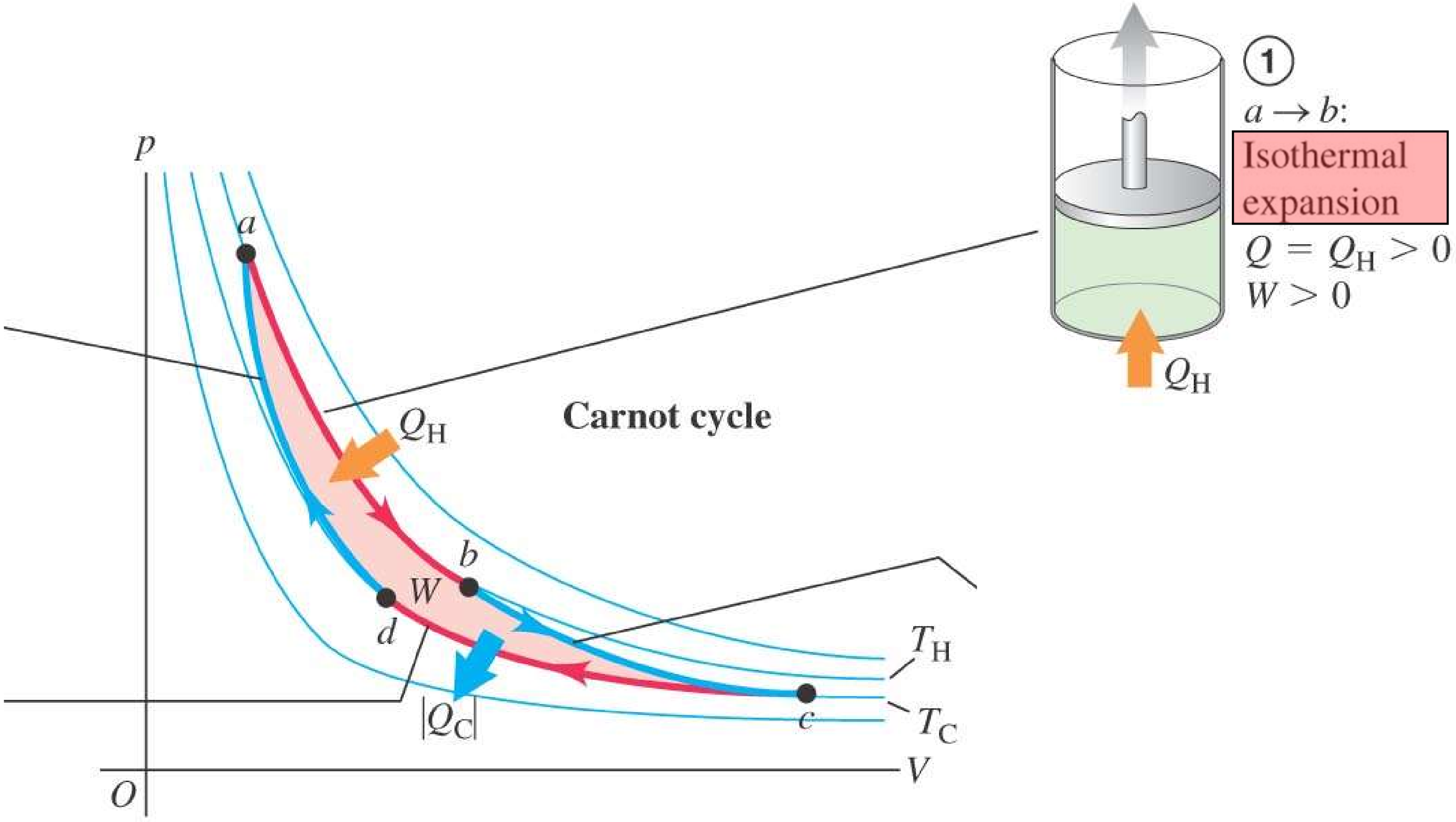
- Thermal Efficiency *e* is defined as the *ratio* of the mechanical energy output to the heat energy input,

