THE

LAST CODEX

If everything were lost, this is where we would start again.

The inventions of humankind: what they are, how they work and how to build them again.

Print edition of October 14, 2026
https://lastcodex.org

Contents

I Survival

Stone Tools · 3.3 million years ago · 5
Control of Fire · 1 million years ago · 9
Rope & Cordage · 50,000 years ago · 13

II Settlement

Bow & Arrow · 62,000 years ago · 18
Pottery · 18,000 years ago · 22
Bread · 12,400 years ago · 26
Lime and lime mortar · 10,000 years ago · 30
Drinking Water · c. 8,400 BCE · 34
Bricks · c. 7,500 BCE · 39
Weaving · c. 6,700 BCE · 43
Salting & Curing · c. 6,050 BCE · 47
Irrigation · c. 6,000 BCE · 51
Cheese · c. 5,500 BCE · 55
Plough · c. 5,000 BCE · 58
Charcoal · c. 4,500 BCE · 62
Dyeing · c. 4,200 BCE · 66
Arch and Vault · c. 3,500 BCE · 70
Beer · c. 3,500 BCE · 74
Wheel & Axle · c. 3,500 BCE · 78
Writing · c. 3,300 BCE · 82
Sail · c. 3,200 BCE · 86
Soap · c. 2,800 BCE · 90
Positional Numerals · c. 2,050 BCE · 94
Leather Tanning · c. 1,500 BCE · 98
Sundial · c. 1,500 BCE · 102
Crop Rotation · c. 700 BCE · 106
Lock & Key · c. 700 BCE · 111

III Crafts & cities

Potter's Wheel · c. 4,000 BCE · 116
Bronze · c. 3,300 BCE · 120
Measures and standards · c. 3,000 BCE · 124
Glass · c. 2,500 BCE · 129
Iron Smelting · c. 1,200 BCE · 133
Steel · c. 1,000 BCE · 137
Aqueduct · c. 690 BCE · 141
Crane & Pulley · c. 515 BCE · 145
Gears · c. 300 BCE · 149
Water Wheel · c. 300 BCE · 153
Piston Pump · c. 270 BCE · 157
Roman Concrete · c. 200 BCE · 161
Paper · c. 150 BCE · 165
Distillation · c. 300 · 169
Horse Collar · c. 480 · 173
Gunpowder · c. 850 · 177
Windmill · c. 900 · 181
Spinning Wheel · c. 1000 · 185
Magnetic Compass · c. 1088 · 189
Eyeglasses · c. 1286 · 192
Mechanical Clock · c. 1300 · 196
Printing Press · c. 1440 · 200

IV Science & industry

Celestial Navigation c. 1460 · 205
Microscope c. 1590 · 209
Telescope 1608 · 213
Thermometer and barometer c. 1654 · 217
Steam Engine 1712 · 221
Hot-Air Balloon 1783 · 225
Vaccination 1796 · 229
Battery 1800 · 234
Steam Locomotive 1804 · 238
Canning & Pasteurisation 1810 · 242
Bicycle 1817 · 246
Portland Cement 1824 · 250
Photography c. 1827 · 254
Water Turbine 1827 · 258
Sewing Machine 1830 · 262
Electric Generator 1831 · 266
Electric Motor 1834 · 270
Refrigeration 1834 · 274
Electric Telegraph 1837 · 278
Vulcanised Rubber 1839 · 282
Anaesthesia 1846 · 286
Hygiene & Antisepsis 1847 · 290
Lead-Acid Battery 1859 · 294

V Electric age

Reinforced Concrete c. 1848 · 299
Internal Combustion Engine 1876 · 303
Telephone 1876 · 306
Incandescent Light Bulb 1879 · 310
Steam Turbine 1884 · 314
Transformer 1885 · 318
Aluminium 1886 · 322
Wind Turbine 1887 · 326
Radio c. 1895 · 330
X-Ray Imaging 1895 · 334
Aeroplane 1903 · 338
Penicillin 1928 · 342
Transistor 1947 · 347
Computer 1948 · 351
Solar cell 1954 · 355
Oral rehydration 1968 · 360

