Fundamentals Physics

Eleventh Edition

Halliday

Chapter 20

Entropy and the Second Law of Thermodynamics

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20-1 Entropy (1 of 6)

Learning Objectives

20.01 Identify the second law of thermodynamics: If a process occurs in a closed system, the entropy of the system increases for irreversible processes and remains constant for reversible processes; it never decreases.

20.02 Identify that entropy is a state function (the value for a particular state of the system does not depend on how that state is reached).

20.03 Calculate the change in entropy for a process by integrating the inverse of the temperature (in kelvins) with respect to the heat Q transferred during the process.

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20-1 Entropy (2 of 6)

20.04 For a phase change with a constant temperature process, apply the relationship between the entropy change ΔS, the total transferred heat Q, and the temperature T (in kelvins).

20.05 For a temperature change ΔT that is small relative to the temperature T, apply the relationship between the entropy change ΔS, the transferred heat Q, and the average temperature T_{avg} (in kelvins).

20-1 Entropy (3 of 6)

20.06 For an ideal gas, apply the relationship between the entropy change ΔS and the initial and final values of the pressure and volume.

20.07 Identify that if a process is an irreversible one, the integration for the entropy change must be done for a reversible process that takes the system between the same initial and final states as the irreversible process.

20.08 For stretched rubber, relate the elastic force to the rate at which the rubber's entropy changes with the change in the stretching distance.

20-1 Entropy (4 of 6)

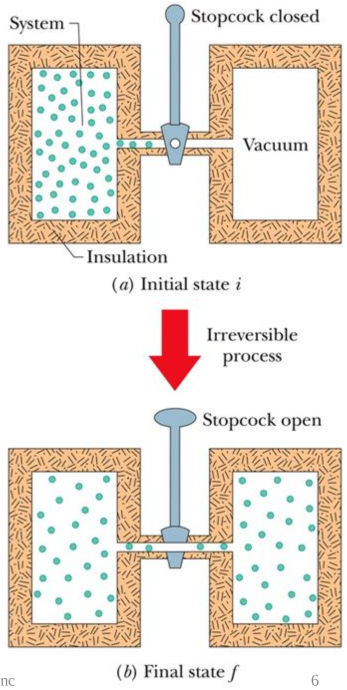
The direction of some process in nature can be reversed, while many cannot be reversed.

For irreversible process, even though the reverse process does not violate the conservation of energy (the first law of thermodynamics), however it never happens

20-1 Entropy (4 of 6)

If an irreversible process occurs in a closed system, the entropy *S* of the system always increases; it never decreases.

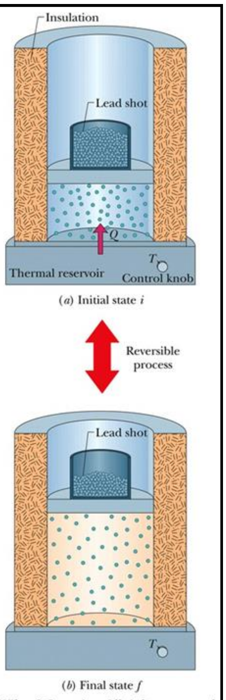
This process is irreversible; that is, it does not occur in reverse, with the gas spontaneously collecting itself in the left half of the container.



20-1 Entropy (4 of 6)

The isothermal expansion of an ideal gas, done in a reversible way.

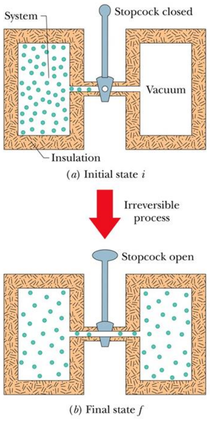
If a process occurs in a closed system, the entropy of the system **increases** for **irreversible** processes and remains **constant** for **reversible** processes.



