17. a. What is entropy? How does it relate to disorder?
    b. Why is the entropy of the universe said to be always increasing? Give examples.

18. a. Explain why no heat engine can be more efficient than a Carnot engine working between the same two temperatures.
    b. Describe the practical limitations of real engines compared with the ideal Carnot engine.
    c. A Carnot engine works between a source at 500 K and a sink at 300 K. Calculate its efficiency.

19. A heat engine has an efficiency of 25%. How much heat does it reject if it absorbs 600 J of heat from the source?

20. A Carnot engine rejects heat at 400 K and absorbs heat at 800 K. If it does 300 J of work per cycle, calculate a. its efficiency, b. the heat it absorbs per cycle.

A companion to your textbook, not a replacement for it: study from the book your school uses, and where the two differ, follow your teacher. Found a mistake? Please tell us.

Unit 5

Second Law of Thermodynamics

This unit online, with its interactives:
science-playground.com/s/12f5

A cup of hot tea left on the table always cools to the temperature of the room; it never takes heat from the room and starts to boil. A drop of ink spreads through a glass of water, and never gathers itself back into a drop. A motorbike's engine burns petrol, and most of the fuel's energy leaves as heat from the exhaust and the hot engine, however well it is made. None of this breaks the first law: energy would be conserved just as well the other way round. Something else decides which way things go.

That something is the **second law of thermodynamics**. It explains why heat flows from hot to cold by itself, why no engine can turn all its heat into work, how a refrigerator manages to pump heat "uphill", and why the best possible engine's efficiency depends only on two temperatures. It ends with **entropy**, the quantity that measures how spread out energy is, and that never decreases in the universe as a whole.

5.1 Introduction

The first law of thermodynamics (Unit 4) says that heat and work can be changed into each other, with energy always conserved. But it is silent on four things: **which way** a change goes by itself, **how much** of the heat can become work (the efficiency), whether a process is **reversible**, and under what **conditions** heat can be turned into work. The **second law of thermodynamics** was brought in to answer them.

The second law is about the **direction** of natural processes. It explains:

- why heat flows by itself from a hotter body to a colder one, and never the other way;
- why every natural process is **irreversible**: in each, the total **entropy** (Section 5.8) of the system and its surroundings increases;
- why no engine can be 100% efficient: some of the heat it takes in must always be passed on to something colder, where it can no longer do work;
- how heat engines and refrigerators work, and the best that each can possibly do.

It became a cornerstone of physics and of engineering, and of chemistry and biology too: it tells which reactions can go by themselves.

A STORY FROM SCIENCE

The man who named entropy

Rudolf Julius Emanuel Clausius (1822–1888) was born in Köslin in Prussia (now Koszalin in Poland), the son of a pastor who ran a small school. In 1850, as a young teacher in Berlin, he published a paper that made sense of two ideas everyone thought were at war: Joule's, that heat is energy, and Sadi Carnot's, that an engine works by letting heat fall from hot to cold. Both were right, Clausius showed, but it needed a second law: **heat does not pass by itself from a colder body to a hotter one**.

Fifteen years later he gave the quantity behind that law a name, **entropy**, from a Greek word for *transformation*, made to sound like *energy* because the two were so closely related. He summed up his work in two sentences: "The energy of the universe is constant. The entropy of the universe tends to a maximum." He also worked out the mean free path of gas molecules, the distance a molecule travels between collisions, which you met in Grade 11's kinetic theory.

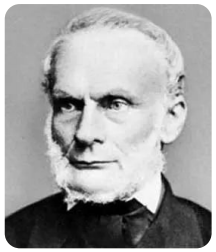


Figure 5.1 *Rudolf Clausius, who stated the second law and named entropy.*
Photo: Unknown, Public domain

5.2 Second law of thermodynamics

The **second law of thermodynamics** is the basic principle that gives the direction of natural processes and the limits of turning heat into work. It can be stated in many ways; two are famous, the **Kelvin–Planck statement** and the **Clausius statement**. They look at different things, an engine and a refrigerator, but they are **equivalent**: if either one were false, the other would be false too.

Kelvin–Planck statement (about a heat engine)

> It is impossible to make an engine, working in a cycle, that takes heat from a single reservoir and converts all of it into work.

So every heat engine takes in heat from a hot **source**, turns part of it into work, and must give out the rest, as waste heat, to a colder **sink**. An engine needs both a source at a higher temperature and a sink at a lower one, and no heat engine can be 100% efficient. (The words "in a cycle" matter: a gas expanding at constant temperature does turn all the heat it takes in into work, as in Unit 4, but then it is left at a larger volume, and can't keep doing it.)

Clausius statement (about a refrigerator)

> Heat cannot flow by itself from a colder body to a hotter body; for that to happen, external work must be done.

Heat flows naturally from a hotter body to a colder one; to make it go the other way needs work. That is what a **refrigerator** does: an electric motor does work on its working substance (the **refrigerant**), which takes heat from the cold inside of the refrigerator and gives out a larger amount of heat to the warmer room.

Why the two statements are equivalent

Suppose someone did build a **perfect engine** that broke the Kelvin–Planck statement: it takes heat Q_1 from a hot body and turns all of it into work $W = Q_1$, giving no heat to anything colder. Use that work to drive an ordinary refrigerator working between the same two bodies (Figure 5.2). The refrigerator takes heat Q_2 from the cold body and gives $Q_2 + W = Q_2 + Q_1$ to the hot body.

Treat the two machines as one. The hot body has lost Q_1 and gained $Q_2 + Q_1$: a net gain of Q_2. The cold body has lost Q_2. No work came in from outside. So heat Q_2 has flowed from the cold body to the hot one by itself, which breaks the Clausius statement. In the same way, a refrigerator that broke the Clausius statement could be joined to an ordinary engine to make an engine that breaks the Kelvin–Planck statement. Either both statements are true, or neither is; they are two faces of one law.

Check 17

9. A Carnot refrigerator works between 250 K and 300 K. If it extracts 500 J of heat from the cold reservoir, what work input does it need?

a 50 J b 100 J
c 150 J d 200 J

Check 18

10. A heat engine absorbs 600 J of heat from a reservoir at 500 K and rejects heat to a reservoir at 300 K. What is the greatest possible work it can do?

a 240 J b 300 J
c 360 J d 400 J

Check 19

11. A Carnot engine works between 1000 K and 400 K and produces 2000 J of work per cycle. How much heat must it absorb from the hot reservoir in each cycle?

None of the textbook's options (3000 J, 4000 J, 5000 J, 6000 J) is right: the answer is 3333 J, so the book's numbers don't work. The options below are corrected, and the engine is made a Carnot engine so that the answer is fixed.

a 2000 J b 3333 J
c 5000 J d 6667 J

14.
a. Describe the Carnot cycle and explain its representation on a P–V diagram.
b. Derive the efficiency of a Carnot engine, and explain the significance of the source and sink temperatures.
c. The efficiency of a Carnot engine is 60%. If the sink is at 300 K, what is the temperature of the source?

15.
a. Differentiate between the Otto and Diesel cycles. Show both on P–V diagrams.
b. A diesel engine takes in 5000 J of heat and does 1200 J of work. Calculate the heat it rejects and its efficiency.

16.
a. Describe the working of a refrigerator as a reversed heat engine. Define its coefficient of performance (COP).
b. A refrigerator removes 400 J of heat from its cold compartment and needs 100 J of work. What is its COP?

