PHYN001

Cairo University, Faculty of Engineering

Credit Hours System

Fall 2016

Unit 09 Heat Engines, Entropy and The Second Law

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Reference

Serway, Raymond A. and Jewett, John W. *Physics for scientists and engineers with modern physics*. 9th Ed.

Heat Engines, Entropy and The Second Law

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Heat Engines, Entropy and The Second Law

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INTRODUCTION

- First law of thermodynamics:

$$\Delta E_{int} = Q - W$$

No distinction between the two forms of energy: heat and work.

- However, thermodynamic processes proceed naturally in one direction but not the opposite
- This has to do with the directions of thermodynamic processes and is called the second law of thermodynamics.

HEAT ENGINES, ENTROPY AND THE SECOND LAW

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HEAT ENGINES AND THE SECOND LAW OF THERMODYNAMICS

Heat engine

– Any device that transforms heat partly into work or mechanical energy.

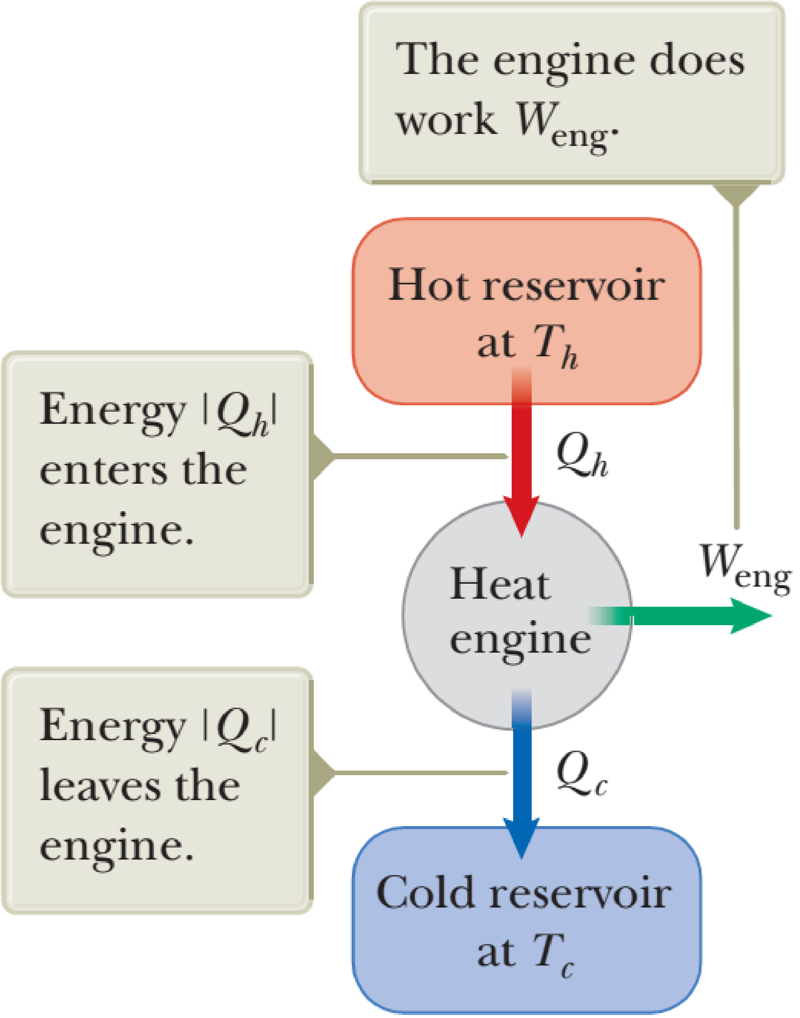
- **Examples**:
  – A power plant produces electricity
  – The internal combustion engine in an automobile