I

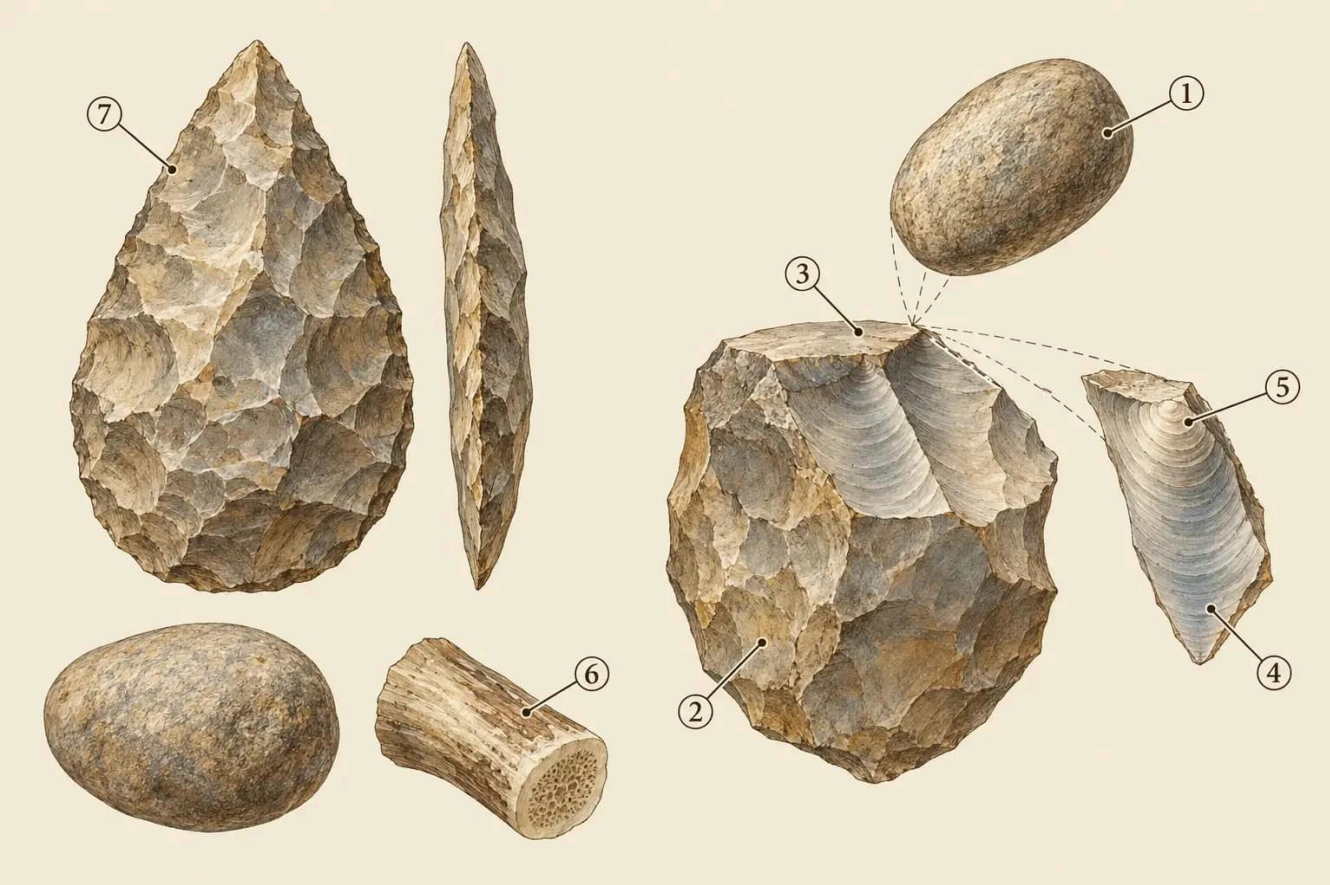
Survival

Stone Tools

The first cutting edge

3.3 million years ago · Prehistory · Survival

Leads to: Arch and Vault (p. 70), Bow & Arrow (p. 18), Charcoal (p. 62), Irrigation (p. 51), Leather Tanning (p. 98), Lime and lime mortar (p. 30), Lock & Key (p. 111), Measures and standards (p. 124), Plough (p. 58), Wheel & Axle (p. 78), Writing (p. 82)



1 Hammerstone 2 Core 3 Striking platform 4 Flake 5 Bulb of percussion 6 Antler billet 7 Hand axe

Most stone tools are pieces of rock broken in a controlled way to give a sharp edge for cutting, scraping or chopping. They are the oldest known technology: the earliest date back about 3.3 million years, and people still made some into the twentieth century.

What it is

Any stone used as a tool counts, from a plain hammerstone to a grinding slab, but most were shaped by breaking off flakes to get a cutting edge or a point. The simplest is a sharp flake knocked off a pebble and used at once to cut meat or strip a branch. The most refined, such as a thin spear point or a polished axe, took hours of skilled work.

For most of human history, stone was the main hard material available. Wood, bone, hide and fibre were worked with stone edges, and stone tools last almost forever, so they are also the main record archaeologists have of how early humans lived.

How it works

Good tool stones are hard, brittle and fine-grained, with no internal grain: flint, chert, obsidian (volcanic glass) and some quartzites. When such a stone is struck near an edge, the blow sends a cone-shaped crack through it, the same shape a pellet makes in a window pane. The crack curves out to the surface and frees a flake. This shell-like break is called conchoidal fracture, and it gives very thin, sharp edges.

The knapper strikes the core on a flat surface called the striking platform, close to its edge. Where the platform meets the face of the core, the angle must be less than 90 degrees, or the blow only crushes the edge. The detached flake carries the marks of the blow: a rounded swelling just below the point of impact, the bulb of percussion, and fine ripples spreading away from it. The core keeps the matching hollow scar, and that scar can serve as the platform for the next blow.

Pressure flaking: an antler tine pushes small flakes off the edge while the leather protects the palm.

Three techniques control the result. A hard hammer, usually a quartzite cobble, removes large, thick flakes. A soft hammer of antler, bone or hardwood removes longer, thinner flakes and is used to thin and shape a tool. Pressure flaking presses an antler tip against the edge until a small flake springs off; it gives the final shape and a straight, sharp edge.

How to build

Knapping is learned by practice, and the first hours produce mostly broken stone. You need nodules of flint or chert, or chunks of obsidian or thick bottle glass; two or three hammerstones of different weights; an antler billet and an antler tine; a thick leather pad; safety glasses; leather gloves; and a tarpaulin to catch the waste.

Choose the stone. Look for a nodule without cracks, holes or coarse patches. Tap it with a small pebble: a clear ring means sound stone, a dull note means hidden flaws.

Find a platform. Look for an edge where two surfaces meet at less than 90 degrees. Strike a little way in from that edge, a few millimetres for a thin flake and more for a thick one, with a short, firm blow that follows through outwards, away from the core. Rest the core on the pad on your thigh, never in your bare palm.

Make a flake tool. A single good flake is already a knife. Use it as it is, or trim its back with small blows to make it easier to hold.

Shape a hand axe. Work round the edge of a flat nodule, taking flakes alternately from one face and the other so the edge becomes a wavy line in the middle of the piece. Switch to the antler billet to thin the faces. Before each blow, grind the edge lightly with a coarse stone so it does not crush.

Finish by pressure. Hold the piece on the pad, press the antler tine down and inwards on the edge, and remove small flakes one after another to straighten and sharpen it.

> **Safety.** Fresh flakes are sharper than a razor and fly off fast. Always wear safety glasses, and protect your hands and thighs with leather. Work outdoors or in a well-ventilated space and do not breathe the fine dust: flint and chert are silica, and years of dust cause silicosis, which killed many professional gunflint knappers. Gather the waste on the tarpaulin, dampen dust instead of sweeping it dry, and put sharp flakes in a closed tin or bucket. Keep children and animals away from the work area.

History and evolution

Oldowan tools: a cobble with a jagged edge, the sharp flakes struck from it and the hammerstone.

The oldest known stone tools come from Lomekwi 3, west of Lake Turkana in Kenya. They are about 3.3 million years old, older than the earliest known fossils of the genus *Homo*. The team found 149 cores, flakes, hammerstones and possible anvils, made with simple techniques close to pounding. Who made them is unknown; *Kenyanthropus* and *Australopithecus* lived in the region at the time.