Exercise

Choose the correct option

Check 9

1. The second law of thermodynamics states that:

a energy cannot be created or destroyed
b the entropy of an isolated system always decreases
c heat cannot flow from a colder body to a hotter body without external work
d the internal energy of a system remains constant

Check 10

2. Which of the following statements about entropy is correct?

a entropy measures the orderliness of a system
b the entropy of the universe is always decreasing
c a perfectly reversible process has the greatest entropy production
d the entropy of an isolated system always increases or remains constant

Check 11

3. The efficiency of a Carnot engine depends on:

The textbook's option b, "the temperature difference between heat reservoirs", isn't enough on its own: 500 K and 300 K give 40%, but 1000 K and 800 K only 20%, with the same 200 K difference. It is replaced below.

a the type of working substance
b the temperatures of the two reservoirs
c the amount of heat absorbed
d the entropy change

Check 12

4. The coefficient of performance (COP) of a refrigerator is defined as:

a work output divided by heat absorbed
b heat absorbed (from the cold body) divided by work input
c work input divided by heat rejected
d heat rejected divided by work input

Check 13

5. In an ideal Otto cycle, the efficiency depends on:

a the pressure ratio
b the temperature of the heat source
c the compression ratio
d the volume expansion ratio

Check 14

6. A Carnot engine works between 500 K and 300 K. What is its efficiency?

a 20%
b 30%
c 40%
d 50%

Check 15

7. A refrigerator absorbs 200 J of heat from a cold reservoir, with 50 J of work done. What is its COP?

a 2
b 3
c 4
d 5

Check 16

8. A diesel engine has a compression ratio of 18 and a cut-off ratio of 2. If $\gamma = 1.4$, its ideal efficiency is closest to:

The textbook gives only the compression ratio and expects the petrol engine's formula, $1 - 1/r^{\gamma-1} = 68.5\%$, which is not the diesel cycle's. A diesel cycle's efficiency also needs its cut-off ratio, so the question and its options are corrected below.

a 52%
b 58%
c 63%
d 69%

Answer these questions

12. a. State and explain the second law of thermodynamics, using the Kelvin–Planck and Clausius statements.

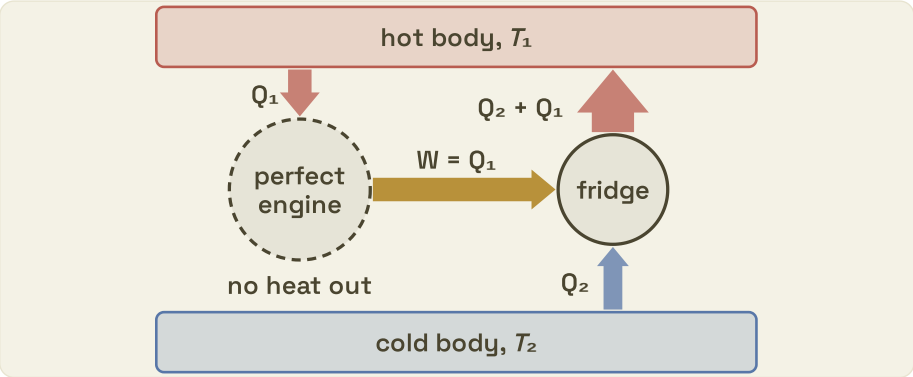


Figure 5.2 *If the Kelvin–Planck statement were false: a perfect engine turns heat Q_1 from the hot body entirely into work, which drives a refrigerator. The hot body loses Q_1 and gains $Q_2 + Q_1$; the cold body loses Q_2. Taken together, Q_2 has flowed from cold to hot with no work from outside, breaking the Clausius statement.*

Check 1

An inventor claims an engine that runs in a cycle, takes 1000 J of heat from a hot boiler and does 1000 J of work, and needs no cooling. It breaks:

a the first law of thermodynamics
b the second law of thermodynamics (Kelvin–Planck statement)
c both laws
d neither law

Comparing the first and second laws

Both laws are about energy, but they say different things: the first, how much energy there is; the second, which way it goes and how much of it can be used.

	First law of thermodynamics	Second law of thermodynamics
Direction of heat flow	Says nothing about it: by the first law alone, heat could flow either way, as long as energy is conserved	Heat flows by itself only from hot to cold; to make it flow the other way needs external work
Efficiency of turning heat into work	Says nothing about it: by the first law alone, an engine could be 100% efficient	No heat engine working in a cycle can be 100% efficient; the best possible efficiency depends on the two temperatures (Section 5.5)
What it is about	The quantity of energy: conservation	The direction of processes, irreversibility, entropy

5.3 Heat engine

A **heat engine** is a device that turns heat into mechanical work by using the difference in temperature between a hot reservoir (the **source**) and a cold reservoir (the **sink**). It takes in heat from the source, does useful work, and gives out the rest of the heat to the sink. It works in a **cycle**, returning to its first state after each cycle, so it can keep going. There are **internal combustion engines** (petrol and diesel engines, jet engines) and **external combustion engines** (steam engines, Stirling engines, the steam turbines of coal-fired power stations). Heat engines power vehicles, generators, ships, aircraft and most of the world's electricity.

The essential parts of a heat engine:

- **Heat source (high-temperature reservoir):** a body kept at a high temperature, with so large a heat capacity that any amount of heat can be taken from it without lowering its temperature. *Examples:* the furnace and boiler of a steam engine; the burning fuel in the cylinder of a petrol or diesel engine.
- **Heat sink (low-temperature reservoir):** a body kept at a low temperature, so large that any amount of heat can be given to it without raising its temperature. *Examples:* the atmosphere, for a petrol or diesel engine; the cooling water of a power station's condenser, or a river.
- **Working substance (working fluid):** the material that takes in heat from the source, changes its temperature, pressure and volume to do work, and gives out the remaining heat to the sink. *Examples:* water and steam in a steam engine; air and

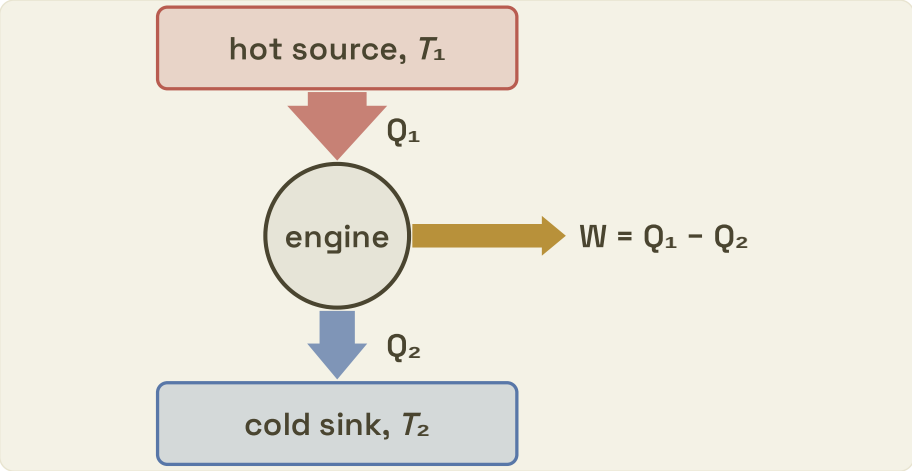


Figure 5.3 *A heat engine: heat Q_1 flows in from the hot source; part comes out as work W; the rest, Q_2, goes to the cold sink. The bands are to scale for Example 5.2: 1000 J in, 400 J of work, 600 J out.*

fuel gases in a petrol or diesel engine.

Thermal efficiency of a heat engine

Let the working substance of an engine take in heat Q_1 from a source at temperature T_1 (in kelvin), do work W, and give out the remaining heat Q_2 to a sink at the lower temperature T_2 (Figure 5.3). Over a whole cycle the working substance returns to its first state, so its internal energy doesn't change, and by the first law the heat turned into work is

$$W = Q_1 - Q_2$$

The **thermal efficiency** η (eta) of the engine is the ratio of the work it does to the heat it takes from the source:

$$\eta = \frac{\text{work done}}{\text{heat taken from the source}} = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$\boxed{\eta = 1 - \frac{Q_2}{Q_1}}$$

As a percentage, $\eta = \left(1 - \dfrac{Q_2}{Q_1}\right) \times 100\%$.

For the efficiency to be 100%, Q_2 would have to be zero: no heat given to the sink. That is exactly what the Kelvin–Planck statement rules out. So Q_2 is always greater than zero, and **the efficiency of a heat engine is always less than 100%**.

Check 2

An engine takes in 500 J of heat from its source in each cycle and gives out 350 J to its sink. Its efficiency is:

a 70%
b 30%
c 43%
d 150 J

DID YOU KNOW?

How efficient are real engines?