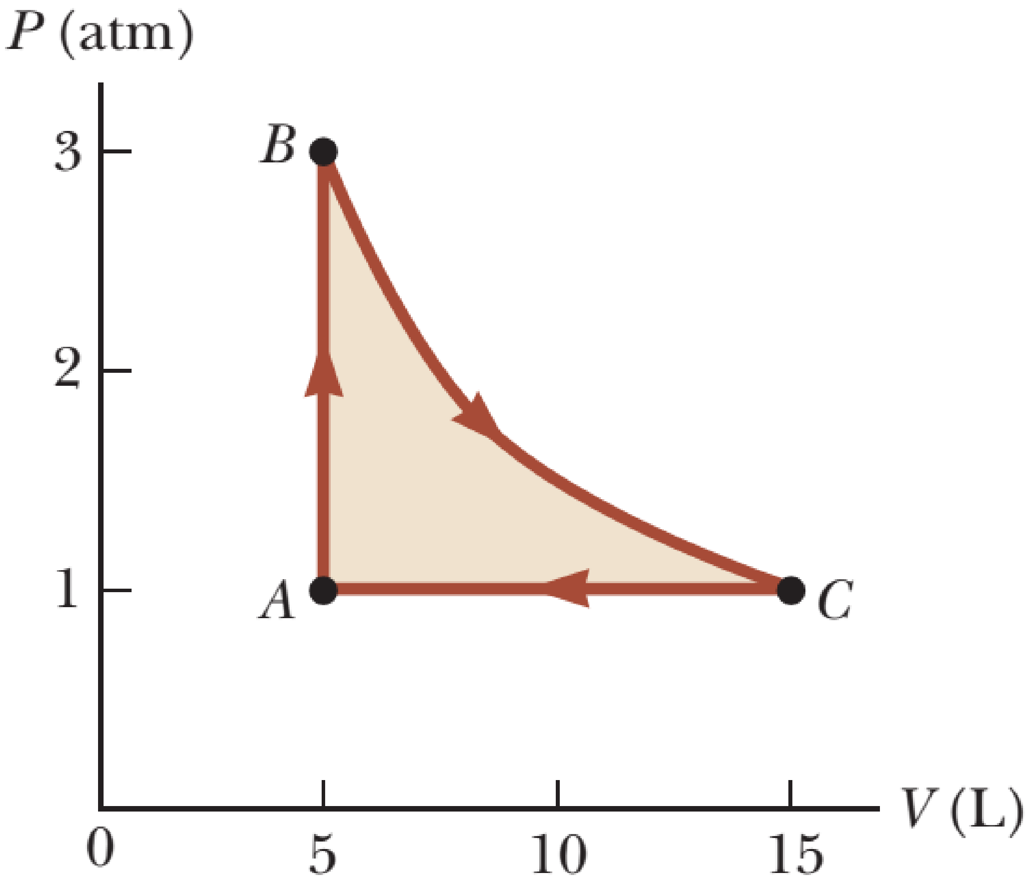
Heat Engines and The Second Law of Thermodynamics

A heat engine carries a quantity of matter (working substance) through a cyclic process during which

1. the working substance absorbs energy by heat from a high-temperature energy reservoir,
2. work is done by the engine,
3. energy is expelled by heat to a lower-temperature reservoir.

Heat Engines and The Second Law of Thermodynamics





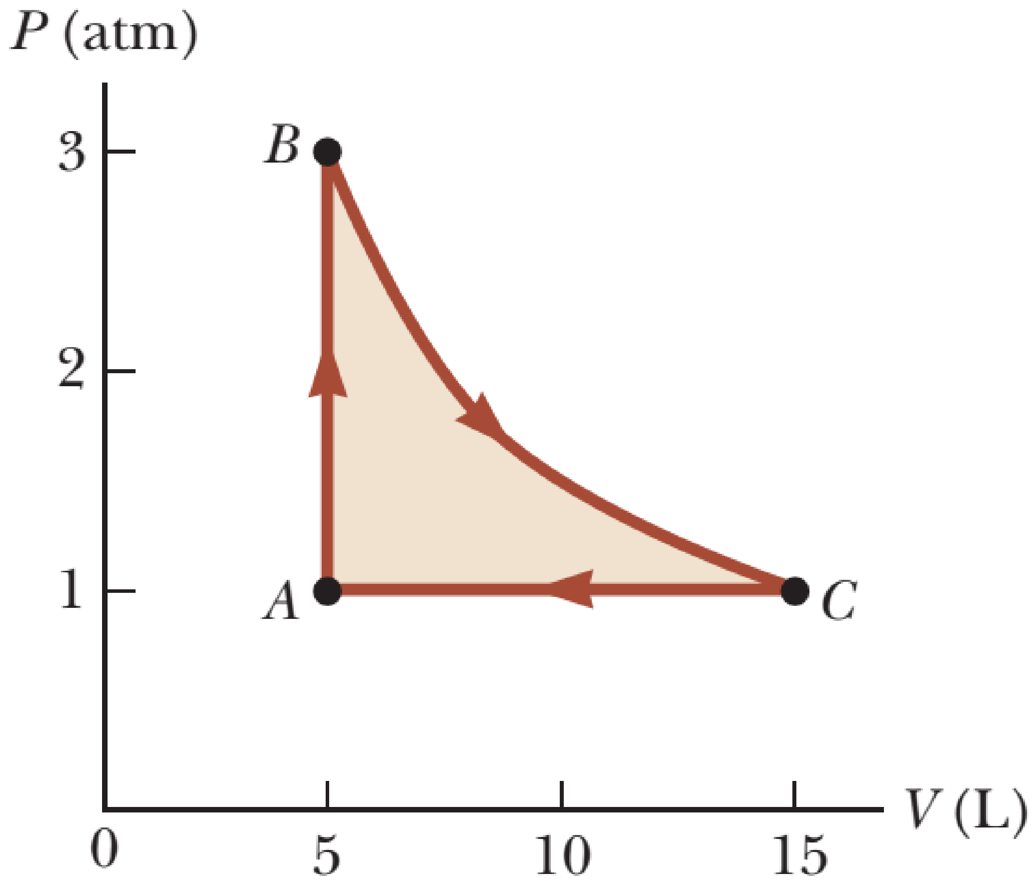
Heat Engines and The Second Law of Thermodynamics