Oldowan tools appear at several East African sites from about 2.6 million years ago, and perhaps 2.9 million years ago at Nyayanga in Kenya: cobbles with a few flakes removed, the sharp flakes themselves and hammerstones. Around 1.7 million years ago, in East Africa, the first widely accepted hand axes appear, large tools shaped on both faces into a teardrop with a long cutting edge. People went on making them for more than a million years, across Africa, Europe and Asia.

Later toolmakers learned to prepare a core so that one blow would release a flake of planned shape. By about 200,000 years ago, points were fixed to wooden shafts as spears, and stone awls and scrapers were used on hides and wood. In Europe and western Asia, between about 50,000 and 10,000 years ago, long thin blades became the standard blank. Microliths, small blade segments set in rows into handles and arrows, appear in southern Africa about 71,000 years ago and became common in many regions near the end of the last Ice Age.

In the Neolithic, axe heads were ground and polished on sandstone to make them tougher.

Farmers of the Neolithic, from about 10,000 BCE, ground and polished stone axes to clear forest. Metal replaced stone slowly and never completely. Gunflints for flintlock guns were knapped at Brandon, in England, into the twentieth century, and obsidian blades are still used for some delicate surgery because their edges are finer than those of steel scalpels.

Key figures

Oldest known stone tools
About 3.3 million years, Lomekwi 3 (Kenya)

First hand axes
About 1.7 million years ago, East Africa

Life of the hand axe
Made for more than a million years

A late knapping trade
Gunflints, made in quantity at Brandon (England) into the 20th century

Sources

1. Stone Tools · Smithsonian National Museum of Natural History, Human Origins Program https://humanorigins.si.edu/evidence/behavior/stone-tools
2. Scientists Discover World's Oldest Stone Tools · Columbia Climate School, State of the Planet https://news.climate.columbia.edu/2015/05/20/scientists-discover-worlds-oldest-stone-tools/
3. Small, lethal tools have big implications for early modern human complexity · Arizona State University https://news.asu.edu/content/small-lethal-tools-have-big-implications-early-modern-human-complexity
4. Stone tool · Wikipedia https://en.wikipedia.org/wiki/Stone_tool
5. Knapping · Wikipedia https://en.wikipedia.org/wiki/Knapping
6. Introducing a new experimental design for controlled studies of flake formation: results for exterior platform angle, platform depth, angle of blow, velocity, and force · Journal of Archaeological Science https://doi.org/10.1016/j.jas.2009.05.004
7. A Synthesis of the Dibble et al. Controlled Experiments into the Mechanics of Lithic Production · Journal of Archaeological Method and Theory https://doi.org/10.1007/s10816-022-09586-2
8. The results of lithic experiments performed on glass cores are applicable to other raw materials · Archaeological and Anthropological Sciences https://doi.org/10.1007/s12520-019-00963-9

Fact-checked on 2026-10-11

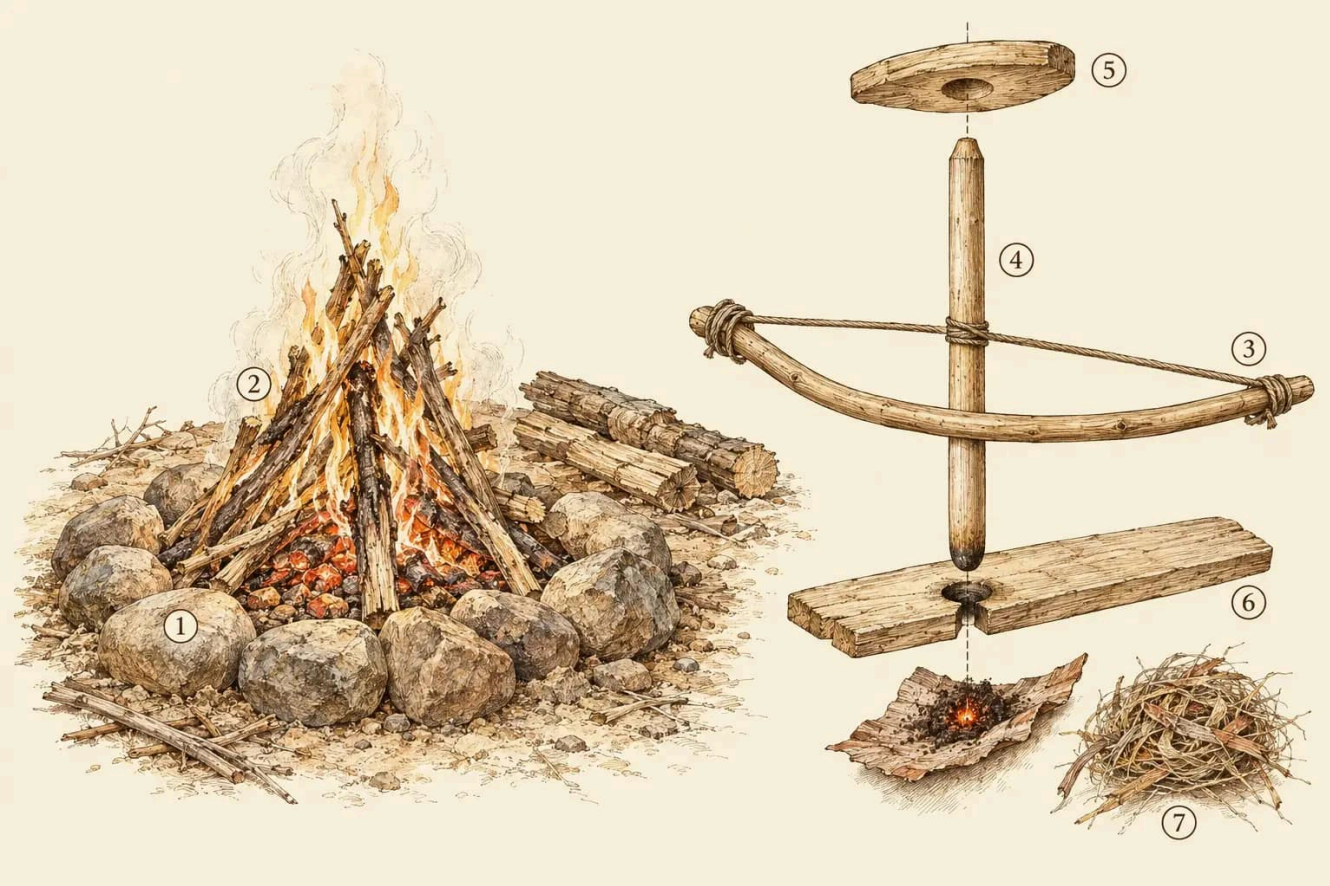
I · FIRE & SHELTER

Control of Fire

Light, heat and cooked food

1 million years ago · Prehistory · Survival

Leads to: Bread (p. 26), Bronze (p. 120), Canning & Pasteurisation (p. 242), Charcoal (p. 62), Distillation (p. 169), Drinking Water (p. 34), Dyeing (p. 66), Gunpowder (p. 177), Hot-Air Balloon (p. 225), Leather Tanning (p. 98), Lime and lime mortar (p. 30), Pottery (p. 22), Roman Concrete (p. 161), Soap (p. 90), Vulcanised Rubber (p. 282)