Roughly: a motorbike or car petrol engine, 25–35% at its best (less in city traffic); a large diesel engine in a lorry or ship, 40–50%; a coal-fired power station, about 33–40%; a combined-cycle gas power station, which uses its hot exhaust to raise steam for a second turbine, about 60%; the steam locomotives of the old Darjeeling Himalayan Railway, under 10%. The electric motor of an electric vehicle turns about 90% of its electrical energy into motion, but it isn't a heat engine, so the second law's limit doesn't apply to it: no heat is turned into work. Nepal's electricity, which comes almost all from hydropower, doesn't come from a heat engine either.

able to do work. Looking far ahead, physicists have imagined a **heat death** of the universe, in which everything has come to one temperature and no work can be done any more.

A STORY FROM SCIENCE

Counting the ways

In the 1870s the Austrian physicist **Ludwig Boltzmann** found what entropy *is*, at the level of molecules. A state of a gas that we see (its pressure, volume, temperature) can be made by an enormous number W of different arrangements of its molecules. Boltzmann showed that the entropy grows with the logarithm of that number; in the form Max Planck later wrote it,

$$S = k_B \ln W$$

where k_B is the Boltzmann constant. A disordered state, energy spread among many molecules, can be made in vastly more ways than an ordered one, so it is overwhelmingly more likely, and a system left alone drifts towards it. Ink spreading through water isn't obeying a rule against gathering back; there are just unimaginably more ways for it to be spread than gathered. The equation is carved on Boltzmann's gravestone in Vienna.

Check 8

A glass of water is put in a freezer and turns to ice. What happens to entropy?

a the entropy of the water rises, since its energy spreads out as it freezes
b the total entropy falls, which is allowed because work is done
c the water's entropy falls, but the total entropy (including the room, warmed by the freezer) rises
d nothing changes, since freezing is reversible

IN SHORT

Key ideas of Unit 5

- The **second law** gives the direction of natural processes. **Kelvin–Planck:** no engine working in a cycle can turn all the heat from one reservoir into work. **Clausius:** heat can't flow by itself from a colder body to a hotter one. The two are equivalent.
- The first law says how much energy; the second, which way it goes and how much can be used.
- A **heat engine** takes Q_1 from a source, does work $W = Q_1 - Q_2$, gives Q_2 to a sink: $\eta = 1 - Q_2/Q_1 < 1$.
- **Carnot's theorem:** no engine between two temperatures beats a reversible one, and all reversible ones are equally efficient.
- **Carnot's cycle:** isothermal expansion at T_1, adiabatic expansion, isothermal compression at T_2, adiabatic compression. $W = nR(T_1 - T_2)\ln(V_2/V_1)$, $\eta = 1 - T_2/T_1$, $Q_2/Q_1 = T_2/T_1$ (kelvin).
- A **refrigerator** is a reversed engine: $Q_1 = Q_2 + W$, coefficient of performance $\beta = Q_2/W = Q_2/(Q_1 - Q_2)$, ideally $T_2/(T_1 - T_2)$.
- **Petrol engine** (Otto): four strokes, spark ignition, heat added at constant volume, $\eta = 1 - 1/r^{\gamma-1}$, r 8–12. **Diesel engine:** compression ignition, heat added at constant pressure, r 14–25, more efficient in practice.
- **Entropy** measures disorder, how spread out energy is: $dS = dQ/T$ (J/K). The total entropy of a system and its surroundings never decreases: it rises in irreversible processes, stays the same in reversible ones.

where dS is the change in entropy, dQ the heat added and T the absolute temperature at which it is added. The unit of entropy is **J/K**. Heat added raises a system's entropy; heat taken out lowers it. The same heat raises the entropy more at a low temperature than at a high one, as a coin matters more to a poor person than a rich one.

- The molecules of a **solid** are the most ordered, held in place; those of a **gas** the least, flying anywhere. So, for the same substance, entropy of gas > entropy of liquid > entropy of solid.
- In a **reversible adiabatic** process no heat is exchanged, so $dS = 0$: the entropy stays constant. (An irreversible adiabatic process, like the free rushing of a gas into a vacuum, raises the entropy, though no heat flows.)
- To **lower** the entropy of a system, heat must be taken out of it. A cup of tea cooling on the table loses entropy by itself, because the cooler room gains more. But to cool something below the temperature of its surroundings, as when food is cooled in a refrigerator on a warm day, work must be done.

WORKED EXAMPLE

Melting ice

How much does the entropy of 1 kg of ice at 0 °C change when it melts to water at 0 °C? (Specific latent heat of fusion of ice = 334 000 J/kg.)

Answer

The ice takes in $Q = mL = 1 \times 334\,000 = 334\,000$ J at the steady temperature $T = 273$ K, so

$$\Delta S = \frac{Q}{T} = \frac{334\,000}{273} = \mathbf{1223\ J/K}$$

an **increase**: the molecules of water, free to slide past one another, are less ordered than those locked in ice.

Check 7

600 J of heat is given reversibly to a large body at 300 K, and another 600 J to a large body at 600 K. Whose entropy rises more?

a the body at 300 K: by 2 J/K, against 1 J/K
b the body at 600 K, because it is hotter
c both by the same, since the heat is the same
d neither: entropy changes only when a body melts or boils

Second law in terms of entropy

> In every process, the total entropy of a system and its surroundings taken together (or of any isolated system) either increases or, for a reversible process, stays the same. It never decreases.

$$\Delta S_{\text{total}} \geq 0 \qquad \begin{cases} \Delta S_{\text{total}} > 0 & \text{irreversible process} \\ \Delta S_{\text{total}} = 0 & \text{reversible process} \end{cases}$$

The entropy of one part can fall, but only if another part's rises by more. When water freezes in a freezer, its entropy falls, but the refrigerator gives the room more than enough heat to make up for it.

WORKED EXAMPLE

Why heat flows from hot to cold

1000 J of heat flows from a hot body at 400 K to a cold body at 300 K (both so large that their temperatures don't change). Find the change in the total entropy.

Answer

The hot body loses 1000 J at 400 K: $\Delta S_{\text{hot}} = -\dfrac{1000}{400} = -2.50$ J/K.

The cold body gains 1000 J at 300 K: $\Delta S_{\text{cold}} = +\dfrac{1000}{300} = +3.33$ J/K.

$$\Delta S_{\text{total}} = -2.50 + 3.33 = \mathbf{+0.83\ J/K}$$

The total entropy rises, so this can happen by itself. Heat flowing from cold to hot would give −0.83 J/K, a fall, which the second law forbids: that is the Clausius statement in the language of entropy.

In a Carnot cycle, the gas gains entropy Q_1/T_1 from the source and gives out Q_2/T_2 to the sink. Since $Q_2/Q_1 = T_2/T_1$, these are equal: the total entropy doesn't change, as it shouldn't for a reversible cycle. An engine that gave out less heat than $Q_1 T_2/T_1$, to beat Carnot's efficiency, would destroy entropy: the second law forbids it.

The principle of increase of entropy (or of the **degradation of energy**): almost every natural process is irreversible, so the entropy of the universe keeps increasing. Energy is never destroyed, but each irreversible process leaves it more spread out, less



Figure 5.4 *A steam locomotive of the Darjeeling Himalayan Railway, just across Nepal's eastern border. Its source is the coal fire in its firebox, at the back of the boiler; its sink is the open air, which the exhaust steam and smoke carry the waste heat into.*

Photo: Ankur P from Pune, India, CC BY 2.0

5.4 Carnot's theorem

In 1824 the young French engineer **Sadi Carnot** worked out the best that any heat engine can possibly do. His **theorem** sets a fundamental limit on the efficiency of heat engines: the efficiency of a reversible engine depends only on the temperatures of its source and sink, not on its working substance.

Carnot's theorem:

> All reversible engines working between the same two reservoirs have the same efficiency, and no engine working between the same two reservoirs can have a greater efficiency than a reversible engine.

So no heat engine can be more efficient than **Carnot's engine** working between the same two temperatures.

Why? Suppose some engine X were more efficient than a reversible engine R between the same two reservoirs. Since R is reversible, it can be run backwards as a refrigerator. Let X drive R backwards. X takes heat from the hot reservoir and does work; being more efficient than R, it can supply all the work R needs while taking less heat from the hot reservoir than R puts back into it. Taken together, the two machines do no net work, yet the hot reservoir gains heat and the cold reservoir loses the same amount: heat has flowed from cold to hot by itself, against the Clausius statement. So X can't exist. The same argument, with any two reversible engines, shows that neither can beat the other, so all reversible engines between the same reservoirs are equally efficient.