20-1 Entropy (6 of 6)

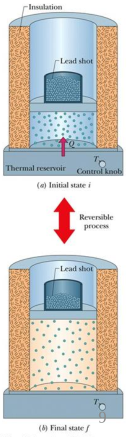
Change in Entropy

$$\Delta S = S_f - S_i = \int_i^f \frac{dQ}{T}$$



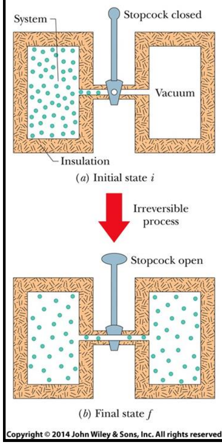
Here Q is the energy transferred as heat to or from the system during the process, and T is the temperature of the system in kelvins during the process.

To find the entropy change for an irreversible process, replace that process with any reversible process that connects the same initial and final states. Calculate the entropy change for this reversible process with the above equation.



20-1 Entropy (6 of 6)

If a process occurs in a closed system, the entropy of the system increases for irreversible processes and remains constant for reversible processes. It never decreases.



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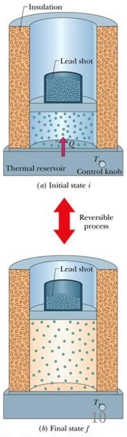
The Second Law of Thermodynamics

$$\Delta S \geq 0 \quad \text{(second law of thermodynamics)},$$

where the greater-than sign applies to irreversible processes and the equals sign to reversible processes. Equation applies only to closed systems.



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20-2 Entropy in the Real World: Engines

Learning Objectives

20.09 Identify that a heat engine is a device that extracts energy from its environment in the form of heat and does useful work.

20.10 Sketch a *p*-*V* diagram for the cycle of a Carnot engine, indicating the direction of cycling, the nature of the processes involved, the work done during each process , the net work done in the cycle, and the heat transferred during each process.

20.11 Sketch a Carnot cycle on a temperature–entropy diagram, indicating the heat transfers.

20.12 Determine the net entropy change around a Carnot cycle.

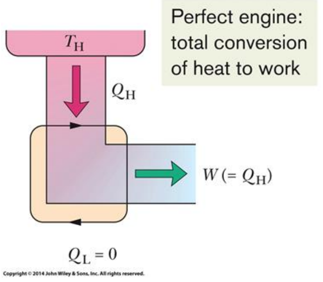
20-2 Entropy in the Real World: Engines

20.13 Calculate the efficiency ε_C of a Carnot engine in terms of the heat transfers and also in terms of the temperatures of the reservoirs.

20.14 Identify that there are no perfect engines in which the energy transferred as heat *Q* from a high temperature reservoir goes entirely into the work W done by the engine.

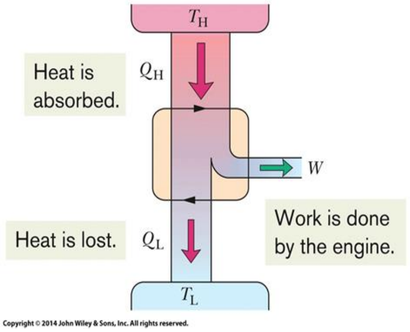
20.15 Sketch a *p-V* diagram for the cycle of a Stirling engine, indicating the direction of cycling, the nature of the processes involved, the work done during each process (including algebraic sign), the net work done in the cycle, and the heat transfers during each process.

20-2 Entropy in the Real World: Engines



Perfect engine: total conversion of heat to work

The elements of a perfect engine — that is, one that converts heat Q_H from a high-temperature reservoir directly to work *W* with 100% efficiency.



Heat is absorbed.

Heat is lost.

Work is done by the engine.