1 Hearth stones 2 Firewood 3 Bow 4 Spindle 5 Bearing block 6 Hearth board and notch 7 Tinder bundle

Controlling fire means keeping a flame alive, moving it, and in the end lighting it at will. Human ancestors used fire at least a million years ago, and it gave them warmth, light, protection and cooked food.

What it is

Fire is a chemical reaction: fuel combines with oxygen from the air and gives off heat and light. People learned to control it in stages: first keeping a fire started by lightning or a bush fire, then carrying it and feeding it for days, and last lighting one at will.

A fire keeps people warm at night and lets them live in colder places. It lights up caves after dark, keeps animals away, hardens wooden spear points and cooks food. Cooked meat and tubers are softer and release more energy in digestion than raw ones.

How it works

A fire needs three things at once: fuel, oxygen and enough heat to keep the reaction going. Take any one away and it dies.

Wood does not burn directly. Heat first breaks it down into flammable gases and leaves charcoal behind. The gases burn in the flame above the wood, and the charcoal glows below. This is why a fire is built from small to large: thin dry twigs heat up and give off gas quickly, and they bring thicker branches up to temperature.

There are two common traditional ways to make fire. Friction methods rub one piece of wood against another until fine, hot wood dust collects and starts to glow. The hand drill spins a stick between the palms; the bow drill drawn on the plate does the same job with a cord wrapped round the spindle, which gives more speed with less effort. The glowing dust is an ember. Placed in a nest of dry grass and shredded bark and blown on gently, it becomes a flame.

Percussion methods strike sparks. When a hard flint edge hits iron pyrite, it tears off tiny grains of the mineral, which burn in the air as sparks. Flint struck on flint gives almost none. The sparks are small and short-lived, so they need tinder that catches easily, such as the inner layer of the hoof fungus, dried and pounded into a soft, fluffy mass.

Flint struck on pyrite throws off sparks hot enough to set dry tinder fungus smouldering.

How to build

In the hand drill, the palms spin a stick back and forth until the wood dust in the notch starts to glow.

The bow drill is the most reliable friction method to learn. You need a knife or a sharp stone flake, a cord, and dry, dead, medium-soft wood such as willow, lime, poplar or cedar.

Prepare the hearth. Choose bare, level ground away from overhanging branches and dry grass. Clear a circle about three metres across of grass, leaves and twigs, and ring the fire pit with stones. Gather everything first: a double handful of tinder, a bundle of pencil-thin twigs, then sticks as thick as a thumb and as thick as a wrist.

Carve the kit. The spindle is a straight stick about 20 cm long and as thick as a thumb, rounded at the top and blunt at the bottom. The hearth board is a flat piece about 2 cm thick. The bearing block is a palm-sized piece of harder wood or a stone with a small hollow on its underside; a smear of fat or a green leaf in that hollow keeps the top of the spindle from heating. The bow is a stiff, slightly curved stick about as long as your arm, with the cord just slack enough to take one turn round the spindle; once twisted in, it must grip the spindle firmly.

Burn in and notch. Drill a shallow socket near the edge of the board until it is black, then cut a V-shaped notch from the socket to the edge, about one eighth of the circle. Put a piece of bark under the notch to catch the dust.

Drill. Kneel with one foot on the board, brace the wrist holding the block against your shin, press down steadily on the block and saw the bow with long, even strokes. Speed up when the socket smokes. When the notch is full of dark dust that keeps smoking on its own, you have an ember.

Grow the flame. Tip the ember into the tinder nest, fold it closed and blow slowly until it flares. Set it in the pit, lean twigs over it in a cone, and add larger wood only once the twigs are burning well.

> **Safety.** Fire spreads faster than you can run in dry grass or wind. Never light a fire in a drought, under a fire ban or in strong wind, and keep water or loose earth at hand. Do not use wet river stones round the pit: trapped water can make them burst. Never leave a fire alone. To put it out, drown it, stir the ashes and drown it again until everything, buried embers included, is cold to the touch. Practise outdoors only: an open fire in a shelter or cave fills the air with smoke and carbon monoxide, which can kill.

History and evolution

The oldest well-established traces of fire in a human context come from Wonderwerk Cave in South Africa. In 2012, a team found microscopic ash and burned bone there, in layers about a million years old that also held Acheulean stone tools, probably made by *Homo erectus*. A study published in 2026 found burned bone deeper in the same sequence, in layers dated between 1.07 and 1.79 million years ago, about 30 metres inside the cave, where wildfire could not have reached. Older claims from Kenya, around 1.5 million years ago, rest on reddened soil that a natural fire could also explain.

At Gesher Benot Ya'aqov in Israel, burned seeds, wood and clusters of burned flint suggest fires kept in fixed places about 790,000 years ago. Clear hearths become common only between about 400,000 and 300,000 years ago, in Africa, the Near East and Europe. Until then, people probably collected fire from natural blazes and kept it going.

The oldest evidence of making fire comes from Barnham in Suffolk, England, published in 2025. About 400,000 years ago, people there heated the same patch of clay again and again above 700 °C, and left fire-cracked hand axes and two pieces of pyrite, a mineral so rare in that landscape that it was probably brought in on purpose. The earlier record, from Neanderthal sites in northern France, was about 50,000 years old.

Archaeologists find old fires in section: ash and charcoal on top of earth baked red by the heat.

