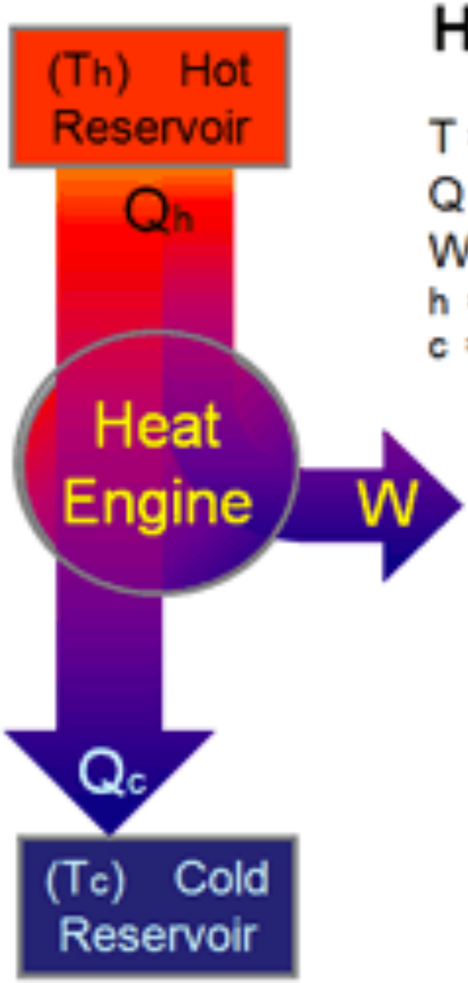
# College Physics I: 1511 Mechanics & Thermodynamics


Professor Jasper Halekas

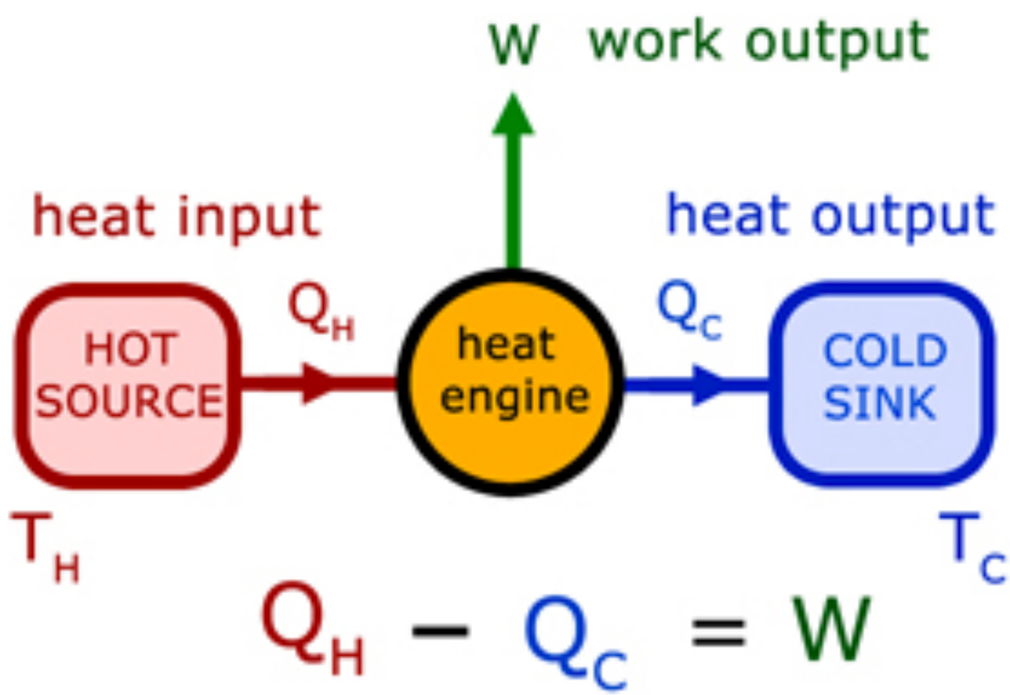
Van Allen Lecture Room 1
MWF 8:30-9:20 Lecture