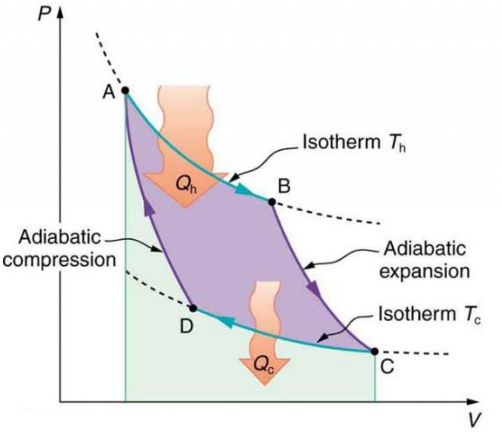
The elements of a real engine. The two black arrowheads on the central loop suggest the working substance operating in a cycle, as if on a *p-V* plot.

20-2 Entropy in the Real World: Engines

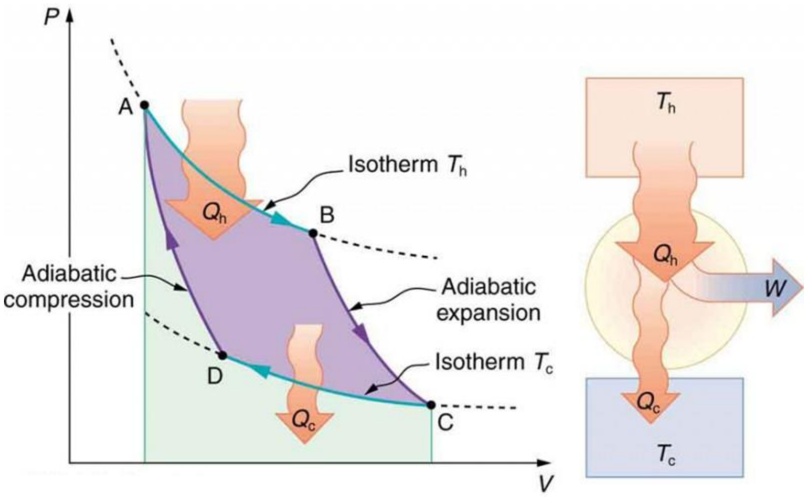
In an ideal engine, all processes are reversible and no wasteful energy transfers occur due to, say, friction and turbulence.

Carnot Engine

A pressure–volume plot (on the left) of the cycle followed by the working substance of the Carnot engine (on the right). The cycle consists of two isothermal (ab and cd) and two adiabatic processes (bc and da). The shaded area enclosed by the cycle is equal to the work W per cycle done by the Carnot engine.



20-2 Entropy in the Real World: Engines



20-2 Entropy in the Real World: Engines

No series of processes is possible whose sole result is the transfer of energy as heat from a thermal reservoir and the complete conversion of this energy to work.

Efficiency of a Carnot Engine

Efficiency of any engine:

$$\varepsilon = \frac{\text{energy we get}}{\text{energy we pay for}} = \frac{|W|}{|Q_\mathrm{H}|}$$

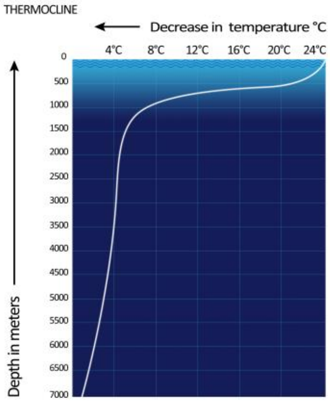
Efficiency of Carnot engine:

$$\varepsilon_C = 1 - \frac{T_\mathrm{L}}{T_\mathrm{H}}$$

20-2 Entropy in the Real World: Engines

Example : A Tropical Ocean as a Heat Engine

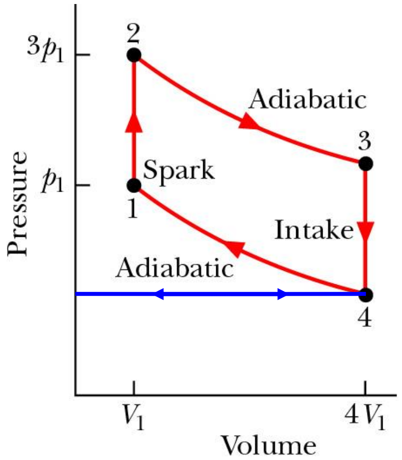
Water near the surface of a tropical ocean has a temperature of 298.2 K, whereas the water 700 meters beneath the surface has a temperature of 280.2 K. It has been proposed that the warm water be used as the hot reservoir and the cool water as the cold reservoir of a heat engine. Find the maximum possible efficiency for such and engine.