Key figures

Oldest traces of fire use
About 1 million years ago, Wonderwerk Cave (South Africa), perhaps up to 1.8 million

Oldest evidence of fire-making
About 400,000 years ago, Barnham (England)

Habitual use
Widespread from about 400,000–300,000 years ago

Hearth temperature at Barnham
Above 700 °C

Sources

1. Control of fire by early humans · Wikipedia https://en.wikipedia.org/wiki/Control_of_fire_by_early_humans
2. Evidence that human ancestors used fire one million years ago · ScienceDaily (University of Toronto) https://sciencedaily.com/releases/2012/04/120402162548.htm
3. Early humans were bringing fire into caves 1.8 million years ago · ScienceDaily (Hebrew University of Jerusalem) https://sciencedaily.com/releases/2026/06/260623083123.htm
4. Evidence of Hominin Control of Fire at Gesher Benot Ya'aqov, Israel (Science, 2004) · Hebrew University of Jerusalem https://cris.huji.ac.il/en/publications/evidence-of-hominin-control-of-fire-at-gesher-benot-yaaqov-israel/
5. Earliest fire making, dating back 400,000 years, unearthed in Suffolk · Natural History Museum, London https://www.nhm.ac.uk/discover/news/2025/december/earliest-fire-making-dating-back-400-000-years-unearthed-in-suffolk-england.html
6. Research shows humans making fire 350,000 years earlier than thought · University of Liverpool https://news.liverpool.ac.uk/?p=131468
7. Wood Handbook, chapter 4: Moisture Relations and Physical Properties of Wood (FPL-GTR-190) · USDA Forest Service, Forest Products Laboratory https://research.fs.usda.gov/download/treesearch/37428.pdf
8. The Physics of Fire by Friction · University of Dayton (Bradley D. Duncan) https://ecommons.udayton.edu/ece_fac_pub/418
9. Lighting a fire using friction requires an understanding of some physics principles · University of Dayton Magazine https://udayton.edu/magazine/2023/12/lighting-fire.php
10. Ignition of Wood (Vytenis Babrauskas) · Fire Science and Technology Inc., via CFITrainer.net https://www.cfitrainer.net/programs/35a84de0-e505-4899-be34-f31de9d9d570/document/2005_CCAI_Wood_ignition.pdf

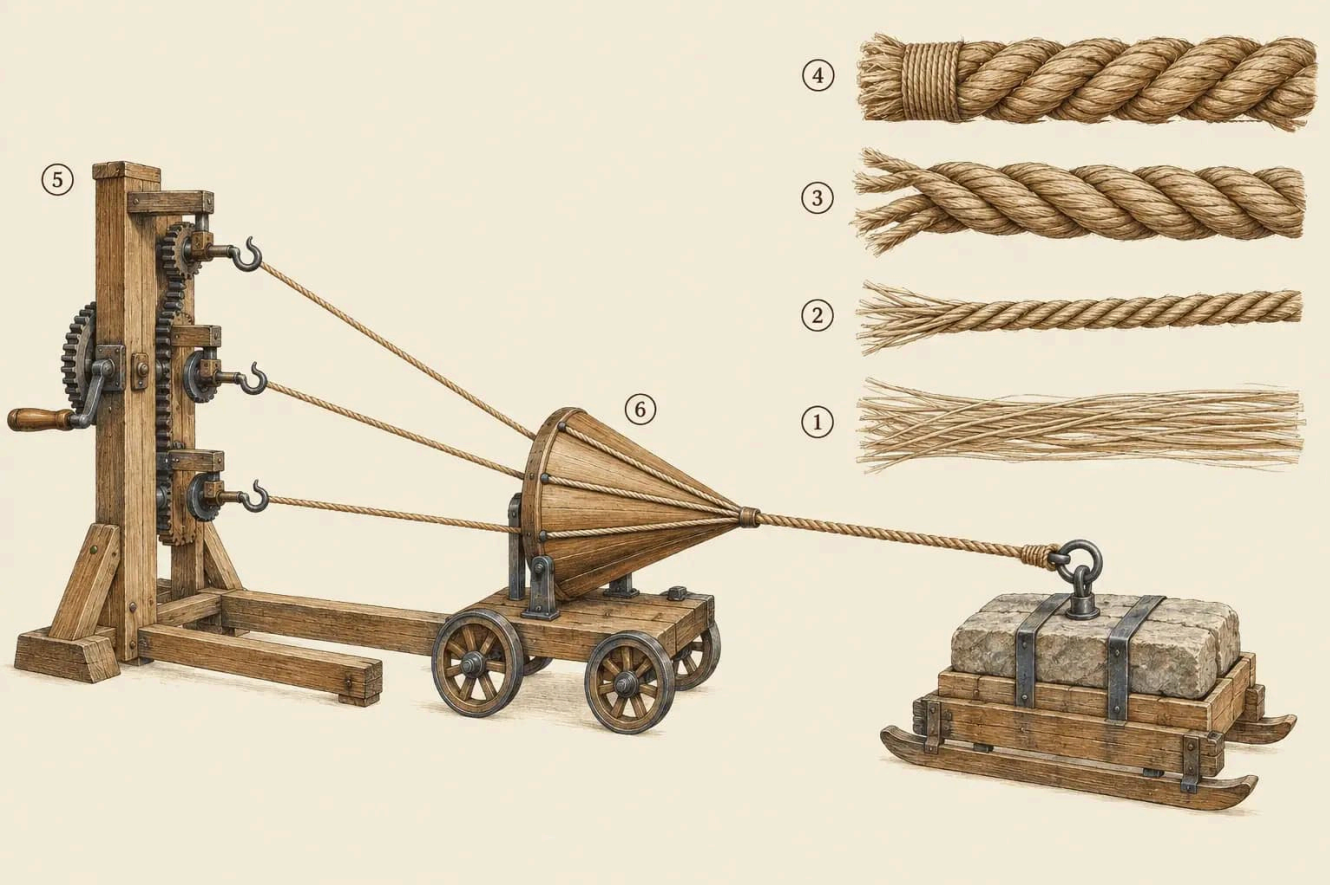
Fact-checked on 2026-10-11

Rope & Cordage

Twisted fibres that hold the world

50,000 years ago · Prehistory · Survival

Leads to: Bow & Arrow (p. 18), Crane & Pulley (p. 145), Drinking Water (p. 34), Dyeing (p. 66), Horse Collar (p. 173), Irrigation (p. 51), Measures and standards (p. 124), Plough (p. 58), Sail (p. 86), Spinning Wheel (p. 185), Weaving (p. 43), Windmill (p. 181)



1 Fibres 2 Yarn 3 Strand 4 Three-strand rope 5 Crank and hooks (jack) 6 Top

Traditional rope is made of short fibres twisted into yarns, the yarns into strands and the strands into rope, giving a line far longer and stronger than any single fibre. Neanderthals were already twisting cord more than 40,000 years ago, and people have used rope ever since to tie, haul, lift and rig.