# Heat Engines

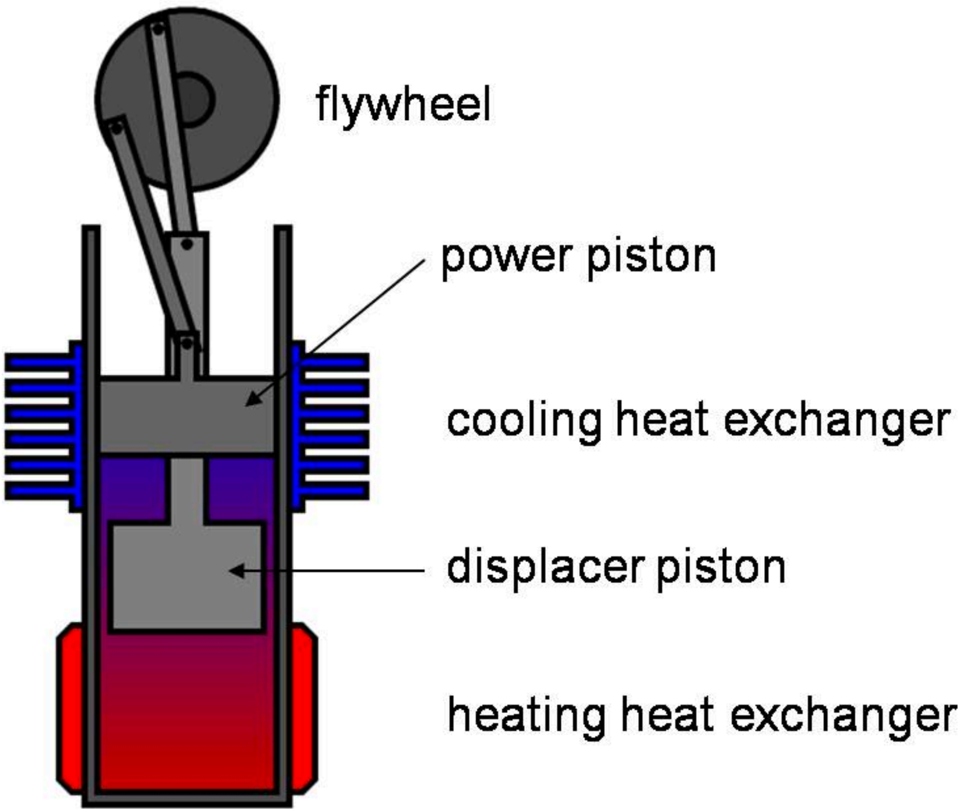


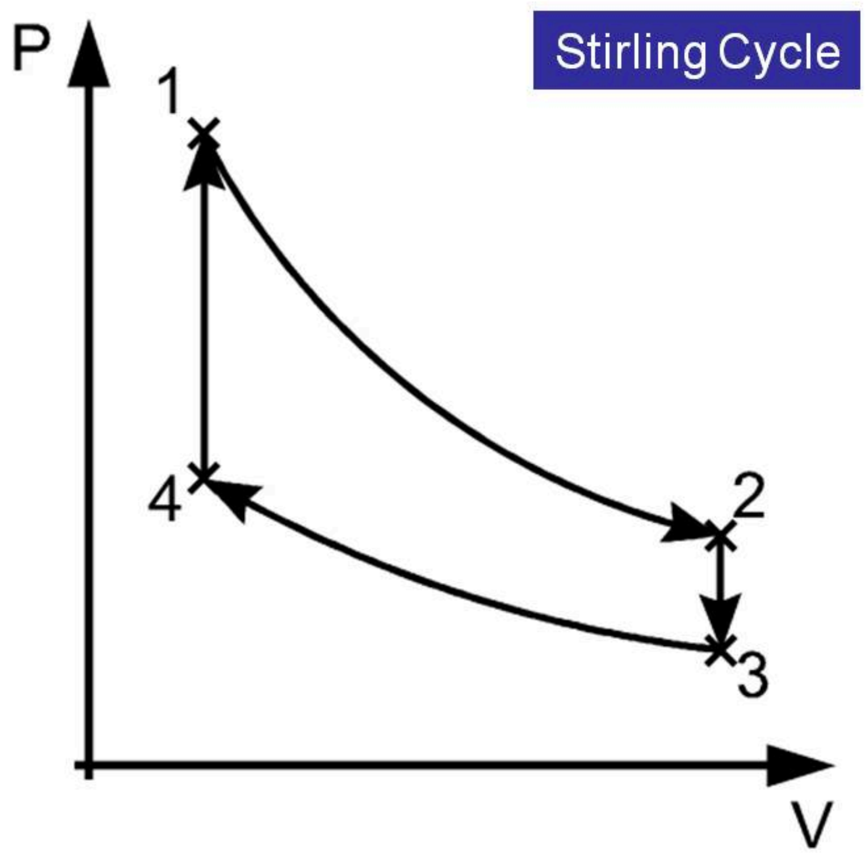

### Heat Engine

T = Temperature (°K)
Q = Heat (J)
W = Work (J)
h = hot
c = cold

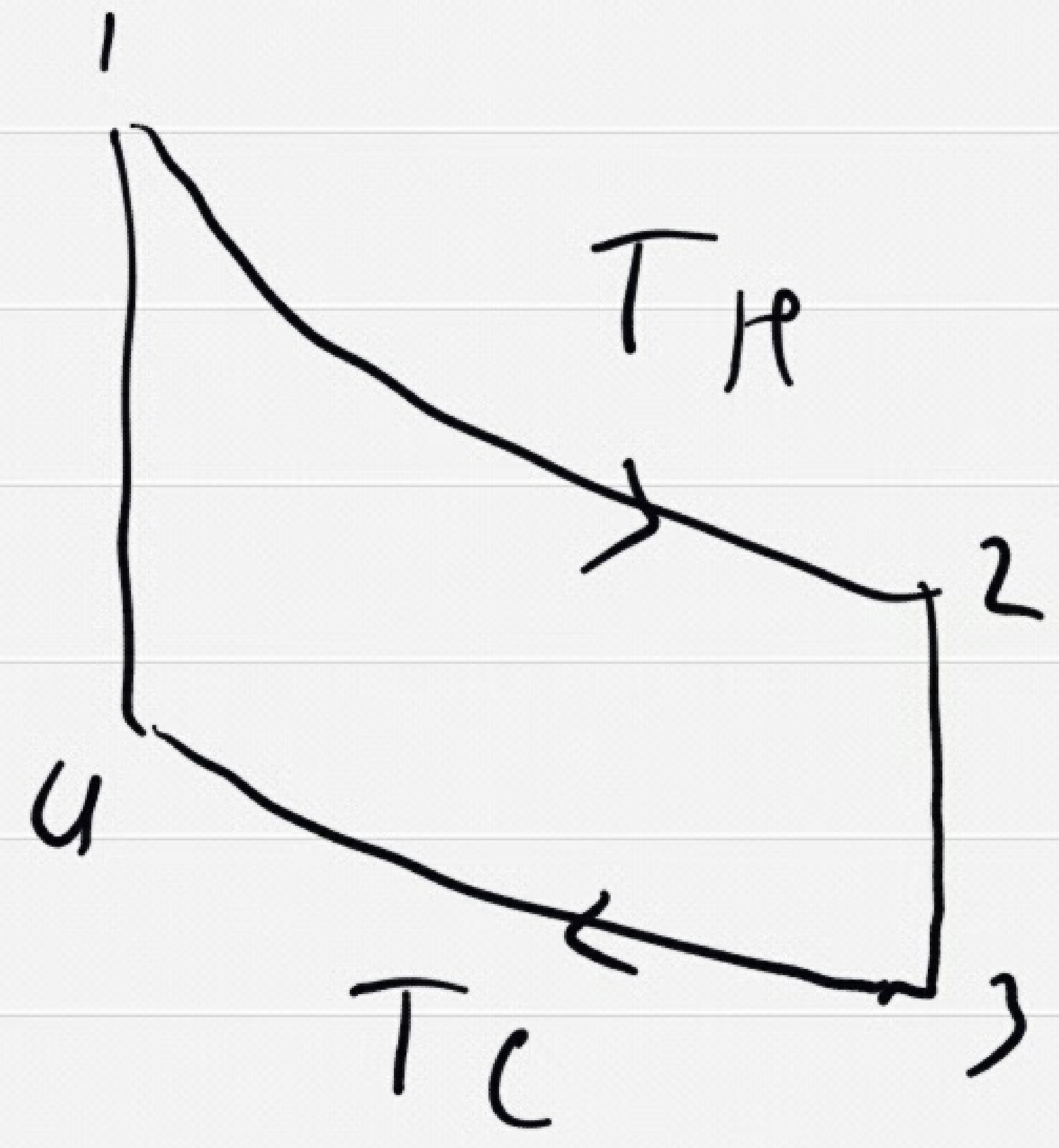


# Stirling Engine



# Stirling Cycle




$W_{23} = W_{41} = 0$

$$W_{12} = nRT_H \ln\left(V_{23}/V_{14}\right)$$
$$= Q_H > 0$$

$$W_{34} = nRT_C \ln\left(V_{14}/V_{23}\right)$$
$$= Q_C < 0$$

$$W_{tot} = W_{12} + W_{34}$$
$$= Q_H + Q_C$$
$$= |Q_H| - |Q_C|$$

$$\varepsilon = W / |Q_H| = \frac{|Q_H| - |Q_C|}{|Q_H|}$$

$$= 1 - |Q_C| / |Q_H|$$

But $|Q_H| = nRT_H \left| \ln \left( V_{23} / V_{41} \right) \right|$

