SECOND LAW OF THERMODYNAMICS I

Intended Learning Outcomes – after this lecture you will learn:
1. heat engine and refrigerator
2. Otto cycle (internal combustion engine) as an example of a real engine
3. operation of a real refrigerator
4. stating the second law of thermodynamics in terms of heat engine and refrigerator
5. irreversible processes and relation to the second law of thermodynamics

Textbook Reference: Ch 20.1 – 20.5

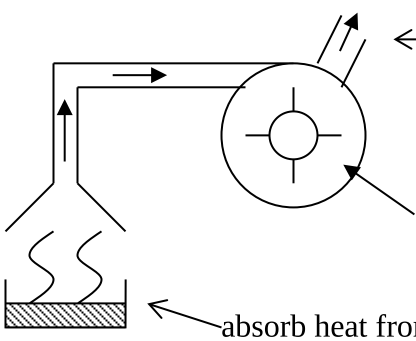
Heat Engine

A **heat engine** is a device that transform heat *partly* into work or mechanical energy

Demonstrations:

Stirling engine | Thermo-electric converter

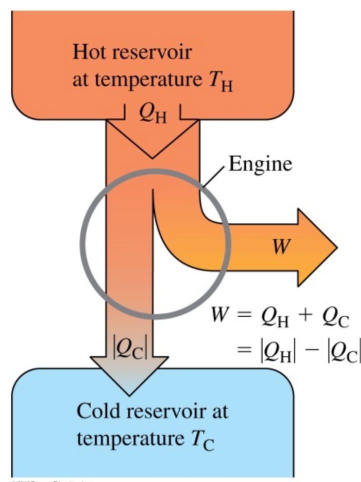
E.g. a steam turbine, the working substance is water



dump heat into **cold reservoir** (atmosphere), steam condense into water and recycled

steam drives turbine, producing mechanical work

absorb heat from **hot reservoir** (boiler) to convert water into steam



After one cycle, the working substance (water) returns to its original state, $\Delta U = 0$

From first law of thermodynamics

$$W = Q = |Q_\mathrm{H}| - |Q_\mathrm{C}|$$

Define the **thermal efficiency** of the engine

$$\boxed{e = \frac{W}{|Q_\mathrm{H}|} = 1 - \left|\frac{Q_\mathrm{C}}{Q_\mathrm{H}}\right|}$$

Question

Rank the thermal efficiency of the following heat engines in descending order:

a) an engine that in one cycle absorbs 5000 J of heat and rejects 4500 J of heat

b) an engine that in one cycle absorbs 25000 J of heat and does 2000 J of work

c) an engine that in one cycle does 400 J of work and rejects 2800 J of heat

Answer: see inverted text on P. 675 of textbook

Example 20.1 P. 674

A gasoline engine takes in 10,000 J of heat and delivers 2,000 J of mechanical work per cycle. The heat is obtained by burning gasoline with heat of combustion $L_c = 5.0 \times 10^4\ \mathrm{J/g}$.

(a) Thermal efficiency

$$e = \frac{W}{Q_{\mathrm{H}}} = \frac{2{,}000\ \mathrm{J}}{10{,}000\ \mathrm{J}} = 20\%$$