In any cyclic process

$$\Delta E_{int} = Q - W_{eng} = 0$$

$$Q = |Q_h| - |Q_c|$$

$$\therefore W_{eng} = |Q_h| - |Q_c|$$



HEAT ENGINES AND THE SECOND LAW OF THERMODYNAMICS

Thermal efficiency e of a heat engine

- The ratio of the work done by the engine in one cycle to the energy input at the higher temperature during the cycle:

$$e = \frac{W_{eng}}{|Q_h|} = \frac{|Q_h| - |Q_c|}{|Q_h|} = 1 - \frac{|Q_c|}{|Q_h|}$$

In practice, $e < 100\%$

- For a good automobile engine, $e \approx 20\%$
- For a diesel engine, $e \approx 35\% - 40\%$

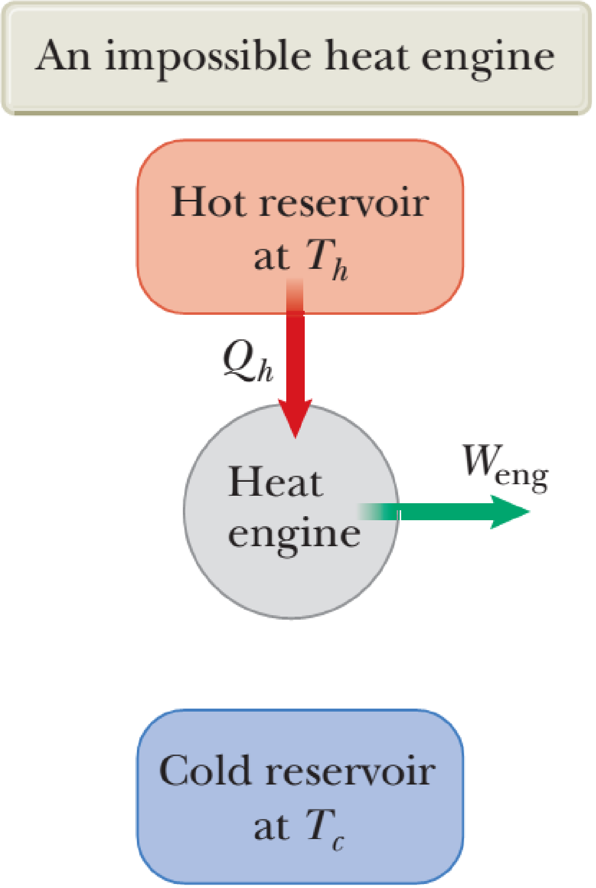
HEAT ENGINES AND THE SECOND LAW OF THERMODYNAMICS

$$e = 1 - \frac{|Q_c|}{|Q_h|}$$

$e = 100\%$ only if $|Q_c| = 0$

That is no energy is expelled to the cold reservoir and expels all of the input energy by work.

