Thermodynamics
Second Law
Heat Engines

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Last time

- entropy (microscopic perspective)

Overview

- heat engines
- heat pumps
- Carnot engines

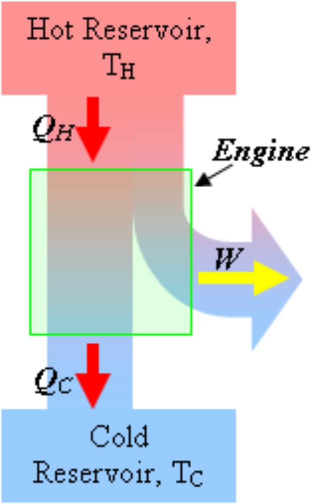
Heat Engines

Steam engines and later incarnations of the engine run on a very simple principle: heat is transferred from a hot object to a colder object and mechanical work is done in the process.

Heat engines run in a cycle, returning their *working fluid* back to its initial state at the end of the cycle.

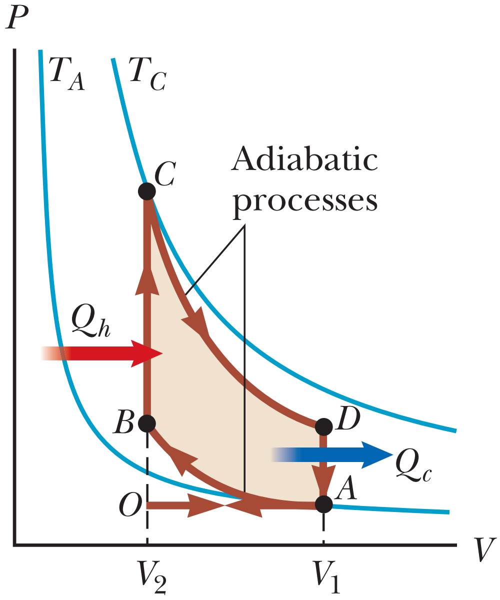
In practice, usually some chemical energy (burning fuel) is used to raise the temperature of one object, and the colder object remains at the ambient temperature.

Heat Engines



[1] Diagram from http://www2.ignatius.edu/faculty/decarlo/

Example of a Heat Engine Cycle



Efficiency of a Heat Engine

The working fluid returns to its initial state, so in the entire cycle $\Delta E_{\text{int}} = 0$.

First law:

$$\Delta E_{\text{int}} = W + Q = 0$$

where W is the work done *on* the system.

This means

$$W_{\text{eng}} = Q_{\text{net}} = |Q_h| - |Q_c|$$

where W_{eng} is the work done <u>*by*</u> the engine (working fluid).

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We define the **efficiency** to be:

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

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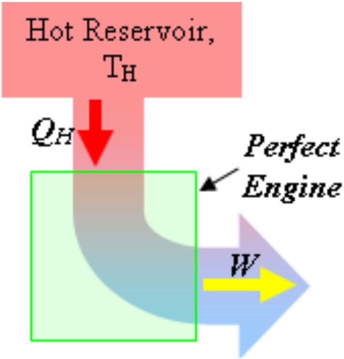
Ideally, we would like to have an efficiency of 1.

This would mean all heat that enters our fluid is converted to work.

Since we usually supply this heat through a chemical reaction, ideally all the energy from the reaction would become useful work.

“Perfect” but Impossible Engine

It would be nice if all heat energy Q_h could be converted to work.



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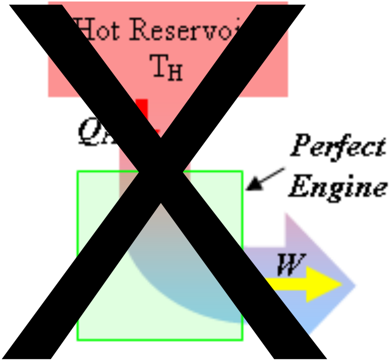


But this is not possible.

We will see why shortly.

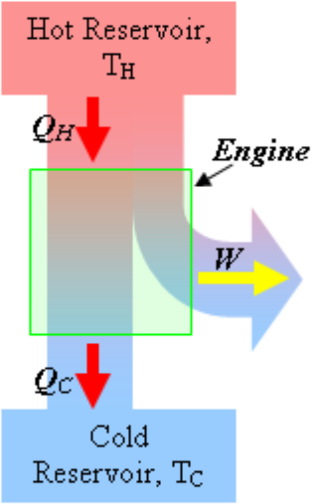
Second Law and Heat Engines

We can state the second law also as a fundamental limitation on heat engines.