Check 3

Two reversible engines work between the same boiler and the same river. One uses steam, the other air. Which is more efficient?

a the steam engine, since steam carries more heat
b the air engine, since air is an ideal gas
c neither: both have the same efficiency
d it depends on the size of the engines

A STORY FROM SCIENCE

The engineer who never saw his law accepted

Nicolas Léonard Sadi Carnot (1796–1832) was the son of Lazare Carnot, one of the leaders of the French Revolution and a famous mathematician of machines. A French army engineer, he worried that Britain's steam engines gave it an advantage France lacked. In 1824 he published, at his own expense, a short book, *Reflections on the Motive Power of Fire*, which asked how much work an engine can possibly get from heat. His answer, that it depends on the temperatures between which the heat "falls", as the work of a water wheel depends on the height the water falls, was decades ahead of its time. Hardly anyone read it. He died of cholera in Paris at 36, and most of his papers were burned with his belongings, as was done then for fear of infection. His ideas survived through a paper by Émile Clapeyron, and in the late 1840s Kelvin and Clausius took them up and built the second law on them.



Figure 5.5 *Sadi Carnot at 17, as a student of the École polytechnique in Paris.*
Photo: Louis-Léopold Boilly, Public domain

5.5 Carnot's engine and Carnot's cycle

Carnot's engine is an imaginary, ideal engine designed to get the greatest possible efficiency from a given source and sink. It is free of all the imperfections of real engines: no friction, no heat leaking, and every step reversible. Its working cycle, **Carnot's cycle**, is made of **two isothermal and two adiabatic processes** (Unit 4). Its parts (Figure 5.6):

1. **Source:** a hot body of infinite heat capacity, kept at a constant high temperature T_1. Any amount of heat can be taken from it without lowering its temperature. *For example,* a furnace or a boiler.
2. **Sink:** a cold body of infinite heat capacity, kept at a constant low temperature T_2. Any amount of heat can be given to it without raising its temperature. *For example,* the atmosphere, or the water of a river or heat exchanger.
3. **Insulating stand:** a perfectly non-conducting platform. On it, the cylinder can exchange no heat.
4. **Working substance:** an **ideal gas**.
5. **Cylinder and piston:** the gas is held in a cylinder with **perfectly non-conducting walls** but a **perfectly conducting base**, closed by a frictionless, weightless, airtight and non-conducting piston.

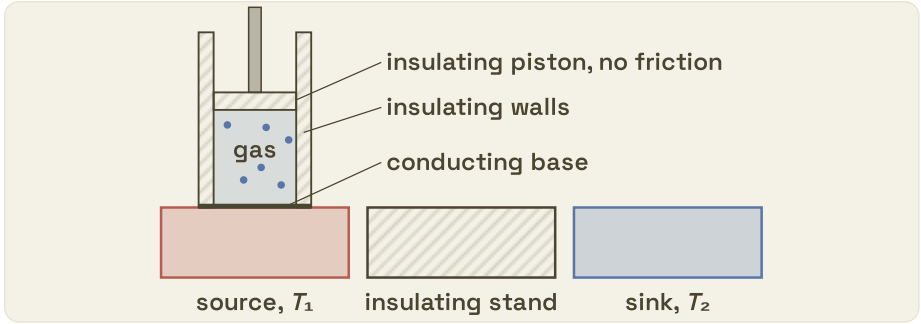


Figure 5.6 *Carnot's engine. The cylinder of ideal gas has insulating walls and piston but a conducting base, so heat can pass only through its base. It is moved in turn between the source, the insulating stand and the sink.*

Working of Carnot's engine

Take n moles of ideal gas in the cylinder, starting at point $A(P_1, V_1, T_1)$ on the P–V diagram (Figure 5.7). The cycle has four steps.

Step 1: isothermal expansion (AB). The cylinder is placed on the source at T_1, and the gas expands slowly at that temperature from $A(P_1, V_1, T_1)$ to $B(P_2, V_2, T_1)$. It takes in heat Q_1 from the source through the base. For an isothermal process $\Delta U = 0$, so all of Q_1 comes out as work (Unit 4, Section 4.11):

$$W_1 = Q_1 = nRT_1 \ln \frac{V_2}{V_1} \tag{5.1}$$

Step 2: adiabatic expansion (BC). The cylinder is moved onto the insulating stand, and the gas keeps expanding, now with no heat coming in, from $B(P_2, V_2, T_1)$ to $C(P_3, V_3, T_2)$. It does work out of its own internal energy, so it cools until it reaches the

A STORY FROM SCIENCE

The engine that was meant to beat the steam engine

Rudolf Diesel (1858–1913) was born in Paris to German parents from Bavaria, and studied engineering in Munich, where he heard a lecture on Carnot's cycle and the poor efficiency of steam engines, which wasted about 90% of their coal. He set out to build an engine as close to Carnot's as he could, and in 1893 patented one that lit its fuel by compressing air alone. His first test engine exploded and nearly killed him; by 1897 one ran at about 26% efficiency, more than twice that of the best steam engines of the time. Diesel hoped his engine would let small workshops compete with big factories, and it could burn vegetable oils as well as mineral oil. In 1913 he vanished from a ship crossing the English Channel; his body was found in the sea days later, and what happened has never been settled.

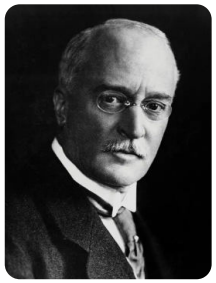


Figure 5.14 *Rudolf Diesel.*
Photo: Unknown author, Public domain

	Petrol engine (Otto cycle)	Diesel engine (Diesel cycle)
Takes in	air–petrol mixture	air only
Ignition	by a spark plug	by the heat of compression (no spark)
Fuel enters	with the air, in the suction stroke	sprayed in by an injector at the end of compression
Heat added	at constant volume	at (roughly) constant pressure
Compression ratio	about 8 to 12 (limited by knocking)	about 14 to 25
Ideal efficiency	$1 - 1/r^{\gamma-1}$: 56–63%	about 59–68% (cut-off ratio 2)
Real efficiency	about 25–35%	about 35–45%
Build	lighter, cheaper	heavier, stronger, dearer

The worked examples on Carnot's engine (Examples 5.1–5.3) are in Section 5.5, beside the formula they use.

Check 6

Why don't petrol engines use compression ratios of 20, like diesel engines, to be more efficient?

a. a spark can't jump across such a small gap
b. the squeezed petrol–air mixture would get hot enough to catch fire by itself before the spark (knocking)
c. the Otto cycle's efficiency falls when the compression ratio is above 12
d. petrol doesn't burn at high pressure

5.8 Entropy

Entropy is the key to the direction of natural processes and to the limits of efficiency. It is a **state variable**, like temperature or internal energy (Unit 4): a system in a given state has a definite entropy. It was first brought in by Clausius, from the study of heat engines, and it was later understood as a measure of the **disorder** (randomness) of the particles in a system, or more exactly, of how spread out its energy is among them. The more spread out the energy, the less of it is available to do useful work.

Entropy can't be felt or seen, as temperature or pressure can; we know it through the changes it measures. A **small change in entropy** is defined as the heat dQ given to a system **reversibly**, divided by the absolute temperature T at which it is given:

$$\boxed{dS = \frac{dQ}{T}}$$

4. **Exhaust stroke:** the exhaust valve opens and the pressure falls to atmospheric, heat Q_2 leaving with the gas at almost constant volume, line **EB**; then the piston pushes the burnt gas out at atmospheric pressure, back to the clearance volume, line **BA**.