Impossible



Heat Engines and The Second Law of Thermodynamics

Kelvin–Planck form of the second law of thermodynamics:

It is impossible to construct a heat engine that, operating in a cycle, produces no effect other than the input of energy by heat from a reservoir and the performance of an equal amount of work.

$$W_{eng} \neq |Q_h|$$

$$Q_c \neq 0$$

Heat Engines, Entropy and The Second Law

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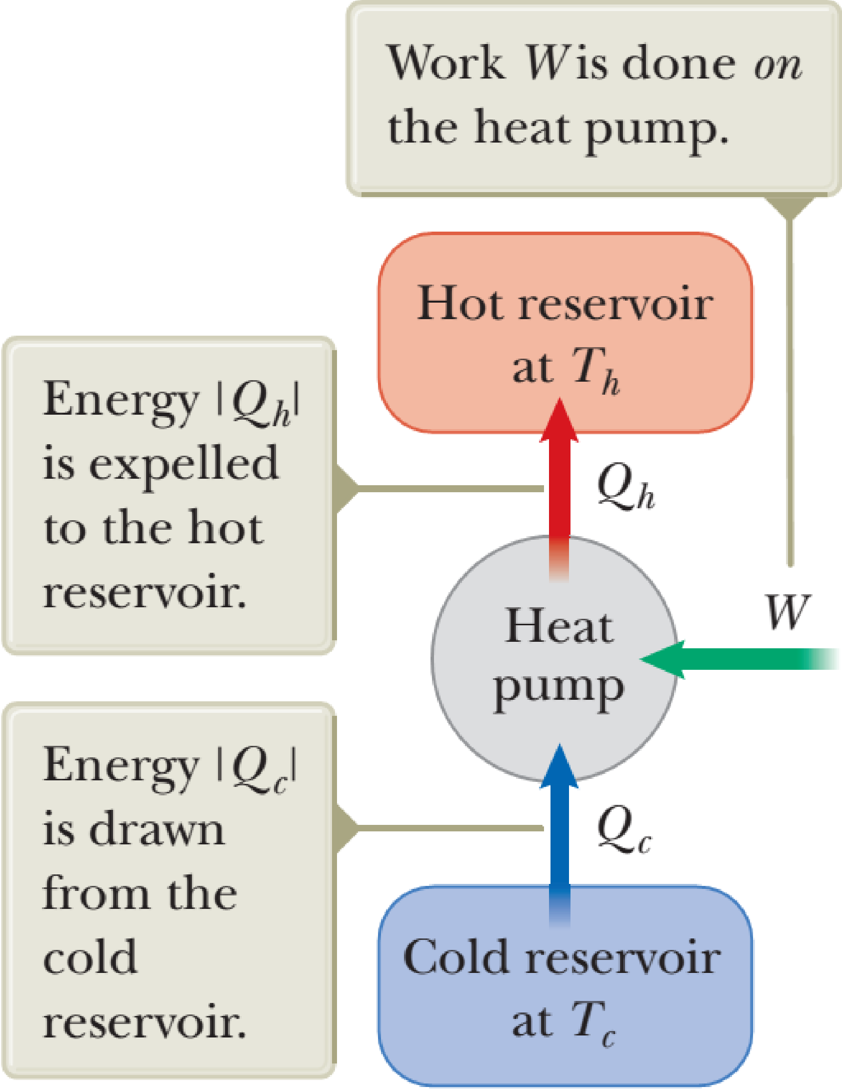
Heat Pumps and Refrigerators

Devices that transfer energy from the cold reservoir to the hot reservoir.

- Air conditioners
- Refrigerators

Can be accomplished only if work is done on the engine.