⚠ thermal efficiency of heat engines are in general quite low

(b) Heat dissipated in each cycle

$$Q_{\mathrm{C}} = W - Q_{\mathrm{H}} = -8000\ \mathrm{J}$$

(c) If the engine goes through 25 cycles per second, its power output is

$$P = (2000\ \mathrm{J/cycle})(25\ \mathrm{cycle/s}) = 50\ \mathrm{kW}$$

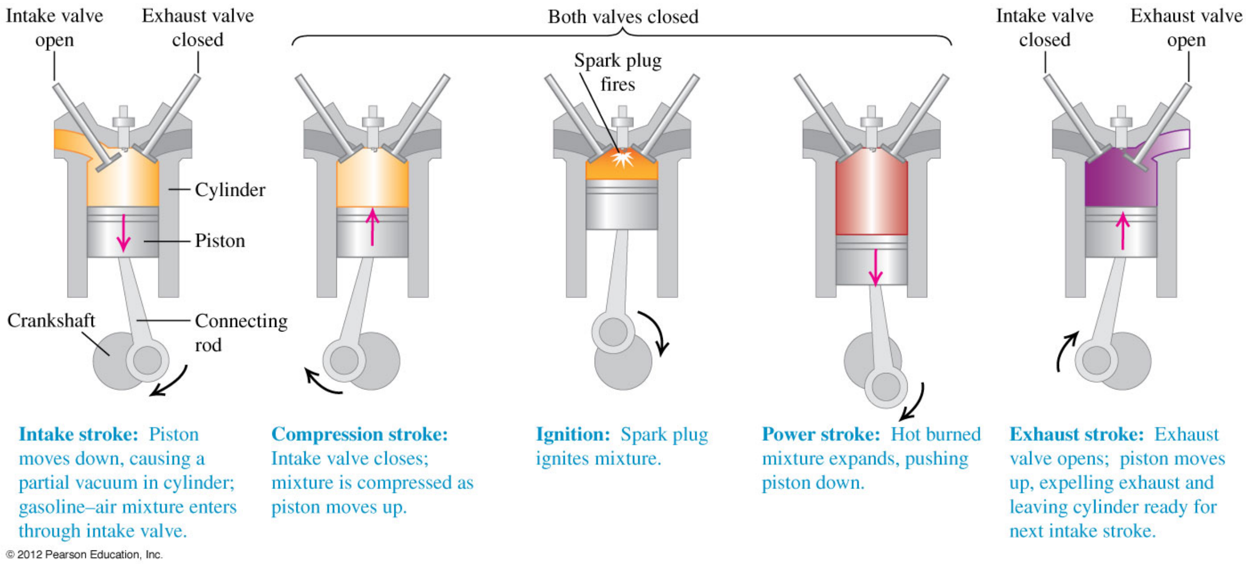
(d) amount of gasoline burnt in one cycle

$$m = \frac{Q_{\mathrm{H}}}{L_c} = \frac{10000\ \mathrm{J}}{5.0 \times 10^4\ \mathrm{J/g}} = 0.20\ \mathrm{g}$$

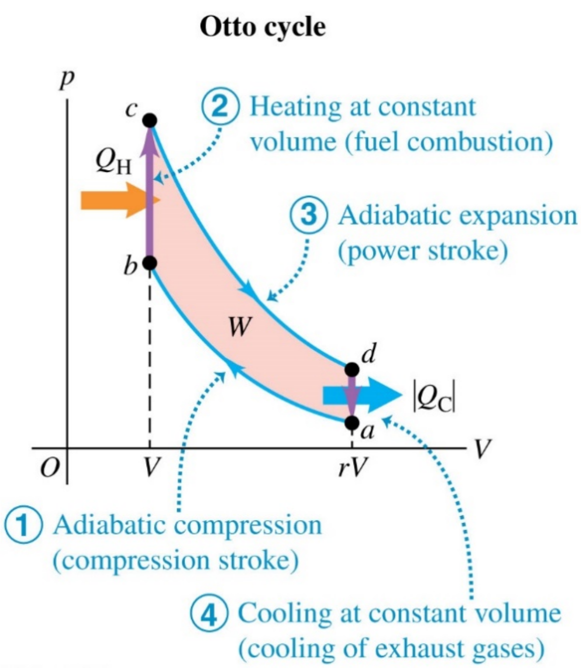
(e) rate of gasoline consumption

$$= (0.20\ \mathrm{g/cycle})(25\ \mathrm{cycle/s}) = 5.0\ \mathrm{g/s}$$

Otto cycle (as in internal combustions engine in vehicles)
An idealized model, assuming ideal gas; neglecting friction, turbulence, heat loss to surrounding.



Animation: "Four Strokes.swf"



For the isochoric processes *bc* and *da*

$$Q_{\mathrm{H}} = nC_V(T_c - T_b) > 0$$
$$Q_{\mathrm{C}} = nC_V(T_a - T_d) < 0$$

therefore

$$e = \frac{Q_{\mathrm{H}} + Q_{\mathrm{C}}}{Q_{\mathrm{H}}} = 1 - \frac{T_d - T_a}{T_c - T_b}$$

For the adiabatic processes *ab* and *cd*

$$T_a(rV)^{\gamma-1} = T_b V^{\gamma-1}$$
$$T_d(rV)^{\gamma-1} = T_c V^{\gamma-1}$$

Hence

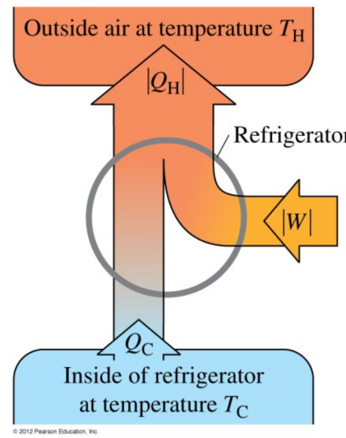
$$\boxed{e = 1 - \frac{1}{r^{\gamma-1}}} < 1$$