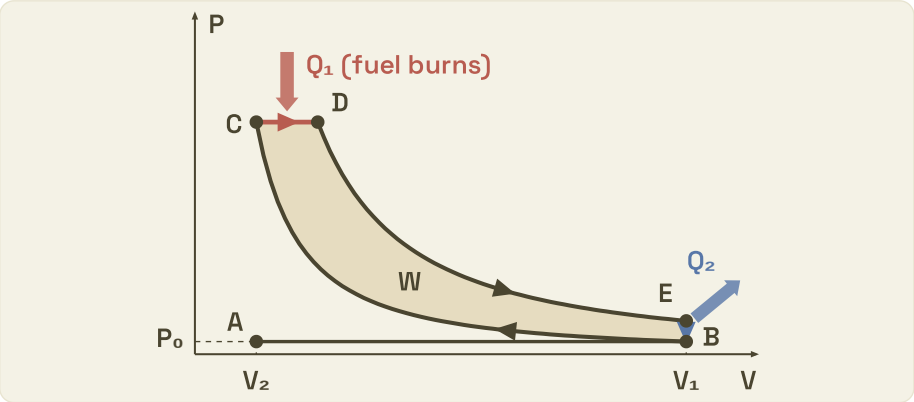


Figure 5.13 *The Diesel cycle, computed for air with a compression ratio of 8 and a cut-off ratio of 2 (real engines 14 to 25): suction AB, adiabatic compression BC, heat Q_1 added at constant pressure CD as the fuel burns, adiabatic expansion DE, heat Q_2 out at constant volume EB, exhaust BA.*

Efficiency of the diesel engine

The difference from the Otto cycle is that the heat comes in at **constant pressure**, so it carries a second ratio, the **cut-off ratio** $\rho_c = V_D/V_C$, how much the gas expands while fuel is burning.

1. Heat in, at constant pressure (CD): $Q_1 = nC_P(T_D - T_C)$. Heat out, at constant volume (EB): $Q_2 = nC_V(T_E - T_B)$. So, with $C_P = \gamma C_V$,

$$\eta = 1 - \frac{T_E - T_B}{\gamma\,(T_D - T_C)}$$

2. BC adiabatic: $T_C = T_B\, r^{\gamma-1}$. CD at constant pressure: $T_D = \rho_c\, T_C$. DE adiabatic from $V_D = \rho_c V_C$ to V_1: $T_E = T_D\left(\frac{\rho_c}{r}\right)^{\gamma-1} = T_B\,\rho_c^{\gamma}$.
3. Putting these in:

$$\boxed{\eta = 1 - \frac{1}{r^{\gamma-1}} \cdot \frac{\rho_c^{\gamma} - 1}{\gamma\,(\rho_c - 1)}}$$

The second factor is always greater than 1, so **at the same compression ratio** a diesel cycle is a little **less** efficient than an Otto cycle. But the diesel engine compresses only air, which can't knock, so it can use much higher compression ratios, and that makes it the more efficient engine. With $\rho_c = 2$: about 59% at $r = 14$ and 68% at $r = 25$ in theory; real diesel engines reach 35–45%, and the largest ship engines over 50%.

> CAREFUL
> **Not the Otto formula**
>
> Some books give the diesel engine the same formula as the petrol engine, $1 - 1/r^{\gamma-1}$, and so ideal efficiencies of 65% to 72% for compression ratios of 14 to 25. That formula is for heat added at constant volume; the diesel engine adds it at constant pressure, and its efficiency also depends on the cut-off ratio, as above. The Otto formula overstates it: it is the most a diesel engine with that compression ratio could reach. If a question gives a diesel engine's compression ratio and nothing else, it expects $1 - 1/r^{\gamma-1}$: use it, and add that this is the upper limit, since the true value needs the cut-off ratio.

Uses of diesel engines: cars, buses and lorries; tractors and irrigation pumps; excavators, bulldozers, cranes and generators; ships, boats and fishing vessels; power plants and backup generators; military vehicles and submarines; railway locomotives.

Merits: high fuel efficiency; durable, with a long working life; diesel is cheaper (in many countries) and less of a fire risk; better for heavy loads, with strong pulling force at low speed; useful for a wide range of jobs.

Demerits: costs more to buy; heavier and larger for the same power; noisier, with more vibration; servicing and repairs cost more; more soot and nitrogen oxides in the exhaust unless cleaned; not well suited to light vehicles.

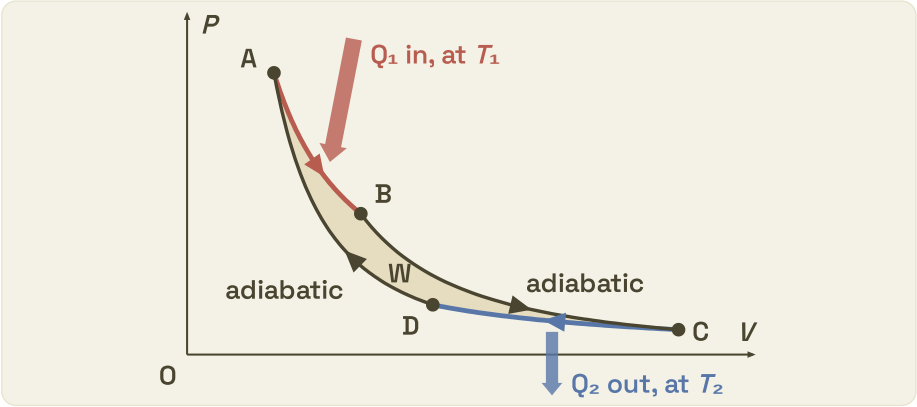


Figure 5.7 *Carnot's cycle, computed for a monatomic ideal gas between $T_1 = 500$ K and $T_2 = 250$ K: isothermal expansion AB at T_1, adiabatic expansion BC, isothermal compression CD at T_2, adiabatic compression DA. It goes round clockwise, and the shaded area is the net work done in each cycle.*

sink's temperature T_2. By Section 4.12,

$$W_2 = \frac{nR(T_1 - T_2)}{\gamma - 1} \tag{5.2}$$

Step 3: isothermal compression (CD). The cylinder is placed on the sink at T_2, and the gas is compressed slowly from $C(P_3, V_3, T_2)$ to $D(P_4, V_4, T_2)$. Work is done on the gas, and since its temperature doesn't change, it gives out an equal amount of heat Q_2 to the sink:

$$W_3 = nRT_2 \ln\frac{V_4}{V_3} = -nRT_2 \ln\frac{V_3}{V_4}, \qquad Q_2 = nRT_2 \ln\frac{V_3}{V_4} \tag{5.3}$$

(W_3 is negative, work done on the gas; Q_2 is the heat given out, a positive amount.)

Step 4: adiabatic compression (DA). The cylinder is moved back onto the insulating stand, and the gas is compressed from $D(P_4, V_4, T_2)$ back to $A(P_1, V_1, T_1)$. The work done on it raises its internal energy, and its temperature rises back to T_1:

$$W_4 = \frac{nR(T_2 - T_1)}{\gamma - 1} = -\frac{nR(T_1 - T_2)}{\gamma - 1} \tag{5.4}$$

The gas is back where it started, and the engine is ready for the next cycle.

Net work and efficiency

1. The net work done in one cycle is the sum of the four:

$$W = W_1 + W_2 + W_3 + W_4 = nRT_1 \ln\frac{V_2}{V_1} + \frac{nR(T_1 - T_2)}{\gamma - 1} - nRT_2 \ln\frac{V_3}{V_4} - \frac{nR(T_1 - T_2)}{\gamma - 1}$$

The two adiabatic works cancel, so

$$W = nRT_1 \ln\frac{V_2}{V_1} - nRT_2 \ln\frac{V_3}{V_4} = Q_1 - Q_2 \tag{5.5}$$

2. B and C lie on the same adiabat, and so do D and A. By $TV^{\gamma-1} = \text{constant}$ (Section 4.12):

$$T_1 V_2^{\gamma-1} = T_2 V_3^{\gamma-1} \tag{5.6}$$

$$T_1 V_1^{\gamma-1} = T_2 V_4^{\gamma-1} \tag{5.7}$$

3. Dividing (5.6) by (5.7):

$$\left(\frac{V_2}{V_1}\right)^{\gamma-1} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} \quad \Rightarrow \quad \frac{V_2}{V_1} = \frac{V_3}{V_4} \tag{5.8}$$

4. Putting (5.8) into (5.5):

$$W = nRT_1 \ln\frac{V_2}{V_1} - nRT_2 \ln\frac{V_2}{V_1} = nR(T_1 - T_2)\ln\frac{V_2}{V_1} \tag{5.9}$$

Since $T_1 > T_2$ and $V_2 > V_1$, W is positive: the engine does net work in each cycle, the area enclosed by the loop, and repeating the cycle gives as much work as we want.