$$e = \frac{W}{Q_H} = \frac{\text{what you get out}}{\text{what you put in}}$$

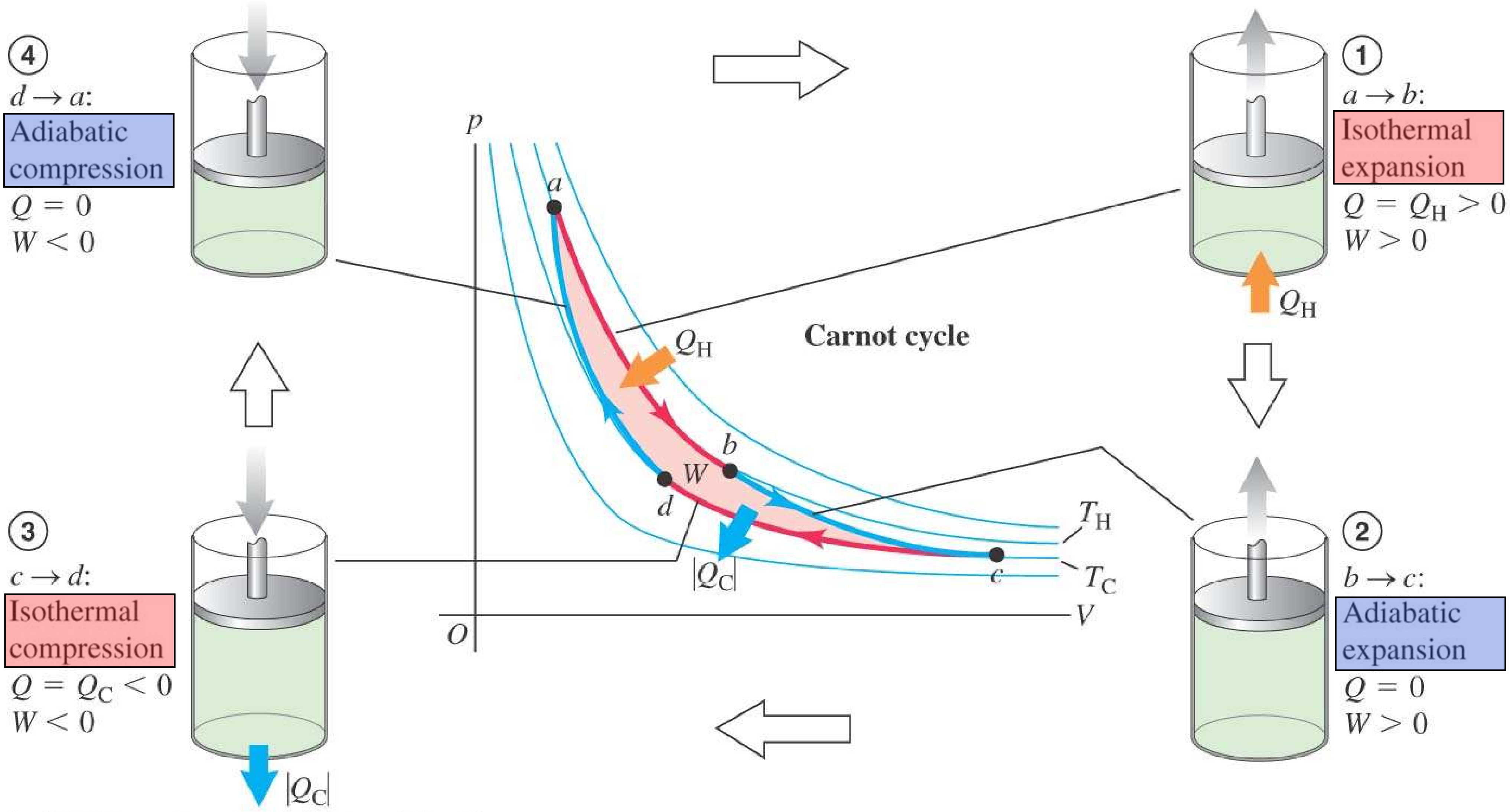
$$\vdots$$

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

Carnot Cycle: Ideal Heat Engine



Steps of the Carnot Cycle



Efficiency of the Carnot Cycle

By explicitly calculating Q_C and Q_H in $e = 1 - \dfrac{|Q_C|}{|Q_H|}$ $\cdots$

⇒ $$e \equiv 1 - \frac{|Q_C|}{|Q_H|} = 1 - \frac{T_C}{T_H}$$ (T must be in K)

(Carnot Cycle only)

Efficiency of the Carnot Cycle

$$e_{carnot} = 1 - \frac{T_C}{T_H} \quad \text{(Carnot Cycle)}$$

General Comments:

- Higher efficiency if either T_C is lower and/or T_H is higher.
- For any *realistic* thermal process, the cold reservoir is far above absolute zero, i.e., $T_C > 0$.
- Thus, a *realistic e* is *strictly less* than 1! (No 100% efficient heat engine)
- *Realistic* heat engines must take in energy from the high T reservoir for the work that it produces AND some heat energy must be *released* back to the lower T reservoir.

(Kelvin-Planck's Statement)

skip

Entropy

$dS \equiv \frac{dQ}{T}$ and $\oint_{cycle} dS = \frac{dQ_r}{T} = 0$ $[S] = J/K$

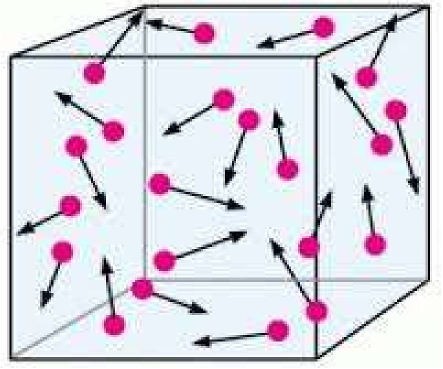
This state variable S is called the **entropy** of the system.

Entropy is macroscopic variable describing the degree of disorder of the system.