⚠ With $r = 8$ and $\gamma = 1.4$, $e \approx 56\%$. Real gasoline engines are less efficient, typically $\approx 35\%$

⚠ e can be larger if r is larger, but it may raise the temperature T_b by too much

Refrigerator

A **refrigerator** is a heat engine operating in reverse – extract heat from a cold reservoir (inside a refrigerator) and dump heat to a hot reservoir (the atmosphere)

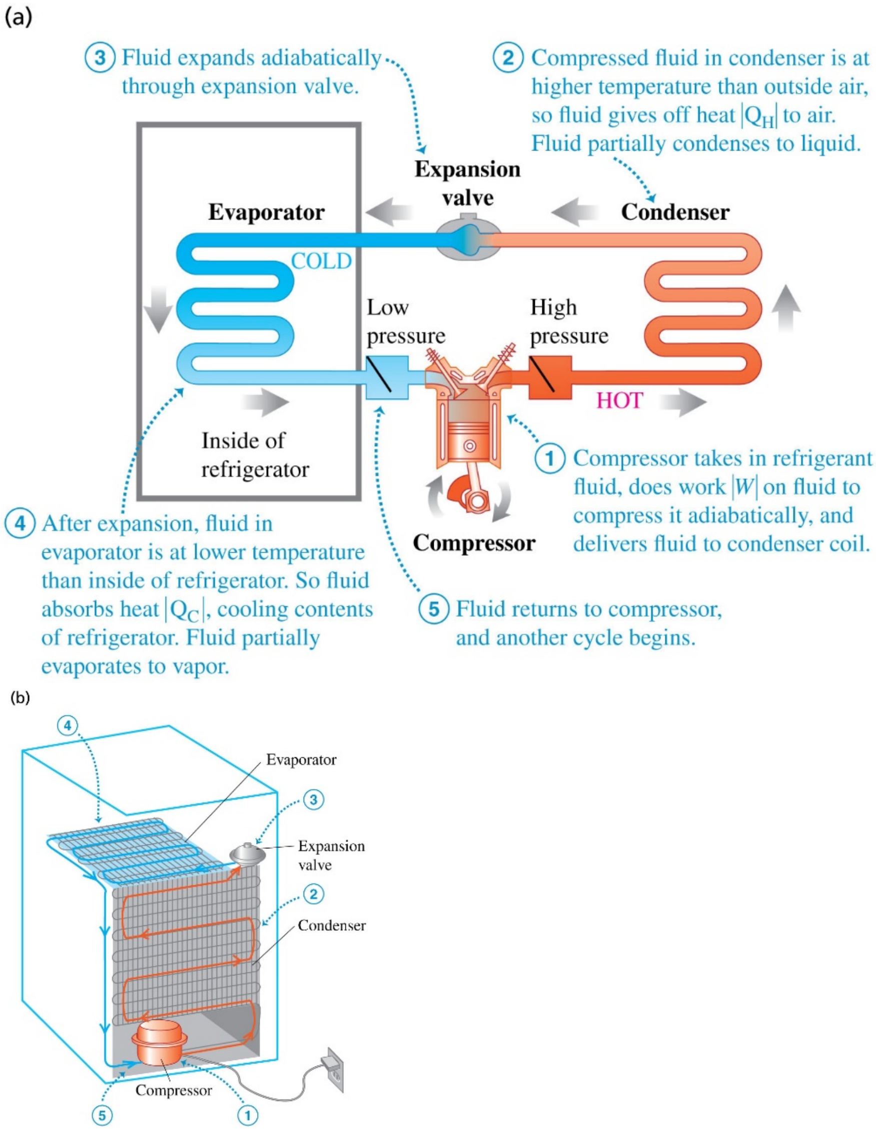


$$|Q_C| + |W| = |Q_H|$$

Define **coefficient of performance**

$$\boxed{K = \frac{|Q_C|}{|W|} = \frac{|Q_C|}{|Q_H| - |Q_C|}}$$

A real refrigerator:



Second Law of Thermodynamics

Two equivalent ways of stating the **Second Law of Thermodynamics**:

(1) The *engine statement*, or the *Kelvin-Planck statement*:

It is impossible for any system to undergo a process in which it absorbs heat from a reservoir at a single temperature and converts the heat completely into mechanical work, with the system ending in the same state in which it began.