Heat Pumps and Refrigerators

Clausius form of the second law of thermodynamics:

It is impossible to construct a cyclical machine whose sole effect is to transfer energy continuously by heat from one object to another object at a higher temperature without the input of energy by work.

$$|Q_h| \neq |Q_c|$$

$$W_{eng} \neq 0$$

HEAT PUMPS AND REFRIGERATORS

Coefficient of performance (COP)

$$COP_{heating} = \frac{|Q_h|}{W}$$

$$COP_{cooling} = \frac{|Q_c|}{W}$$

HEAT ENGINES, ENTROPY AND THE SECOND LAW

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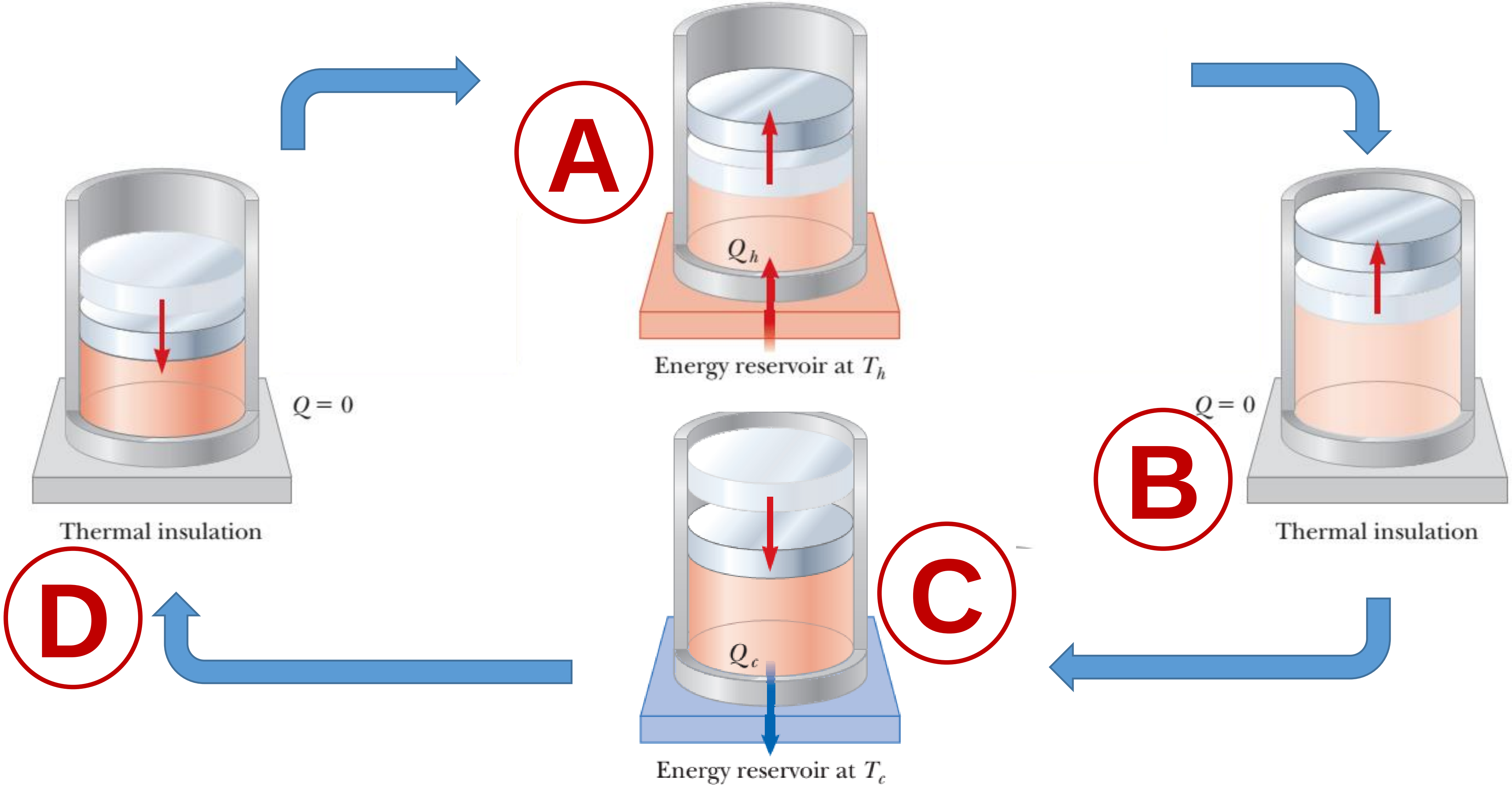
The Carnot Engine

A theoretical engine operating in ideal, reversible cycle between two energy reservoirs, that is the most efficient engine possible.

- Establishes an upper limit on efficiency for any real heat engine operating between the same two heat reservoirs.