Entropy: Disorder (General Reversible Process)

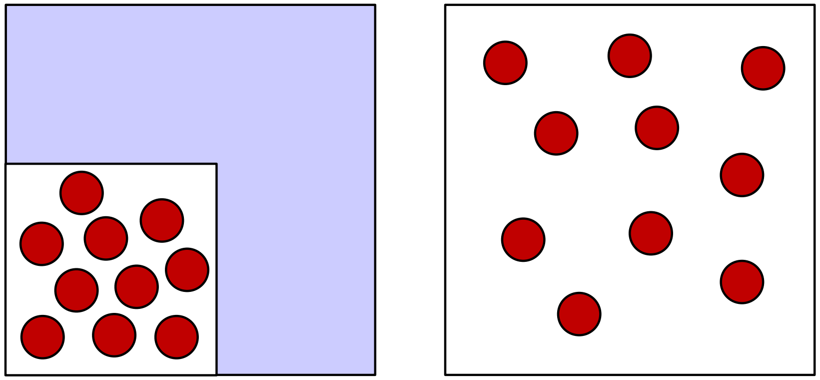
In our discussion of ΔS for an ideal gas through a general reversible process, we just derived the following relation,

$$dS = \frac{dQ_r}{T} = \frac{nC_V dT}{T} + nR\frac{dV}{V}$$



$$\frac{dT}{T}\uparrow \quad \Rightarrow \quad S\uparrow$$

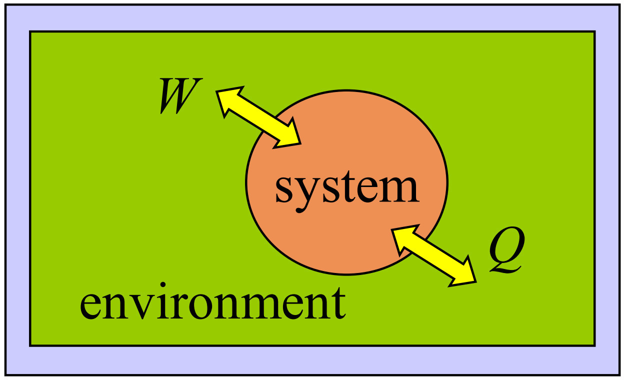
Thermal agitations



$$\frac{dV}{V}\uparrow \quad \Rightarrow \quad S\uparrow$$

Availability of space

2nd Law (Quantitative Form)



$$\Delta S_{tot} = \Delta S_{sys} + \Delta S_{env} \geq 0$$

$$(\Delta S_{tot} = 0 \quad reversible; \quad \Delta S_{tot} > 0 \quad irreversible)$$

“The *total* entropy (disorder) of an *isolated* system in any processes can never decrease.”

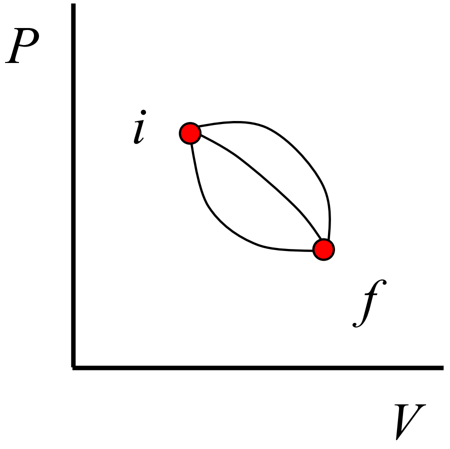
“Nature always tends toward a state with the highest S (disorder) [most probable] in any processes.”

Entropy Changes for Different Processes

1. General *Reversible* Processes:

$$\Delta S = \int_i^f dS = \int_i^f \frac{dQ_r}{T}$$

Note: S is a *state variable*, ΔS is the *same* for *all* processes (including irreversible ones) with the same initial and final states!



NOTE: in most applications, it is the change in entropy ΔS which one typically needs to calculate and not S itself.

Entropy Changes for Different Processes

2. Reversible Cycles:

$$\Delta S_{cycle} = \oint_{cycle} ds = \oint_{cycle} \frac{dQ_r}{T} = 0$$

3. Any Reversible Processes for an Idea Gas:

$$\Delta S = nC_V \ln\left(\frac{T_f}{T_i}\right) + nR\ln\left(\frac{V_f}{V_i}\right)$$

Entropy Changes for Different Processes

4. Calorimetric Changes:

$$dQ = mcdT$$

$$\Delta S = \int_i^f \frac{dQ}{T} = \int_i^f \frac{mcdT}{T}$$

If c is constant within temperature range, $\Delta S = mc\ln\left(\frac{T_f}{T_i}\right)$

If $c(T)$ is a function of T, $\Delta S = m\int_i^f \frac{c(T)dT}{T}$

Entropy Changes for Different Processes

5. During Phase Changes (or other isothermal Processes):

$$\Delta S = \int \frac{dQ}{T} = \frac{1}{T}\int dQ$$

(*T* stays constant during a phase change.)

$$\Delta S = \frac{Q}{T} = \frac{mL}{T}$$