i.e., no ideal heat engine

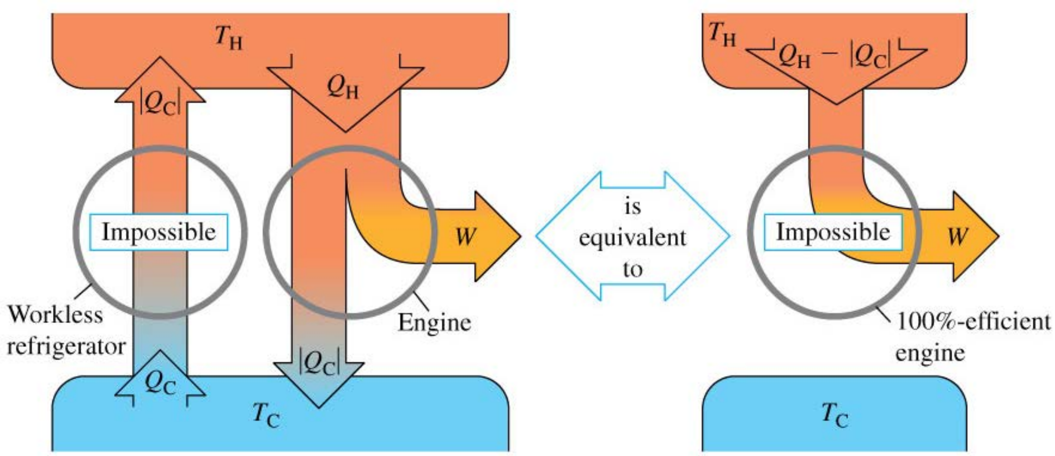
(2) The *refrigerator statement*, or the *Clausius statement*:

It is impossible for any process to have as its sole result the transfer of heat from a cooler to a hotter body.

i.e., no ideal refrigerator

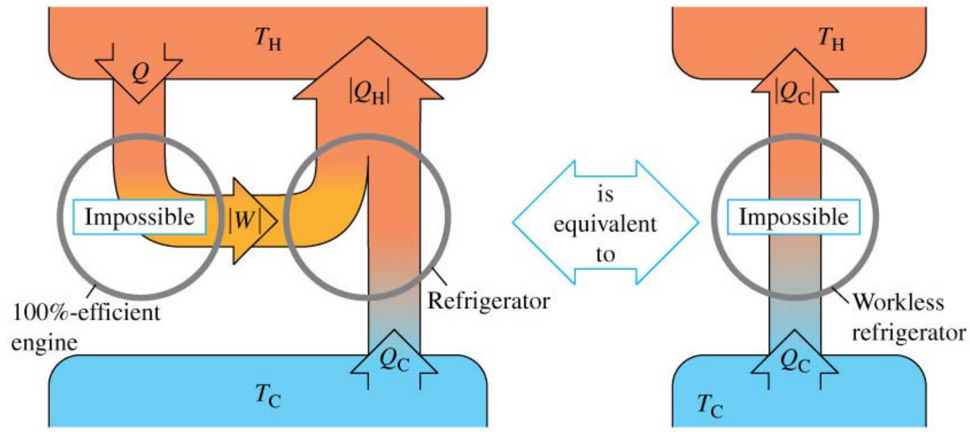
⚠ neither statement violates the First Law of Thermodynamics

To prove the equivalence of the two statements:
First, show that (1) ⟹ (2), i.e., ~(2) ⟹ ~(1)



If a workless refrigerator were possible, it could be used in conjunction with an ordinary heat engine to form a 100%-efficient engine, converting heat $Q_H - |Q_C|$ completely to work.

Second, show that (2) ⟹ (1), i.e., ~(1) ⟹ ~(2)



If a 100%-efficient engine were possible, it could be used in conjunction with an ordinary refrigerator to form a workless refrigerator, transferring heat Q_C from the cold to the hot reservoir with no input of work.

Conclusion: the engine and refrigerator statements of the second law of thermodynamics are equivalent

Everyday life example:
The following processes occur "naturally":
1. Heat flows from a hot to a cold body.
2. A ball falls off from my hand, perhaps bouncing off a few times and eventually becomes at rest on the ground, losing all its mechanical energy.

Why can't the corresponding reverse processes occur "naturally", or "spontaneously"?
Anwser:
1. Heat flows spontaneously from a cold to a hot body would violate the (Kelvin-Planck / Clausius) statement;
2. A ball at rest on the ground spontaneously absorbs heat from the surrounding and jumps up would violates the (Kelvin-Planck / Clausius) statement.