What it is

A rope is a long, flexible line that resists pulling. Traditional rope is built from fibres that are each only a few centimetres to a metre or so long: plant stems and leaves, inner bark, animal sinew or hair. Twisting holds them together. Modern synthetic rope can use continuous filaments, and much of it is braided rather than twisted.

Thin rope is called cord, string or twine. It ties loads, hauls boats and stones, holds up nets and traps, and rigs sailing ships.

How it works

A single fibre is weak and short. When many fibres are twisted together, the twist presses them against each other, and friction keeps them from sliding apart. Pulling on the yarn makes it tighten and press harder, so it grips better the more it is loaded.

A twisted yarn on its own tends to untwist. The answer is to twist again in the opposite direction. Fibres are spun into yarn one way; several yarns are twisted the other way into a strand; three strands are laid together the first way into rope. The leftover twist in each stage pulls in the opposite sense to the twist of the stage inside it, so the forces balance and the rope holds its shape. Three-strand rope built this way is called hawser-laid.

Reverse wrapping: each bundle is twisted one way, then wrapped over the other the opposite way.

The same rule works at the smallest scale. In reverse wrapping, a simple hand method, two bundles of fibre are each twisted one way, then wrapped round each other the other way, and the result is a two-ply cord that does not unravel. A long rope is made the same way on a larger scale: a crank twists the strands, and a grooved wooden block called the top keeps them apart until they lay up together behind it.

How to build

Good cordage fibres are long and strong: nettle, flax, hemp, the inner bark of lime or willow, cattail leaves, or bought cotton or hemp twine for practice.

Prepare the fibre. Cut nettle stems in late summer, wearing gloves. Crush them flat, split them, take out the woody core and peel off the outer skin with its fibres. Let them dry, then dampen them slightly before use. Lime bark needs several weeks of soaking in water before the fibrous layers separate.

Make cord by hand. Take a bundle and bend it at a point a little off its middle, so the two ends are of unequal length. Pinch the bend. Twist the upper bundle away from you, then lay it over the lower bundle towards you. Repeat, moving the pinch along. When a bundle runs short, lay a new piece of fibre alongside it and twist it in; the uneven ends keep the joins from coming at the same place.

Rig a rope walk. For thicker rope, fix a frame with three hooks that a crank turns together. Stretch three equal lengths of cord or yarn from the three hooks to a single swivel hook on a weighted sledge at the other end. Lock the swivel with a peg for now, and set the top between the strands right next to the sledge, one strand in each groove.

Twist and lay. Turn the crank in the direction that tightens the twist already in the yarn, until each strand is hard and starts to kink when slackened. Then pull the peg so the swivel hook can turn. Keep cranking while a helper walks the top slowly towards the frame: behind it, the strands lay up into rope in the opposite direction, and the sledge creeps forward as the rope shortens.

Finish the ends. Bind each end tightly with thin twine, a whipping, before you cut it, or the strands will unlay.

> **Safety.** A loaded rope stores energy; if it breaks, the ends whip back hard, so never stand in line with a rope under strain. Do not use home-made rope for climbing, for lifting people or for loads above anyone's head. The crank stores twist too: hold it when you stop, or it will spin back. Wear gloves for nettles and when running rope through your hands.

History and evolution

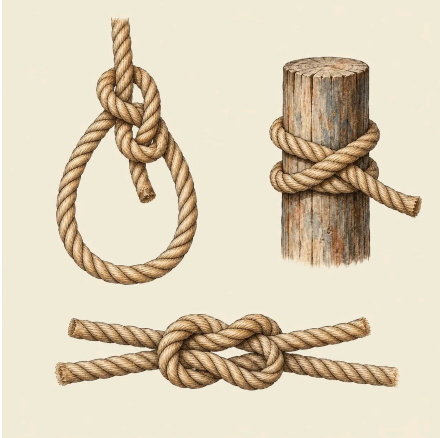
The Hohle Fels ivory tool as reconstructed: fibres fed through its four holes are twisted into rope.

The oldest direct evidence of cord comes from Abri du Maras, a rock shelter in the Ardèche, in France. In 2020, researchers described a fragment about 6 mm long stuck to a stone tool, made of three bundles of fibres from the inner bark of a tree, probably a conifer, twisted and then plied together. It is between 41,000 and 52,000 years old and was made by Neanderthals, who must have known how to twist in two opposing directions.

At Hohle Fels cave in south-western Germany, excavators recovered a strip of mammoth ivory about 20 cm long, with four holes ringed by spiral grooves, dated to 35,000–40,000 years ago. In 2024 Nicholas Conard and Veerle Rots argued that it was probably a rope-making tool: plant fibres were caught in its grooves, and a similar baton from the nearby Geißenklösterle cave has grooves worn as if by fibres pulled through them. With replicas, teams of four or five people made about 5 metres of strong rope in 10 minutes; cattail leaves worked especially well.

Farming societies made rope on a much larger scale. Egyptians made rope from reeds, papyrus, palm fibre and flax, and gangs hauling on ropes moved the stones of the monuments. At Wadi Gawasis, a pharaonic harbour on the Red Sea, archaeologists found coils of ship's rope, neatly knotted and stored in man-made caves used by expeditions to the land of Punt.

In Europe, from the Middle Ages to the nineteenth century, sailing navies made their rope in rope walks, buildings long enough to lay a full-length rope in one piece. The rope walk at Chatham Dockyard in England is nearly 350 metres long, and rope has been made there for more than 400 years. Nylon rope came into use during the Second World War, and from the 1950s synthetic fibres took over most of the work once done by hemp and manila.



A bowline makes a fixed loop, a clove hitch ties to a post, and a reef knot binds a bundle; it is not safe for joining two loaded ropes.