Second Law of Thermodynamics (Heat Engine version)

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.

Heat Engines



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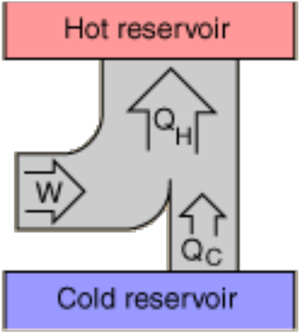
Heat Pump

Refrigerators work by taking electrical energy, converting it to work, then pumping heat from a cold area to a hotter one.



This type of process, where work is converted into a heat transfer from a colder object to a hotter one is called a **heat pump**.

[1]Diagram from http://hyperphysics.phy-astr.gsu.edu

Heat Pump Coefficient of Performance

The effectiveness of a heat pump isn't well represented with our previous definition of efficiency, since now the resource we are considering is work.

Instead we use the **Coefficient of Performance**, COP.

We can use heat pumps for two different purposes:

- to further heat an object (*eg.* a house) that is warmer than its surroundings
- to cool an object (*eg.* in a refrigerator) that is cooler than its surroundings

Each purpose has its own COP.

Heat Pump Coefficient of Performance

For cooling (refrigeration):

$$\text{COP (cooling)} = \frac{|Q_c|}{W}$$

Typical refrigerator COPs are around 5 or 6.

For heating:

$$\text{COP (heating)} = \frac{|Q_h|}{W}$$

Question

Quick Quiz 22.2[1] The energy entering an electric heater by electrical transmission can be converted to internal energy with an efficiency of 100%.

By what factor does the cost of heating your home change when you replace your electric heating system with an electric heat pump that has a COP of 4.00?

Assume the motor running the heat pump is 100% efficient.

(A) 4.00
(B) 2.00
(C) 0.500
(D) 0.250

[1] Serway & Jewett, page 658.

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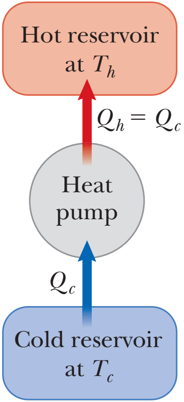
"Perfect" but Impossible Heat Pump



This heat pump violates our first statement of the second law, since heat spontaneous goes from a cooler reservoir to a hotter one.

More formally, the Clausius statement of the second law:

Second Law of thermodynamics (Clausius)

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.

[1] Diagram from Serway and Jewett.

Question

Suppose you have a house with very excellent insulation. If you leave the door to your refrigerator open for the day, what happens to the temperature of your house?

(A) It increases.

(B) It decreases.

(C) It stays the same.

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Carnot Engines

Sadi Carnot wanted to find the fundamental limit of how efficient a heat engine could be.

He imagined a theoretical engine (now called the Carnot engine) that was as efficient as possible.

He realized that no engine would be more efficient than a reversible one.

Only in a reversible process will no energy be lost to friction or turbulence in the fluid.

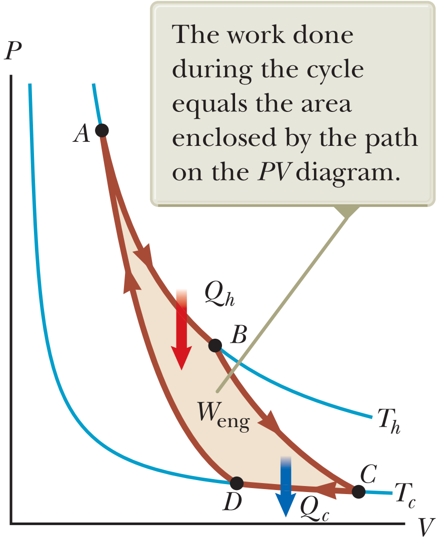
Carnot Engines

Carnot specified that his heat engine should use just two thermal reservoirs, each at constant temperature, T_h and T_c.

In order to be reversible, the heat must be exchanged in the cycle when the system is in thermal contact with the reservoirs.

The other parts of the cycle must be adiabatic ($Q = 0$).

The Carnot Cycle



Maximum Efficiency of an Engine

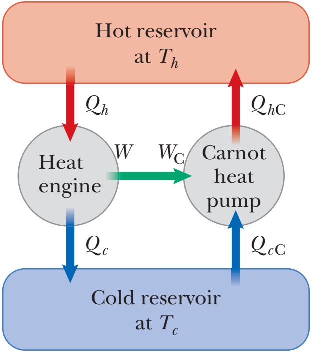
Assume a Carnot engine has efficiency e_C.