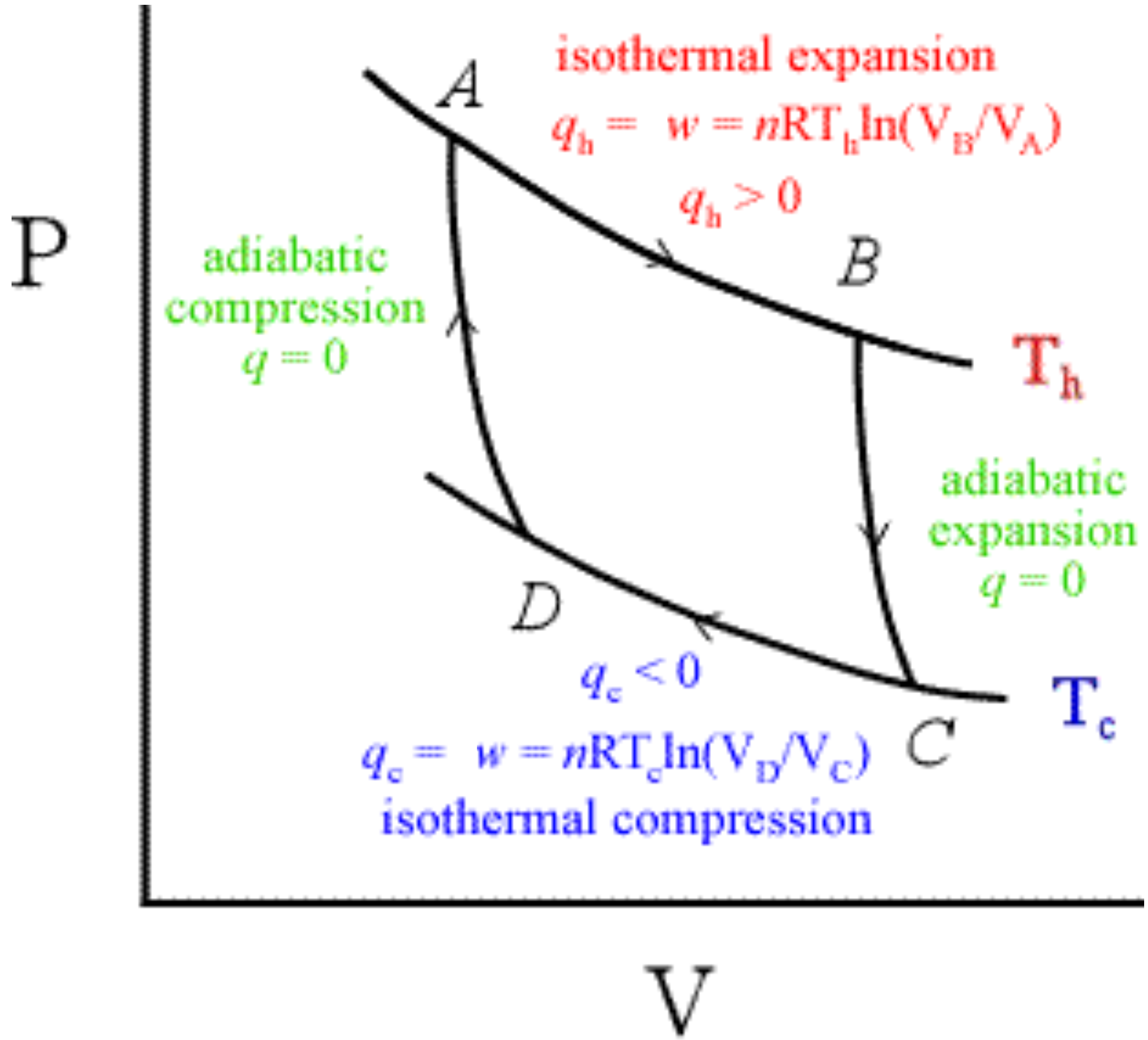
$$|Q_C| = nRT_C \left| \ln \left( V_{14} / V_{23} \right) \right|$$
$$= nRT_C \left| \ln \left( V_{23} / V_{14} \right) \right|$$

$$|Q_C| / |Q_H| = \frac{nRT_C}{nRT_H}$$

$$= T_C / T_H$$

$$\varepsilon = \frac{T_H - T_C}{T_H} = 1 - T_C / T_H$$

# Work and Heat: Carnot Cycle



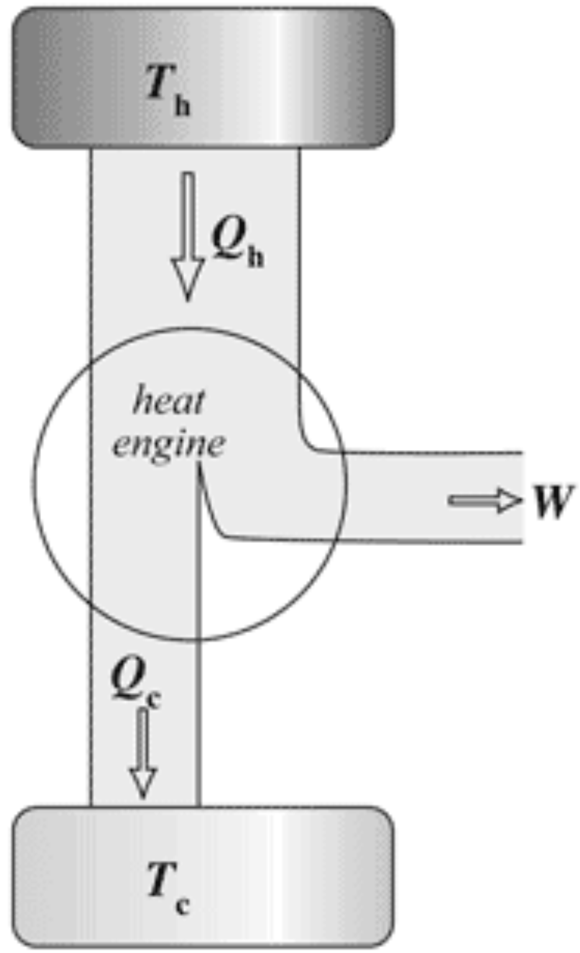
# Heat Engine Efficiency

$$\varepsilon = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h}$$

$$\varepsilon = \frac{T_h - T_c}{T_h} = 1 - \frac{T_c}{T_h}$$

*(with heat input and output occuring at fixed temperatures)*

$\varepsilon$ = thermal efficiency
$W$ = net work
$Q_h$ = heat flow in
$Q_c$ = heat flow out
$T_h$ = hot sink temperature
$T_c$ = cold sink temperature



# Heat Engine Efficiency

- For a reversible cycle the efficiency is $(T_H - T_C)/T_H$
- The only way this efficiency could be 100% is if $T_C$=0 Kelvin (absolute zero)
  - Efficiency of 100% would imply complete conversion of input heat to output work
  - Since it's not possible to reach absolute zero, it's not possible to have a 100% efficient heat engine

# Second Law of Thermodynamics

**2nd Law of Thermodynamics:**

1. Heat flows spontaneously from a hot body to a cool one.
2. One cannot convert heat completely into useful work.
3. Every isolated system becomes disordered in time.