5. The efficiency is

$$\eta = \frac{W}{Q_1} = \frac{nR(T_1 - T_2)\ln(V_2/V_1)}{nRT_1\ln(V_2/V_1)} = \frac{T_1 - T_2}{T_1}$$

$$\boxed{\eta = 1 - \frac{T_2}{T_1}} \tag{5.10}$$

Comparing with $\eta = 1 - Q_2/Q_1$, for a Carnot engine

$$\boxed{\frac{Q_2}{Q_1} = \frac{T_2}{T_1}}$$

The efficiency of Carnot's engine depends **only on the temperatures of the source and the sink**, in kelvin. It doesn't depend on the working substance, or on the design of the engine. That is why all reversible engines working between the same two temperatures have the same efficiency, whatever they are made of. It also shows two things about every engine:

- To raise the efficiency, make the source hotter or the sink colder. A power station's turbines run on steam as hot as their metal can stand, and its condensers are cooled by a river.
- The efficiency could only be 100% if $T_2 = 0$ K, and absolute zero can't be reached: so no engine is ever 100% efficient.

CAREFUL

Kelvin, never Celsius

In $\eta = 1 - T_2/T_1$ and $Q_2/Q_1 = T_2/T_1$, the temperatures **must** be in kelvin. Between 100 °C and 0 °C a Carnot engine has $\eta = 1 - 273/373 = 26.8\%$; with Celsius you would get $1 - 0/100 = 100\%$, which is impossible.

WORKED EXAMPLE

Example 5.1: the same efficiency

A Carnot engine has the same efficiency i. between 100 K and 500 K, and ii. between T K and 900 K. Calculate the temperature T of the sink in ii.

Answer

i. Source $T_1 = 500$ K, sink $T_2 = 100$ K:

$$\eta = 1 - \frac{T_2}{T_1} = 1 - \frac{100}{500} = 1 - 0.2 = 0.8$$

ii. Source $T_1 = 900$ K, the same efficiency 0.8:

$$0.8 = 1 - \frac{T}{900} \quad \Rightarrow \quad \frac{T}{900} = 0.2 \quad \Rightarrow \quad T = \mathbf{180\ K}$$

For the same efficiency, the ratio T_2/T_1 must be the same, 1/5: so the sink is at 900/5 = 180 K.

WORKED EXAMPLE

Example 5.2: one cycle of an engine

A Carnot engine takes in 1000 J of heat from a reservoir at 127 °C and gives out 600 J of heat in each cycle. Calculate i. the efficiency of the engine, ii. the temperature of the sink, iii. the useful work done in each cycle.

Answer

$Q_1 = 1000$ J, $Q_2 = 600$ J, $T_1 = 127 + 273 = 400$ K.

i. $\eta = 1 - \dfrac{Q_2}{Q_1} = 1 - \dfrac{600}{1000} = 0.4 = \mathbf{40\%}$.

ii. For a Carnot engine $\dfrac{Q_2}{Q_1} = \dfrac{T_2}{T_1}$, so

$$T_2 = T_1 \times \frac{Q_2}{Q_1} = 400 \times \frac{600}{1000} = \mathbf{240\ K} = 240 - 273 = \mathbf{-33\ ^\circ C}$$

iii. $W = Q_1 - Q_2 = 1000 - 600 = \mathbf{400\ J}$.

3.

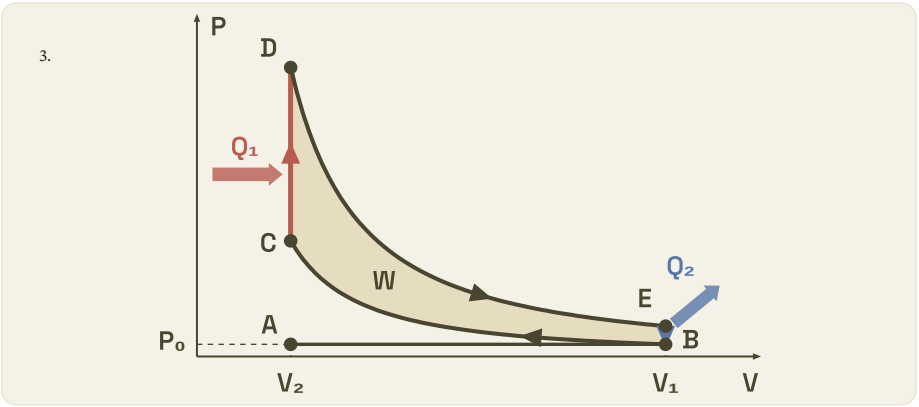


Figure 5.11 *The Otto cycle, computed for air with a compression ratio of 5 (real engines use 8 to 12, which would make the loop a thin spike): suction AB, adiabatic compression BC, heat Q1 added at constant volume CD, adiabatic expansion DE, heat Q2 out at constant volume EB, exhaust BA. The shaded loop BCDE is the work done in each cycle.*

BC is adiabatic, from V_1 to V_2: $T_B V_1^{\gamma-1} = T_C V_2^{\gamma-1}$, so $T_C = T_B\, r^{\gamma-1}$. DE is adiabatic, from V_2 to V_1: likewise $T_D = T_E\, r^{\gamma-1}$.

4. So $T_D - T_C = (T_E - T_B)\, r^{\gamma-1}$, and

$$\boxed{\eta = 1 - \frac{1}{r^{\gamma-1}} = 1 - \left(\frac{V_2}{V_1}\right)^{\gamma-1}}$$

The efficiency of the ideal petrol engine depends only on its **compression ratio** (and γ): the more the mixture is squeezed, the more efficient the engine. For air, $\gamma \approx 1.4$; with compression ratios of 8 to 12, the ideal efficiency is 56% to 63%. (Real petrol engines, with friction, heat lost through the cylinder walls and burning that takes time, reach 25% to 35%.)

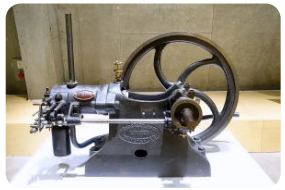


Figure 5.12 *A four-stroke gas engine built to Otto's design by Crossley Brothers of Manchester, between 1876 and 1910 (Tekniska museet, Stockholm). It ran on coal gas, not petrol, but its four strokes are the same.*
Photo: Daderot, CC0

Why not squeeze harder? A petrol–air mixture squeezed too much gets so hot that parts of it catch fire by themselves before the flame from the spark reaches them. The pressure spikes, making a metallic rattle called **knocking**, which wastes power and can damage the engine. That keeps the compression ratio of petrol engines to about 12 or less (higher-octane petrol resists knocking better).

Uses of petrol engines: cars, motorbikes and scooters, light vans and trucks; small aircraft; pumps and compressors; small boats; generators, lawn mowers, chainsaws and other power tools.

Merits: light and compact, with a high power-to-weight ratio; smooth and quiet running; cheaper to buy; easy to start; can run at high speeds (high revolutions per minute); little visible smoke; petrol is easy to get; maintenance is cheap.

Demerits: less fuel-efficient than a diesel engine; petrol costs more; shorter working life and less durable; not suited to heavy loads; risk of knocking (pre-ignition); petrol vapor catches fire easily; limited industrial use; spark plugs can fail.

Diesel engine

A **diesel engine** is a four-stroke internal combustion engine that needs **no spark**: the fuel catches fire in the hot compressed air. It is more efficient than a petrol engine. It is named after the German engineer **Rudolf Diesel**, who designed it in the 1890s. Its working substance is air, with diesel oil as the fuel.

Its cylinder has an **intake valve**, a **fuel injector** (in place of the spark plug) and an **exhaust valve**. Its build and working are much like a petrol engine's:

1. **Suction stroke:** the intake valve opens, the injector and exhaust valve are closed, and the piston moves out, drawing in **air only**, to volume V_1 at atmospheric pressure: line **AB** (Figure 5.13).
2. **Compression stroke:** all valves closed, the piston compresses the air **adiabatically**: line **BC**. Its compression ratio is much higher than a petrol engine's, 14 to 25, so the air becomes very hot, 500 °C or more. At the end, the injector sprays diesel into it, and the fuel catches fire by itself in the hot air. The fuel keeps burning as it is sprayed in while the piston starts to move out, so heat Q_1 is added at roughly **constant pressure**, line **CD**, until the injection stops at D.
3. **Working stroke:** the hot gas expands **adiabatically**, driving the piston out and doing work: line **DE**.