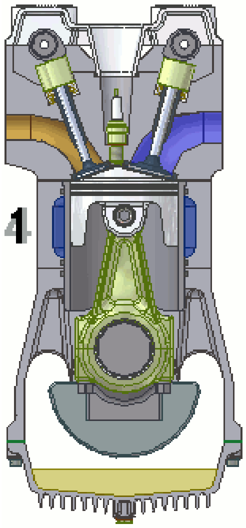


$$e_\text{carnot} = 1 - \frac{T_C}{T_H} = 1 - \frac{280.2\ \text{K}}{298.2\ \text{K}} = 0.060$$

20-2 Entropy in the Real World: Engines

Internal Combustion Engine (Otto Cycle)

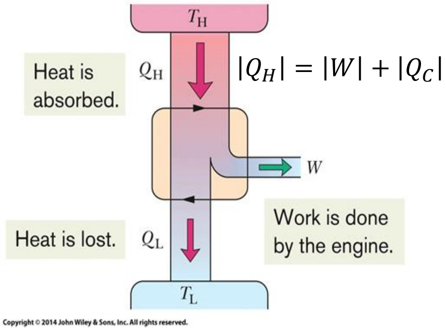




20-2 Entropy in the Real World: Engines

Example : An Automobile Engine

An automobile engine has an efficiency of 22.0% and produces 2510 J of work. How much heat is rejected by the engine?



$|Q_H| = |W| + |Q_C|$

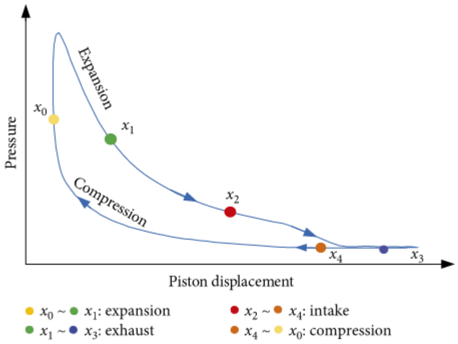
$$e = \frac{|W|}{|Q_H|} \quad \rightarrow \quad |Q_H| = \frac{|W|}{e}$$

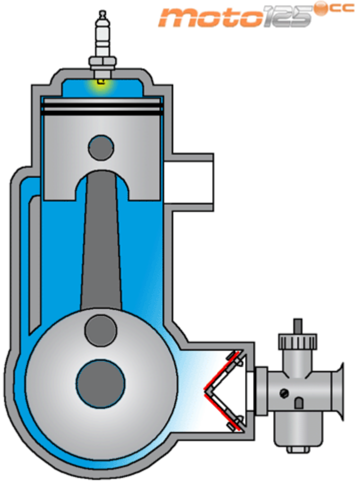
$$|Q_C| = |Q_H| - |W| \quad \leftarrow \quad |Q_H| = |W| + |Q_C|$$

$$|Q_C| = \frac{|W|}{e} - |W| = (2510\ \mathrm{J})\left(\frac{1}{0.220} - 1\right) = 8900\ \mathrm{J}$$