Now supoose it was possible to construct an engine that is even more efficient, with efficiency $e > e_C$.

Since the Carnot cycle is reversible, we could run the Carnot engine in reverse as a heat pump.

Maximum Efficiency of an Engine

Putting the imagined engine and the Carnot heat pump together:



Now, the work from the hypothetical engine drives the Carnot heat pump, so $W = W_C$

$$e > e_C \quad \Rightarrow \quad \frac{|W|}{|Q_h|} > \frac{|W_C|}{|Q_{hC}|}$$

Maximum Efficiency of an Engine

$$e > e_C \quad \Rightarrow \quad \frac{|W|}{|Q_h|} > \frac{|W|}{|Q_{hC}|}$$

This means

$$|Q_h| < |Q_{hC}|$$

We also know that $|W| = |Q_h| - |Q_c|$ (energy conservation). Since the works are equal:

$$\begin{aligned} W &= W_c \\ |Q_h| - |Q_c| &= |Q_{hC}| - |Q_{cC}| \end{aligned}$$

Rearranging:

$$|Q_{hC}| - |Q_h| = |Q_{cC}| - |Q_c|$$

But the LHS is positive if $e > e_C$.

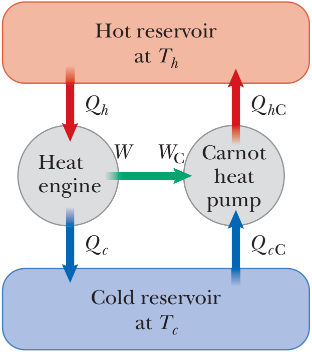
Heat arrives at the hot reservoir and leaves the cold one! $\Rightarrow$ Violates the Second Law.

Maximum Efficiency of an Engine

Putting the imagined engine and the Carnot heat pump together:

$$|Q_{hC}| - |Q_h| > 0$$

$$|Q_{cC}| - |Q_c| > 0$$



$\uparrow Q_{h,\text{net}}$

$\uparrow Q_{c,\text{net}}$

Violates the Second Law.

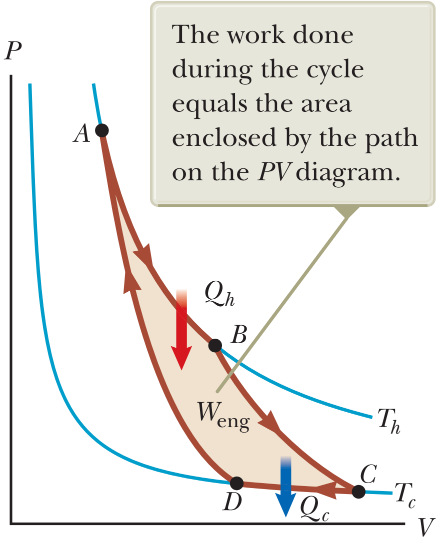
Carnot's Theorem

Carnot's Theorem

No real heat engine operating between two energy reservoirs can be more efficient than a Carnot engine operating between the same two reservoirs.

But how efficient is a Carnot engine?

The Carnot Cycle



Efficiency of a Carnot Engine

First, we can relate the volumes at different parts of the cycle.

In the first adiabatic process:

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

In the second adiabatic process:

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

Taking a ratio, then the $\gamma - 1$ root:

$$\frac{V_B}{V_A} = \frac{V_C}{V_D}$$

Efficiency of a Carnot Engine

First law: $\Delta E_{\text{int}} = Q + W = 0$ gives for the first isothermal process

$$|Q_h| = nRT_h \ln\left(\frac{V_B}{V_A}\right)$$

Second isothermal process:

$$|Q_c| = nRT_c \ln\left(\frac{V_C}{V_D}\right)$$

We will take a ratio of these to find the efficiency. Noting that $\frac{V_B}{V_A} = \frac{V_C}{V_D}$:

$$\frac{|Q_c|}{|Q_h|} = \frac{|T_c|}{|T_h|}$$

Efficiency of a Carnot Engine

Recall, efficiency of a heat engine:

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

Efficiency of a Carnot engine:

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

(T is measured in Kelvin!)

This is the most efficient that any heat engine operating between two reservoirs at constant temperatures can be.

Summary

- heat engines
- heat pumps
- Carnot engines

Homework Serway & Jewett:

- Ch 22, OQs: 1, 3, 7; CQs: 1; Probs: 1, 3, 9, 15, 20, 23, 29, 37, 67, 73, 81 (some of these use info we will cover tomorrow)