The Carnot Engine



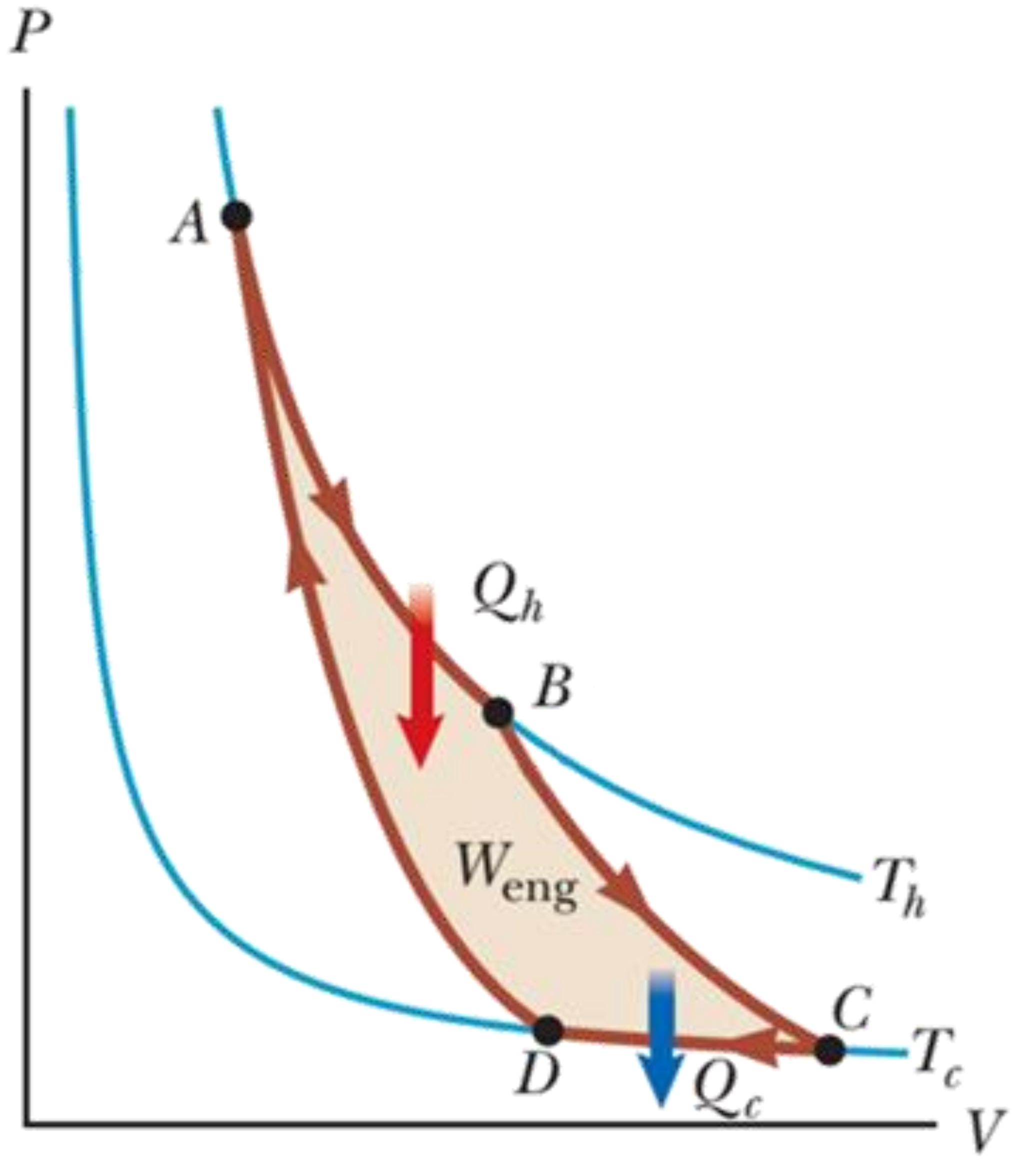
The Carnot Engine

$$e_{Carnot} = 1 - \frac{|Q_c|}{|Q_h|}$$

$$|Q_h| = nRT_h \ln(V_B/V_A)$$

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

$$\therefore e_{Carnot} = 1 - \frac{T_c}{T_h}\frac{\ln(V_C/V_D)}{\ln(V_B/V_A)}$$



The Carnot Engine

$$e_{Carnot} = 1 - \frac{T_c}{T_h}\frac{\ln(V_C/V_D)}{\ln(V_B/V_A)}$$

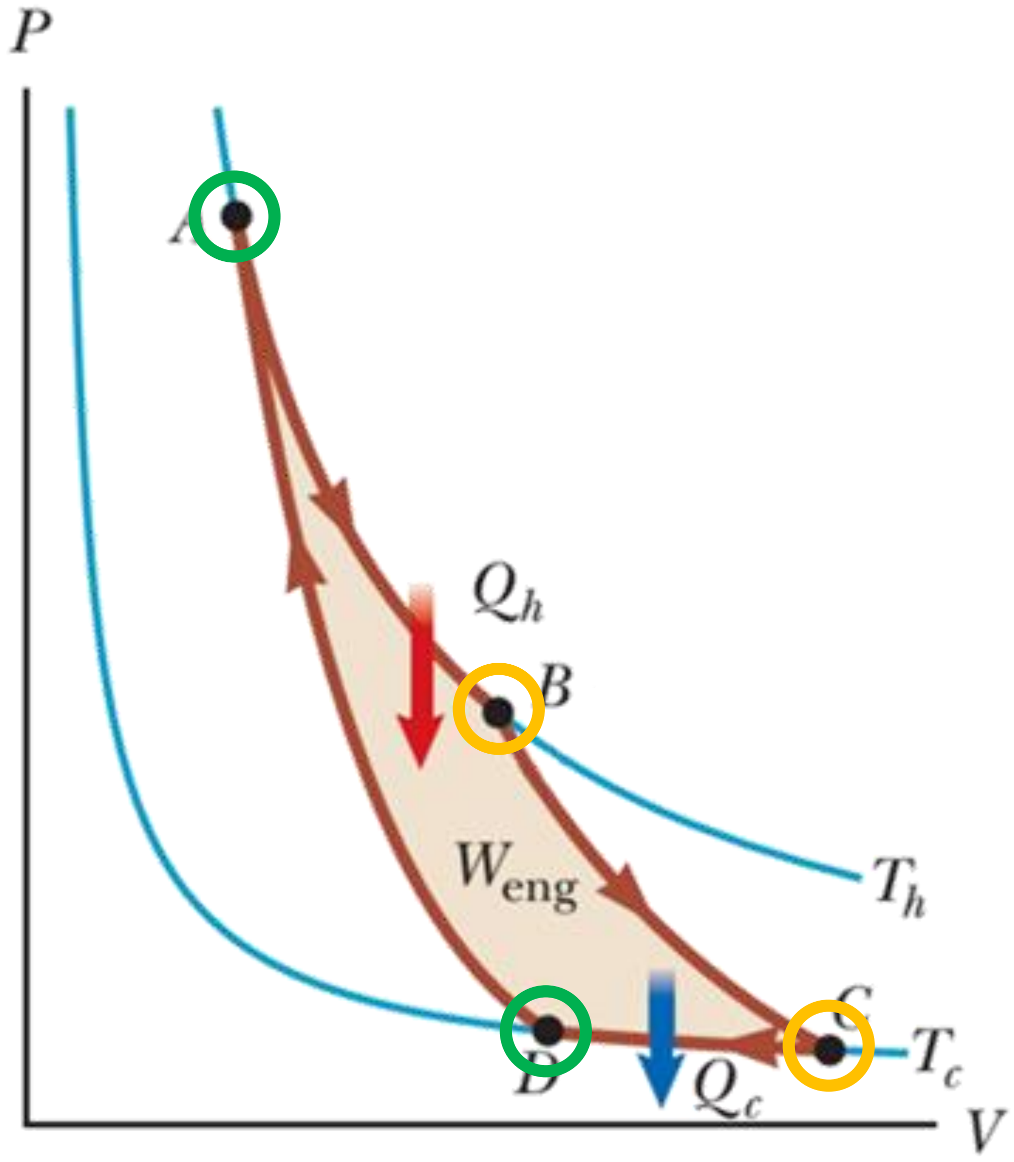
Adiabatic: $TV^{\gamma-1}$ =Const

$$\therefore T_h V_B^{\gamma-1} = T_c V_C^{\gamma-1}$$

$$\& \; T_h V_A^{\gamma-1} = T_c V_D^{\gamma-1}$$

$$\therefore V_B/V_A = V_C/V_D$$

$$\therefore e_{Carnot} = 1 - \frac{T_c}{T_h}$$



THE CARNOT ENGINE

If Carnot is operating in reverse order

$$COP_{heating} = \frac{T_h}{T_h - T_c}$$

$$COP_{cooling} = \frac{T_c}{T_h - T_c}$$

HEAT ENGINES, ENTROPY AND THE SECOND LAW

Contents

- ✓ Introduction
- ✓ Heat Engines and the Second Law of Thermodynamics
- ✓ Heat Pumps and Refrigerators
- ✓ The Carnot Engine
- ❑ Entropy

ENTROPY

- Entropy (S) is a state variable related to disorder in system.
  - State variables: $P, V, T, \Delta E_{int}, \boldsymbol{S}$
- The entropy of an isolated system tends to increase.