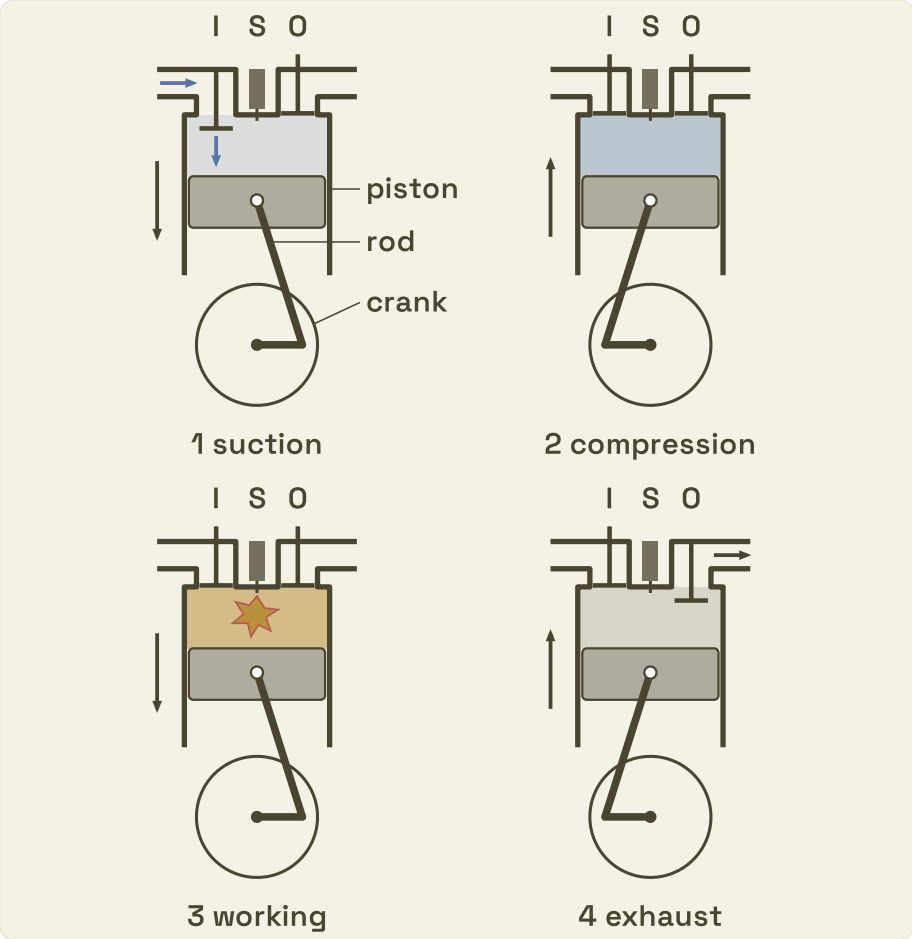


Figure 5.10 *The four strokes of a petrol engine, each drawn halfway through: suction (intake valve I open, piston going down), compression (both valves closed, piston going up), working stroke (the spark plug S has fired and the burning gas drives the piston down) and exhaust (outlet valve O open, piston going up).*

3. **Working (power) stroke:** the hot, high-pressure gas expands **adiabatically**, driving the piston out hard and doing work, until its volume is again V_1: line **DE**. This is the only stroke in which the engine does work; the flywheel carries the engine through the other three.
4. **Exhaust stroke:** the outlet valve opens near the end of the working stroke, and the pressure drops at once to atmospheric as hot gas rushes out, the volume staying almost V_1: heat Q_2 leaves with it, line **EB**. Then the piston moves in and pushes the rest of the burnt gas out at atmospheric pressure, down to the small volume V_2 left above the piston (the **clearance volume**, where the next charge will be squeezed), line **BA**. The cycle starts again.

Lines AB and BA cancel (the same line, gone both ways), so the work done in a cycle is the area of the loop **BCDEB**.

Efficiency of the petrol engine

The **compression ratio** r is the ratio of the largest volume to the smallest: $r = V_1/V_2$. Treat the working substance as n moles of air, an ideal gas with heat capacity C_V and ratio γ, and call the temperatures at B, C, D, E T_B, T_C, T_D, T_E.

1. Heat in, at constant volume (CD): $Q_1 = nC_V(T_D - T_C)$. Heat out, at constant volume (EB): $Q_2 = nC_V(T_E - T_B)$.
2. So

WORKED EXAMPLE

Example 5.3: cool the sink, double the efficiency

A reversible engine turns one sixth of the heat it takes in into work. When the temperature of the sink is lowered by 62 °C, its efficiency doubles. Find the temperatures of the source and the sink.

Answer

At first, $\eta = \dfrac{W}{Q_1} = \dfrac{1}{6}$, and $\eta = 1 - \dfrac{T_2}{T_1}$, so

$$\frac{T_2}{T_1} = 1 - \frac{1}{6} = \frac{5}{6} \quad \Rightarrow \quad T_1 = 1.2\,T_2 \tag{i}$$

A fall of 62 °C is a fall of 62 K, so the new sink temperature is $T_2 - 62$, and the new efficiency is $2 \times \frac{1}{6} = \frac{1}{3}$:

$$\frac{1}{3} = 1 - \frac{T_2 - 62}{T_1} \quad \Rightarrow \quad \frac{T_2 - 62}{T_1} = \frac{2}{3} \quad \Rightarrow \quad T_1 = 1.5\,(T_2 - 62) \tag{ii}$$

From (i) and (ii): $1.5(T_2 - 62) = 1.2\,T_2$, so $0.3\,T_2 = 93$, $T_2 = \mathbf{310\ K}$ (37 °C), and $T_1 = 1.2 \times 310 = \mathbf{372\ K}$ (99 °C).
Check: $1 - 310/372 = 1/6$ and $1 - 248/372 = 1/3$.

Check 4

A Carnot engine works between a source at 600 K and a sink at 300 K. To raise its efficiency the most, which is better: raising the source by 100 K, or lowering the sink by 100 K?

a raising the source: $1 - 300/700 = 57\%$
b lowering the sink: $1 - 200/600 = 67\%$
c both give the same, since the difference grows by 100 K either way
d neither changes the efficiency

5.6 Refrigerator

A **refrigerator** is a heat engine run in reverse. It takes heat from a region at a low temperature (the inside of the refrigerator) and gives it out to a region at a higher temperature (the room), using **work**, usually electrical energy, to move the heat against its natural direction of flow (Figure 5.8). An ideal refrigerator works on a reversed Carnot cycle.

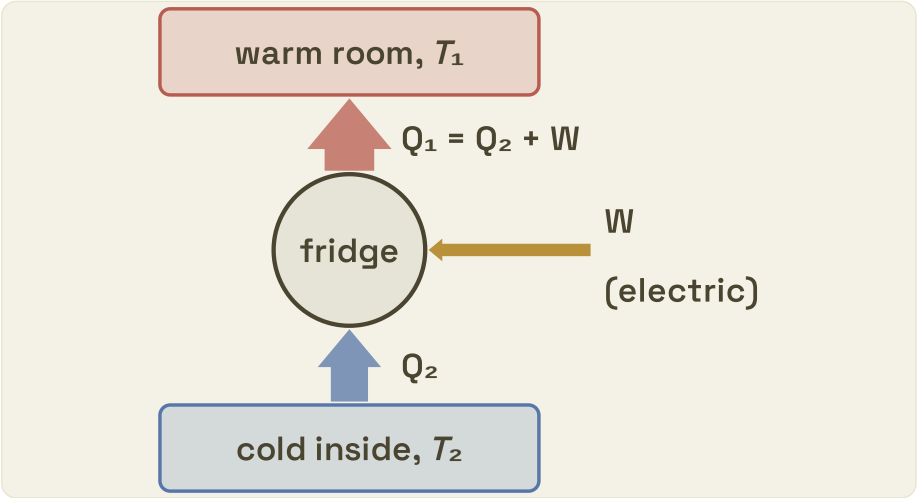


Figure 5.8 *A refrigerator: work W moves heat Q_2 out of the cold inside and gives out $Q_1 = Q_2 + W$ to the warm room. The bands are to scale for a coefficient of performance of 3.*

Its cycle has four parts (Figure 5.9). The **refrigerant**, a liquid that boils at a low temperature, circulates in a closed loop of pipes:

1. **Evaporation:** in the **evaporator** coils inside the cabinet, the cold, low-pressure liquid boils, taking its latent heat, Q_2, from the food and air inside. The inside cools.