**Another statement of the second law of thermodynamics:**

**The total entropy of an isolated system never decreases.**

# Entropy

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

True only for a reversible process!

# Concept Check

- A gas, confined to an insulated cylinder, is compressed adiabatically (and reversibly) to half its original volume. Does the entropy of the gas increase, decrease, or remain unchanged during this process?

- 1) increase
- 2) decrease
- 3) remain unchanged

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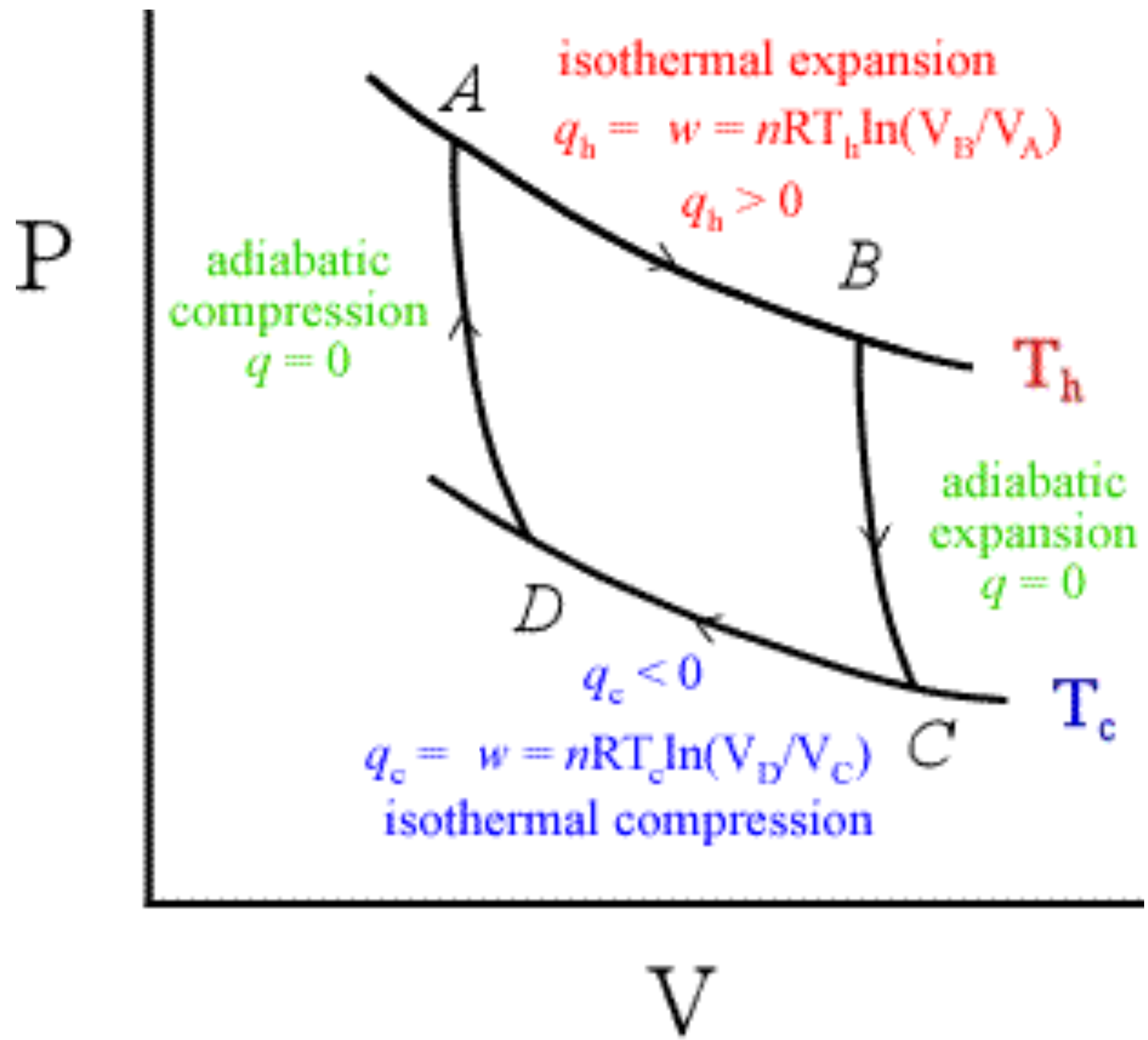
# Work and Heat: Carnot Cycle



# Carnot Cycle Entropy

$\Delta S = 0$ on $B \to C$
and $D \to A$

$$\Delta S_{AB} = Q_H / T_H$$

$$= nRT_H \ln(V_B/V_A) / T_H$$

$$= nR \ln(V_B/V_A)$$

$$\Delta S_{CD} = nR \ln(V_D/V_C)$$
$$= -nR \ln(V_C/V_D)$$

$$\Delta S = nR \left[ \ln(V_B/V_A) - \ln(V_C/V_D) \right]$$

$PV^{\gamma} = \text{const.}$
but $PV = nRT$
$\Rightarrow nRT \cdot V^{\gamma-1} = \text{const.}$

so $T_H V_B^{\gamma-1} = T_C V_C^{\gamma-1}$
$T_H V_A^{\gamma-1} = T_C V_D^{\gamma-1}$