You can rephrase Second Law of Thermodynamics as:

> The entropy of the Universe increases in all real processes.

ENTROPY

- The original formulation of entropy in thermodynamics involves the transfer of energy by heat during a reversible process.
- Consider any infinitesimal process in which a system changes from one equilibrium state to another with dQ_r transferred by heat to the system

$$\boldsymbol{dS = \frac{dQ_r}{T}}$$

Entropy

Example: A solid that has a latent heat of fusion L_f melts at a temperature T_m . Calculate the change in entropy of this substance when a mass m of the substance melts.

Solution

$$dS = \frac{dQ_r}{T} \quad \Rightarrow \Delta S = \int \frac{dQ}{T}$$

$$T = T_m$$

$$\Delta S = \frac{1}{T_m} \int dQ \quad = \frac{mL_f}{T_m}$$

Entropy

Reversible Constant Volume Process

$$\Delta S = \int_i^f \frac{nC_V dT}{T} = nC_V \ln \frac{T_f}{T_i}$$

Reversible Constant Pressure Process

$$\Delta S = \int_i^f \frac{nC_P dT}{T} = nC_P \ln \frac{T_f}{T_i}$$

ENTROPY

Reversible Isothermal Process

$$\Delta S = \frac{1}{T}\int_i^f dQ_r = nR \ln \frac{V_f}{V_i}$$

Reversible Adiabatic Process

$$\Delta S = 0$$

ENTROPY

ΔS of an ideal gas during any reversible process can be calculated from the equation