2. **Compression:** the **compressor**, driven by an electric motor, squeezes the vapor. Work W is done on it, and like any gas compressed fast (Section 4.12), it gets hot, hotter than the room.
3. **Condensation:** in the **condenser** coils at the back, the hot vapor gives out heat Q_1 to the room and condenses back to a liquid.
4. **Expansion:** the liquid passes through a narrow **expansion valve** (or a thin capillary tube). Its pressure drops, part of it boils off at once, and it cools below the temperature inside the cabinet, ready to take in heat again.

A **thermostat** switches the compressor on and off to keep the inside at the chosen temperature.

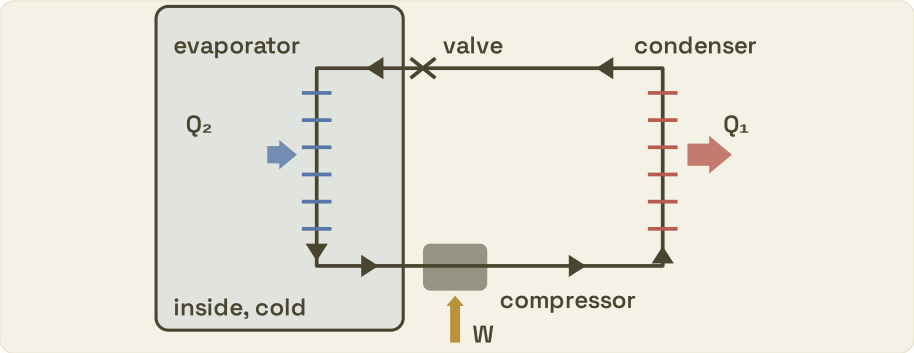


Figure 5.9 *The refrigerant's loop. It boils in the evaporator inside the cabinet, taking in heat Q_2; the compressor squeezes the vapor, doing work W; in the condenser at the back it gives out heat Q_1 to the room and turns liquid; through the expansion valve its pressure drops and it cools again.*

Let the refrigerant take heat Q_2 from the inside at temperature T_2, with work W done by the compressor, and give out heat Q_1 to the room at the higher temperature T_1. By the first law, $Q_1 = Q_2 + W$: the room receives more heat than was taken from inside. Here the work $W = Q_1 - Q_2$ is what we pay for, and the heat Q_2 removed from inside is what we want.

The performance of a refrigerator is measured by its **coefficient of performance** β (COP): the ratio of the heat taken from the cold body to the work done by the compressor:

$$\beta = \frac{\text{heat taken from the cold body}}{\text{work done}} = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2}$$

Dividing the top and bottom by Q_2:

$$\beta = \frac{1}{\dfrac{Q_1}{Q_2} - 1}$$

For an ideal (Carnot) refrigerator, $\dfrac{Q_1}{Q_2} = \dfrac{T_1}{T_2}$, so

$$\beta = \frac{1}{\dfrac{T_1}{T_2} - 1} \quad \Rightarrow \quad \boxed{\beta = \frac{T_2}{T_1 - T_2}}$$

So the coefficient of performance of an ideal refrigerator depends only on the two temperatures: every reversible refrigerator working between the same two temperatures has the same β, whatever its refrigerant. The smaller the difference $T_1 - T_2$, the larger β: less work is needed to move each joule of heat. A real refrigerator always has a smaller β than $T_2/(T_1 - T_2)$. Unlike an efficiency, β is usually **greater than 1**: a refrigerator can move several joules of heat for each joule of work.

CAREFUL

β is not an efficiency

A COP of 4 doesn't mean energy is made from nothing. The refrigerator doesn't turn its work **into** cold; it uses each joule of work to **move** 4 joules of heat that already exist from inside to outside. The room gets all of it back, plus the joule of work: 5 J.

WORKED EXAMPLE

A refrigerator in Biratnagar

On a summer day, the room is at 37 °C and the inside of a refrigerator at 4 °C. a. What is the best possible coefficient of performance? b. If its compressor actually uses 100 J of work for every 300 J of heat it removes, how does it compare?

Answer

a. $T_1 = 37 + 273 = 310$ K, $T_2 = 4 + 273 = 277$ K.

$$\beta_{\max} = \frac{T_2}{T_1 - T_2} = \frac{277}{310 - 277} = \frac{277}{33} = \mathbf{8.4}$$

b. $\beta = \dfrac{Q_2}{W} = \dfrac{300}{100} = \mathbf{3}$, well under the ideal 8.4, as real machines always are: the refrigerant must be colder than the cabinet and hotter than the room for heat to flow into and out of it quickly, and the compressor has losses.

Check 5

A refrigerator takes 300 J of heat out of its cold inside while its compressor does 100 J of work. How much heat does it give out to the kitchen?

a 200 J
b 300 J
c 400 J
d 100 J

DID YOU KNOW?

A heat pump: a refrigerator turned inside out

A **heat pump** is a refrigerator whose "inside" is the outdoors: it takes heat from the cold air outside and gives it to the room, with a COP for heating of Q_1/W, often 3 to 4. So for each unit of electricity it delivers 3 to 4 units of heat, where an electric heater gives exactly 1. The "inverter air conditioners" now sold in Nepal that can heat as well as cool are heat pumps: in Kathmandu's winter, they heat a room for a third of the electricity of a heater.

5.7 Internal combustion engines

Heat engines are of two kinds, which differ in **where the fuel burns**. In an **external combustion engine**, such as a steam engine, the fuel burns outside, under a boiler, and the heat passes through the boiler's walls into the working substance. In an **internal combustion engine**, the fuel burns **inside the cylinder** itself, and the hot gases it makes push directly on the moving part, a piston or a turbine. *Examples:* the engines of cars, buses, lorries, tractors and motorbikes; the jet engines of aircraft.

Internal combustion engines are smaller and lighter than external combustion engines of the same power, and can be more efficient, but they burn fuel inside a machine that moves, and add to air pollution and noise. The two main kinds are the **petrol engine** and the **diesel engine**.

Petrol engine (Otto engine)

A **petrol engine** (gasoline engine) is a four-stroke internal combustion engine whose fuel is lit by a **spark**. Its ideal cycle is the **Otto cycle**, after the German engineer **Nikolaus August Otto**, who built the first successful four-stroke engine in 1876. Its working substance is air mixed with a little petrol vapor (about 2% by volume).

It has a metal cylinder with an **intake valve** I, a **spark plug** S and an **outlet** (exhaust) **valve** O. A piston moves in the cylinder, joined by a connecting rod to a crank, which turns the piston's up-and-down motion into the turning of a shaft, and a heavy **flywheel** keeps the shaft turning smoothly through the strokes that do no work. Cams on a shaft turned by the engine open and close the valves at the right moments. The four strokes (Figure 5.10) take two turns of the crank:

1. **Suction (intake) stroke:** the intake valve opens, the outlet valve stays closed, and the piston moves out (down). The pressure inside falls slightly, and the air–petrol mixture is drawn in (from the carburetor, or from fuel injectors in a modern engine). When the piston reaches the end, the intake valve closes, with the mixture at volume V_1 and atmospheric pressure: line **AB** on the P–V diagram (Figure 5.11).
2. **Compression stroke:** both valves are closed, and the piston moves in, compressing the mixture **adiabatically** to the small volume V_2: line **BC**. Its pressure and temperature rise. At the end, the spark plug fires, and the mixture burns almost at once, before the piston has time to move: heat Q_1 is added **at constant volume** V_2, and the temperature and pressure jump: line **CD**.