Key figures

Oldest known cord
41,000–52,000 years old, Abri du Maras (France)

Early probable rope-making tool
35,000–40,000 years old, Hohle Fels (Germany)

Usual construction
3 strands, twist reversed at each stage

Ice Age rate (replica tool)
About 5 m of rope in 10 minutes, 4–5 people

Sources

1. Neanderthal cord weaver · CNRS https://www.cnrs.fr/en/press/neanderthal-cord-weaver
2. Rope making in the Aurignacian of Central Europe more than 35,000 years ago · Science Advances (PubMed Central) https://pmc.ncbi.nlm.nih.gov/articles/PMC10830101/
3. Archaeologist Kathryn Bard's amazing Egyptian digs · Boston University https://www.bu.edu/articles/2009/archaeologist-kathryn-bard%e2%80%99s-amazing-egyptian-digs/
4. The Ropery · The Historic Dockyard Chatham https://thedockyard.co.uk/attractions/the-ropery
5. Rope · Wikipedia https://en.wikipedia.org/wiki/Rope
6. Ropewalk · Wikipedia https://en.wikipedia.org/wiki/Ropewalk
7. The ancient art of laying rope · Europhysics Letters (arXiv) https://arxiv.org/abs/1004.0814
8. Plymouth Cordage Company Ropewalk · Mystic Seaport Museum https://mysticseaport.org/?p=355570
9. Hawser-laid · Practical Boat Owner https://www.pbo.co.uk/nautical-almanac/glossary-of-nautical-terms/hawser-laid-9204
10. Three strand hawser laid rope · Lifting Equipment Engineers Association https://copsule.leeaint.com/copsule/en-GB/latest/id-b54f2a33-5063-40e7-f243-517683d1bf63.html

Fact-checked on 2026-10-11

II

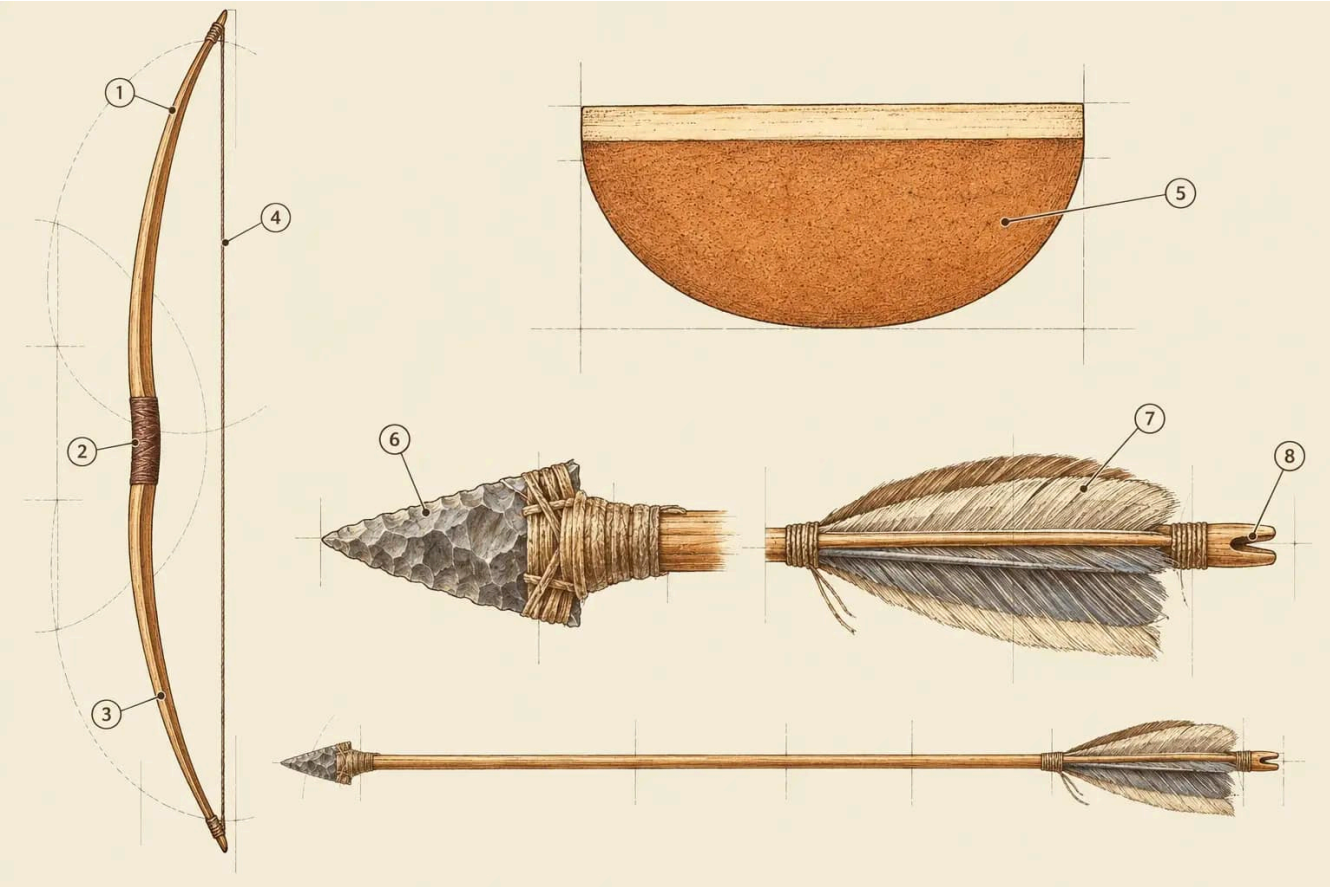
Settlement

Bow & Arrow

Stored energy released at a distance

62,000 years ago · Prehistory · Settlement

Requires: Stone Tools (p. 5), Rope & Cordage (p. 13)



1 Upper limb 2 Grip 3 Lower limb 4 Bowstring 5 Section of a limb: sapwood back, heartwood belly
6 Flint arrowhead bound with sinew 7 Fletching 8 Nock

A bow stores the effort of the archer's arms in its bent limbs and releases it in a fraction of a second, sending an arrow much faster and farther than a hand could throw it. Small stone points from South Africa suggest that people were shooting arrows about 64,000 years ago, and the bow stayed a weapon of hunting and war until firearms replaced it.