20-2 Entropy in the Real World: Engines

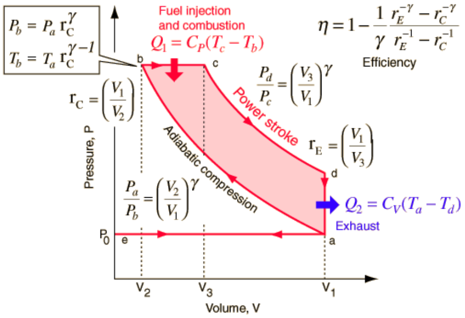
Two-Stroke Engine

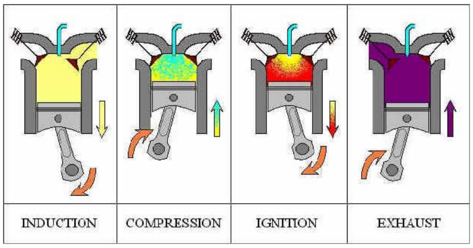




20-2 Entropy in the Real World: Engines

Diesel Engine





20-3 Refrigerator and Real Engines (1 of 4)

Learning Objectives

20.16 Identify that a refrigerator is a device that uses work to transfer energy from a low-temperature reservoir to a high-temperature reservoir.

20.17 Sketch a *p*-*V* diagram for the cycle of a Carnot refrigerator, indicating the direction of cycling, the nature of the processes involved, the work done during each process, the net work done in the cycle, and the heat transferred during each process (including algebraic sign).

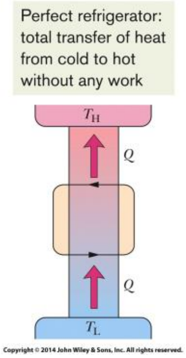
20-3 Refrigerator and Real Engines (2 of 4)

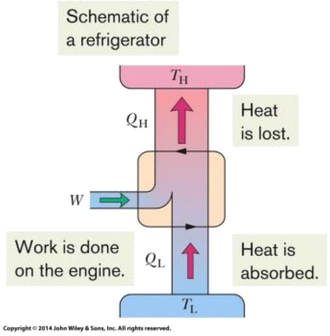
20.18 Apply the relationship between the coefficient of performance *K* and the heat exchanges with the reservoirs and the temperatures of the reservoirs.

20.19 Identify that there is no ideal refrigerator in which all of the energy extracted from the low-temperature reservoir is transferred to the high-temperature reservoir.

20.20 Identify that the efficiency of a real engine is less than that of the ideal Carnot engine.

20-3 Refrigerator and Real Engines (4 of 4)

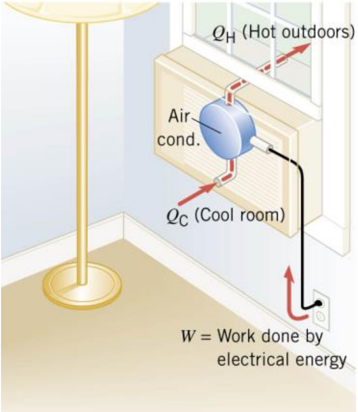


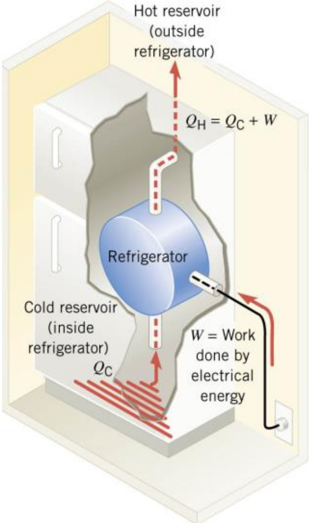


The elements of a perfect refrigerator — that is, one that transfers energy from a low-temperature reservoir to a high-temperature reservoir without any input of work.

The elements of a refrigerator. Work W is done on the refrigerator (on the working substance) by something in the environment.

20-3 Refrigerator and Real Engines (4 of 4)





20-3 Refrigerator and Real Engines (3 of 4)

In an ideal refrigerator, all processes are reversible and no wasteful energy transfers occur as a result of, say, friction and turbulence.