$$\Delta S = \int_i^f \frac{dQ_r}{T} = \int_i^f \frac{dE_{int} + dW}{T}$$

$$\Delta S = \int_i^f \frac{nC_V dT + PdV}{T}$$

$$\Delta S = \int_i^f \left\{ \frac{nC_V dT}{T} + \frac{nRdV}{V} \right\}$$

Entropy

ΔS of an ideal gas during any reversible process can be calculated from the equation

$$\Delta S = \int_i^f \left\{ \frac{nC_V dT}{T} + \frac{nRdV}{V} \right\}$$

$$\Delta S = nC_V \int_i^f \frac{dT}{T} + nR \int_i^f \frac{dV}{V}$$

$$\therefore \Delta S = nC_V \ln \frac{T_f}{T_i} + nR \ln \frac{V_f}{V_i}$$

Heat Engines, Entropy and The Second Law

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THE KINETIC THEORY OF GASES

Process	Isobaric	Isovolumetric	Isothermal	Adiabatic
Relation	$P = Const$	$V = Const$	$T = Const$	$Q = 0$
$\boldsymbol{\frac{PV}{T} = Const}$	$\frac{V}{T} = Const$	$\frac{P}{T} = Const$	$PV = Const$	$PV^{\gamma} = Const$ $TV^{\gamma-1} = Const$
$\boldsymbol{\Delta E_{int} = Q - W}$	$nC_V \Delta T$	$nC_V \Delta T$	0	$nC_V \Delta T$
$\boldsymbol{S}$	$nC_P \ln(T_f/T_i)$	$nC_V \ln(T_f/T_i)$	$nR \ln(V_f/V_i)$	0
$\boldsymbol{W}$	$P(V_f - V_i)$	0	$nRT \ln \frac{V_f}{V_i}$	$-\Delta E_{int}$
$\boldsymbol{Q}$	$nC_P \Delta T$	ΔE_{int}	W	0