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$$(V_B/V_A)^{\gamma-1} = (V_C/V_D)^{\gamma-1}$$

$$V_B/V_A = V_C/V_D$$

$$\Rightarrow \boxed{\Delta S = 0}$$

# Total Entropy in Carnot Cycle

## Carnot Cycle, Entropy $\Delta S = 0$

- Heat is exchanged in the isothermal portions:

  $Q_h = \Delta E_{int} - W_{AB} = nRT_h \ln(V_B/V_A)$

  $Q_c = nRT_c \ln(V_C/V_D)$

- So entropy is also changed:

  $\Delta S = +Q_h/T_h - Q_c/T_c$

  $= R\ln\{(V_B V_D)/(V_A V_C)\}$

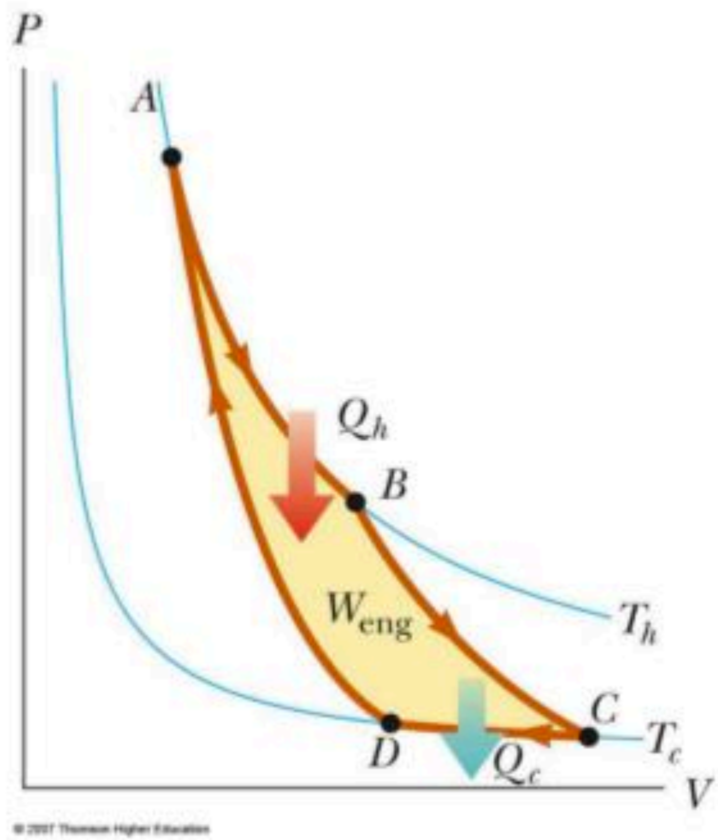
- For the adiabatic portions

  $T_h V_B^{\gamma-1} = T_c V_C^{\gamma-1}$
  $T_h V_A^{\gamma-1} = T_c V_D^{\gamma-1}$
  $\rightarrow V_B/V_A = V_C/V_D$

  Therefore,

  $\ln\{(V_B V_D)/(V_A V_C)\} = 0$

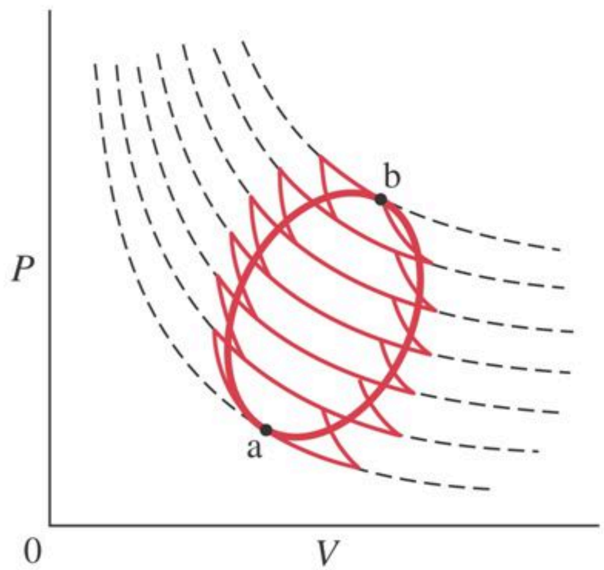
→ So $\Delta S = 0$ as expected for a reversible cycle.