⚠ The above processes are examples of **irreversible processe***s*. The Second Law of Thermodynamics dictates which direction an irreversible thermodynamic process occurs naturally, and consequently defining the **direction of time flow**.

Clicker Question:

Q20.4

During one cycle, an automobile engine takes in 12,000 J of heat and discards 9000 J of heat. What is the efficiency of this engine?

A. 400%

B. 133%

C. 75%

D. 33%

E. 25%

Q20.5

During one cycle, an automobile engine with an efficiency of 20% takes in 10,000 J of heat. How much work does the engine do per cycle?

A. 8000 J

B. 6400 J

C. 2000 J

D. 1600 J

E. 400 J

Ans: Q20.4) E, Q20.5) C

Nicolas Léonard Sadi Carnot

From Wikipedia, the free encyclopedia

Nicolas Léonard Sadi Carnot (1 June 1796 – 24 August 1832) was a French military engineer who, in his 1824 book *Reflections on the Motive Power of Fire*, gave the first successful theoretical account of heat engines, now known as the Carnot cycle; his book also laid the foundations for the second law of thermodynamics. He is often described as the "Father of thermodynamics", being responsible for such concepts as Carnot efficiency, Carnot theorem, the Carnot heat engine, and others.

Sadi Carnot

Nicolas Léonard Sadi Carnot in 1813 at age of 17 in the traditional uniform of a student of the École Polytechnique

Born	1 June 1796 Palais du Petit-Luxembourg, Paris, France
Died	24 August, 1832 (age 36) Paris, France
Nationality	French
Fields	Physicist and engineer
Institutions	French army
Alma mater	École Polytechnique École Royale du Génie Sorbonne Collège de France
Academic advisors	Siméon Denis Poisson André-Marie Ampère François Arago
Known for	Carnot cycle Carnot efficiency Carnot theorem Carnot heat engine
Influenced	Benoît Paul Émile Clapeyron Rudolf Julius Emmanuel Clausius

Notes

He was the brother of Hippolyte Carnot, his father was the mathematician Lazare Carnot, and his nephews were Marie François Sadi Carnot and Marie Adolphe Carnot.

Life

Sadi Carnot was born in Paris, and was the first son of the eminent military leader and geometer, Lazare Nicholas Marguerite Carnot. Sadi was the elder brother of Hippolyte Carnot, and uncle of Marie François Sadi Carnot (President of the French Republic 1887–1894). His father named him after the Persian poet Sadi of Shiraz, and he was always known by this third given name.

From the age of 16, he lived in Paris and attended the École polytechnique where he and his contemporaries, Claude-Louis Navier and Gaspard-Gustave Coriolis, were taught by such notable professors as Joseph Louis Gay-Lussac, Siméon Denis Poisson and André-Marie Ampère. After graduation he became an officer in the French army before committing himself to scientific research; Carnot's research went to make him one of the most celebrated of Fourier's contemporaries who were interested in the theory of heat. He served in the military until 1814; following the defeat of Napoleon in 1815, his father went into exile, and he later obtained permanent leave of absence from the French army. It was during his military leave that he spent time to write his book *Reflections on the Motive Power of Fire*.

Reflections on the Motive Power of Fire

Background

When Carnot began working on his book the use of steam engines was relatively developed; notwithstanding this, there had been no real scientific study concerning steam engines. Steam engines had, however, risen to a widely recognized economic and industrial importance. Newcomen had invented the first piston-operated steam engine over a century before, in 1712; some 50 years after that, James Watt made his celebrated improvements which were responsible for greatly increasing the efficiency and practicality of engines. Compound engines (engines with more than one stage of expansion) had already been invented, and there was even a crude form of internal-combustion engine, which Carnot was familiar with and which he described in some detail in his book. Significant progress had been made concerning engines, so there existed at the time some intuitive understanding of the workings of engines. Despite this, the scientific basis of their operation was almost nonexistent. In 1824 the principle of conservation of energy was still poorly developed and controversial, and an exact formulation of the first law of thermodynamics was still more than a decade away; what's more is that the mechanical equivalent of heat had not been identified and would remain unknown for another two decades. The prevalent theory of heat at the time was the caloric theory, which regarded heat as a sort of weightless and invisible fluid that flowed when out of equilibrium.

Engineers in Carnot's time had tried, by means such as highly pressurized steam and the use of fluids, to improve the efficiency of engines. In these early stages of engine development, the efficiency of a typical engine—the useful work it was able to do when a given quantity of fuel was burnt—was a mere 3%.

For more detail see http://en.wikipedia.org/wiki/Nicolas_L%C3%A9onard_Sadi_Carnot