Refrigerators

Coefficient of Performance

$$K = \frac{\text{what we want}}{\text{what we pay for}} = \frac{|Q_\mathrm{L}|}{|W|}$$

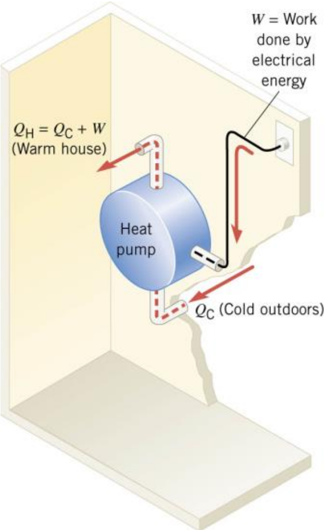
$$K_C = \frac{T_\mathrm{L}}{T_\mathrm{H} - T_\mathrm{L}}$$

(coefficient of performance, Carnot refrigerator)

20-3 Refrigerator and Real Engines (3 of 4)

The ***heat pump*** uses work to make heat from the wintry outdoors flow into the house.

$$\text{Coefficient of performance} = \frac{|Q_H|}{|W|}$$



20-3 Refrigerator and Real Engines (3 of 4)

Example : A Heat Pump

An ideal, or Carnot, heat pump is used to heat a house at 294 K. How much work must the pump do to deliver 3350 J of heat into the house on a day when the outdoor temperature is 273 K?

$$\frac{|Q_C|}{|Q_H|}=\frac{T_C}{T_H} \quad \rightarrow \quad |Q_C|=|Q_H|\frac{T_C}{T_H}$$

$$\begin{aligned}|W| &= |Q_H|-|Q_C| \\ &= |Q_H|\left(1-\frac{T_C}{T_H}\right) \\ &= |Q_H|\left(1-\frac{T_C}{T_H}\right) = (3350\text{ J})\left(1-\frac{273\text{ K}}{294\text{ K}}\right) = 240\text{ J}\end{aligned}$$

Summary (1 of 4)

Irreversible (one-way) Process

- If an irreversible process occurs in a closed system, the entropy of the system always increases.

Entropy Change

- Entropy change for reversible process is given by

$$\Delta S = S_f - S_i = \int_i^f \frac{dQ}{T}$$

Equation 20-1

Summary (2 of 4)

Second Law of Thermodynamics

- If a process occurs in a closed system, the entropy of the system increases for irreversible processes and remains constant for reversible processes.

$$\Delta S \geq 0$$

Equation 20-5

Entropy Change

- The efficiency ε of any engine

$$\varepsilon = \frac{\text{energy we get}}{\text{energy we pay for}} = \frac{|W|}{|Q_{\mathrm{H}}|}$$

Equation 20-11

Summary (3 of 4)

- Efficiency of Carnot engine

$$\varepsilon_C = 1 - \frac{|Q_{\mathrm{L}}|}{|Q_{\mathrm{H}}|} = 1 - \frac{T_{\mathrm{L}}}{T_{\mathrm{H}}}$$

Equation 20-12 & 13

Refrigerator

- Coefficient of performance of a refrigerator:

$$K = \frac{\text{what we want}}{\text{what we pay for}} = \frac{|Q_{\mathrm{L}}|}{|W|}$$

Equation 20-14

- Carnot Refrigerator

$$K_C = \frac{|Q_{\mathrm{L}}|}{|Q_{\mathrm{H}}| - |Q_{\mathrm{L}}|} = \frac{T_{\mathrm{L}}}{T_{\mathrm{H}} - T_{\mathrm{L}}}$$

Equation 20-15 & 16

Summary (4 of 4)

Entropy from Statistical Point of View

- For a system of *N* molecules:

$$W = \frac{N!}{n_1!n_2!}$$ **Equation 20-20**

- Boltzmann's entropy equation:

$$S = k \ln W$$ **Equation 20-21**

- Stirling's approximation:

$$\ln N! \approx N(\ln N) - N$$ **Equation 20-22**

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