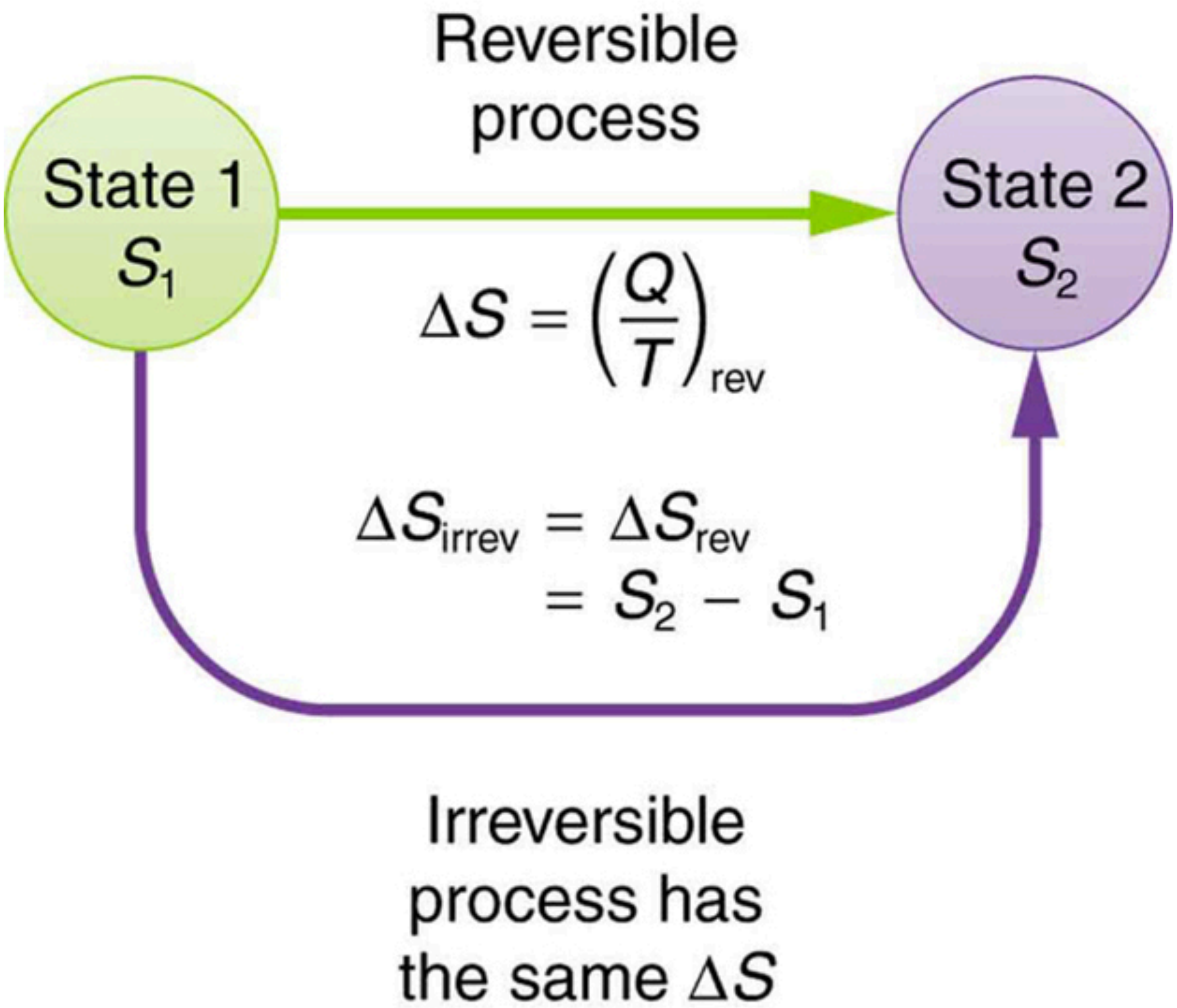
# Total Entropy in Reversible Cycles

## Entropy

**Any reversible cycle can be written as a succession of Carnot cycles; therefore, what is true for a Carnot cycle is true of all reversible cycles.**



# Computing Change in Entropy for Irreversible System



# Concept Check

- Consider all possible isothermal contractions of an ideal gas. The change in entropy of the gas:

- 1) is zero for all of them
- 2) is not negative for any of them
- 3) is not positive for any of them
- 4) is positive for all of them
- 5) is negative for all of them

# Concept Check

- Consider all possible isothermal contractions of an ideal gas. The change in entropy of the gas:

- 1) is zero for all of them
- 2) is not negative for any of them
- 3) is not positive for any of them
- 4) is positive for all of them
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# Concept Check

A hot object and a cold object are placed in thermal contact and the combination is isolated. They transfer energy until they reach a common temperature. The change $\Delta S_h$ in the entropy of the hot object, the change $\Delta S_c$ in the entropy of the cold object, and the change $\Delta S_{total}$ in the entropy of the combination are:

1) $\Delta S_h > 0$, $\Delta S_c > 0$, $\Delta S_{total} > 0$
2) $\Delta S_h < 0$, $\Delta S_c > 0$, $\Delta S_{total} > 0$
3) $\Delta S_h < 0$, $\Delta S_c > 0$, $\Delta S_{total} < 0$
4) $\Delta S_h > 0$, $\Delta S_c < 0$, $\Delta S_{total} > 0$
5) $\Delta S_h > 0$, $\Delta S_c < 0$, $\Delta S_{total} < 0$

# Concept Check

A hot object and a cold object are placed in thermal contact and the combination is isolated. They transfer energy until they reach a common temperature. The change $\Delta S_h$ in the entropy of the hot object, the change $\Delta S_c$ in the entropy of the cold object, and the change $\Delta S_{total}$ in the entropy of the combination are:

1) $\Delta S_h > 0$, $\Delta S_c > 0$, $\Delta S_{total} > 0$
2) $\Delta S_h < 0$, $\Delta S_c > 0$, $\Delta S_{total} > 0$
3) $\Delta S_h < 0$, $\Delta S_c > 0$, $\Delta S_{total} < 0$
4) $\Delta S_h > 0$, $\Delta S_c < 0$, $\Delta S_{total} > 0$
5) $\Delta S_h > 0$, $\Delta S_c < 0$, $\Delta S_{total} < 0$

$$Q_H = -Q_C$$

$$\Delta S_H = Q_H / T_H = -Q_C / T_H$$

$$\Delta S_C = Q_C / T_C$$

$$\Delta S = Q_C / T_C + Q_H / T_H$$

$$= Q_C / T_C - Q_C / T_H$$

$$= Q_C \left( 1/T_C - 1/T_H \right)$$

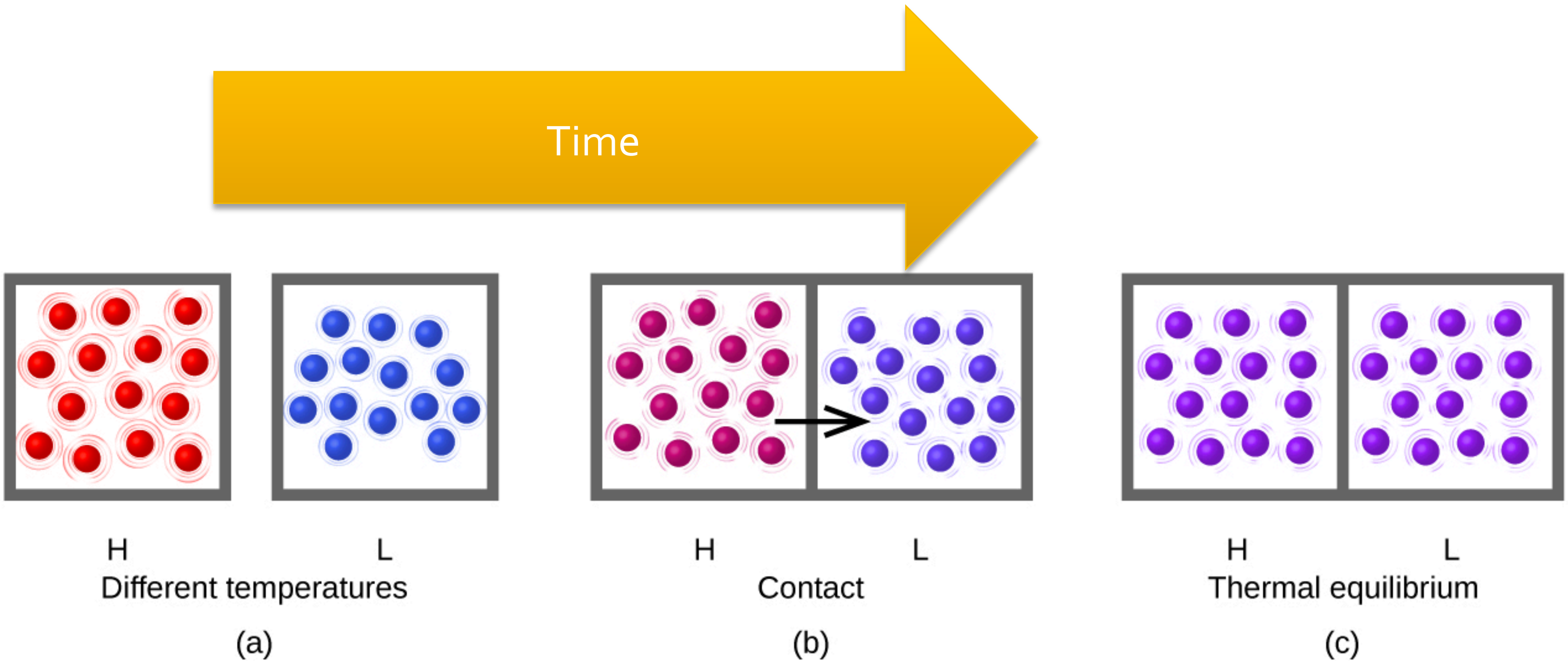
$$> 0$$

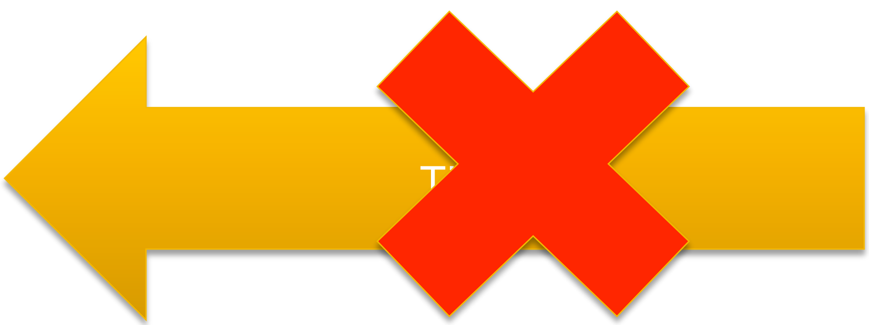
since $1/T_C > 1/T_H$
if $T_H > T_C$

# Heat Transfer and Entropy

- The heat Q transferred from the hot item is equal to the heat Q added to the cold item
- For any given increment of heat:
  - $\Delta S_H = -Q/T_H$ (negative since heat lost)
  - $\Delta S_C = +Q/T_C$ (positive since heat gained)
  - $\Delta S = Q/T_C - Q/T_H$ (positive: $T_H > T_C$ so $1/T_C > 1/T_H$)

# Entropy & Time's Arrow



Both directions conserve energy (1st law), but only one increases entropy (2nd law)