What it is

A bow is a flexible stave, usually of wood, with a string tied between its two tips, and it works as a spring held in the hand. Drawing the string back bends the stave; letting go allows the stave to straighten, and the string throws the arrow forward. The arrow is a light, straight shaft with a sharp head at the front and feathers at the back that keep it flying point first.

The bow on the plate is a self bow, made from a single piece of wood, of the English longbow type: a yew stave about as tall as the archer, flat on the back and rounded on the belly, so its section looks like a letter D. Many bows

are built from several materials instead. The composite bows of Asia glue horn, wood and sinew together, and several peoples of North America glued a layer of sinew along the back of a wooden bow.

How it works

The two faces of a bent bow do opposite work. The back, the side facing away from the archer, is stretched; the belly, facing the archer, is compressed. Wood resists both, so the effort spent in drawing is stored in the limbs as elastic energy, as in a wound spring. A hunting bow commonly needs a pull of about 180 to 270 newtons (40 to 60 lb) at full draw, and heavy war bows needed far more.

Yew suits a self bow because a yew trunk contains two kinds of wood. The pale sapwood under the bark stands stretching well, and the darker heartwood stands crushing well. Bowyers leave a layer of sapwood on the back and heartwood on the belly, as the section on the plate shows. With most other woods the bow is cut wholly from sapwood or wholly from heartwood, and its back follows one growth ring along the whole length.

When the archer lets go, the limbs spring forward and the string pushes the arrow. Not all the stored energy reaches it, because the limbs and string are moving too and keep some of it. Light, evenly bending limbs waste less than heavy ones. Arrows from wooden bows typically leave at 40 to 60 metres per second.

The push is so sudden that the arrow bends and vibrates as it leaves, flexing around the handle of the bow. Archers call this the archer's paradox. For an arrow to fly straight, its stiffness, called its spine, has to suit the draw weight of the bow, taking into account the arrow's length and the weight of its head, which both change how much it flexes. The feathers at the rear create drag behind the arrow's balance point, so any wobble turns the point back into the line of flight, as the flights of a dart do. A heavier head moves the balance point forward and steadies the flight, but it also makes the shaft flex more.

How to build it

A self bow needs a hatchet or drawknife, a rasp, a scraper, a knife, a long cord, a spring scale and a tiller stick: an upright post with a rest for the grip at the top and notches down its length.

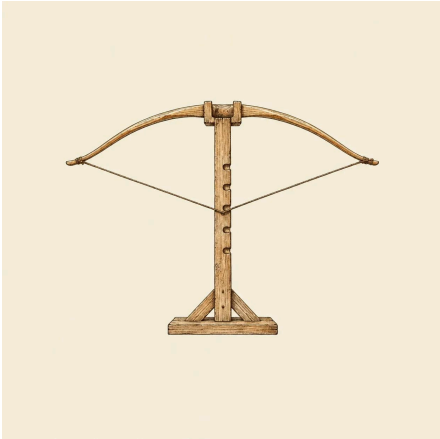
Choose the stave. Pick a straight-grained length of a tough, springy wood such as yew, osage orange, elm, ash, hickory or maple, free of knots and twists. Split it from the log rather than sawing it, so the grain runs the whole length. Seal the ends and let it dry slowly under cover for several months, ideally a year.

Prepare the back. The back is the side that lay under the bark. On most woods, take the bark off and follow one growth ring along the whole length without cutting through it: a cut ring is where a bow breaks. On yew, keep a thin layer of sapwood.

Rough out the shape. Mark a centre line and draw the outline: a narrow, thick grip in the middle and limbs tapering towards the tips. For a longbow, the stave is about the archer's height. Remove wood from the belly only, until each limb flexes a little when the tip rests on the floor and the grip is pushed.

Tiller the bow. Cut grooves for the string near the tips, fit a long string and rest the bow by its grip on the tiller stick. Pull the string down one notch at a time, read the pull on the spring scale and study the curve. Never pull harder than the draw weight you are aiming for, or the unfinished stave will be overstrained. Both limbs should bend in smooth, even arcs, with no flat or sharply bending spots. Let the string back up slowly and lift the bow off the tiller before you touch it with a tool: never scrape a limb while it is under load. Then scrape wood from the belly where a limb is too stiff, a few shavings at a time, and flex the bow a dozen times between steps. Stop a little

short of your full draw length and the weight you want. This is the slowest stage. A short stretch that bends more than the rest, called a hinge, takes too much strain and is where a bow tends to crack.



On the tiller, the bow is drawn a little further at each step, so the bowyer can compare the curve of the two limbs.

Make the string. Twist the string from linen, hemp, sinew or modern polyester thread, with a fixed loop at one end and a timber hitch at the other. When the bow is strung, the string should stand about a hand's breadth from the grip. Put the braced bow back on the tiller with its working string and draw it in stages to full length: both limbs should still bend evenly and the scale should read the planned weight. Take off the last shavings only where this check shows a stiff spot, each time with the string let down and the bow off the tiller.

Three feathers from the same wing, glued on and bound at each end, keep the arrow flying straight.

Make the arrows. Cut straight shoots of dogwood, viburnum or hazel, or split shafts from a straight log. Straighten them over gentle heat and scrape them round. Sort them by stiffness, cut them to the same length and fit heads of the same weight, so that the arrows shot from one bow fly alike. Make each arrow long enough for your full draw, with the head still in front of the bow at full draw. Cut a nock for the string at the rear. At the front, bind on a head of stone, bone or metal with sinew and a glue such as birch tar, or use a blunt wooden tip for practice. Glue three feathers from the same wing along the shaft near the nock, evenly spaced, and bind their ends.

> **Safety.** A bow is a weapon at any draw weight. Never aim at anyone, and shoot only on a range with a backstop and nobody beyond it. Never release a drawn string without an arrow on it: the energy goes into the bow, which can break and throw splinters. Wear eye protection when tillering and testing, check the bow, the string and every arrow shaft and nock for cracks before each session, and use arrows long and stiff enough for the bow. Yew dust is toxic and other wood dusts can harm the lungs and skin, so clear dust away at the source and wear a well-fitting dust mask with a suitable filter when rasping and sanding, even outdoors; take care with the heat source when straightening shafts. Hunting with a bow is regulated or banned in many countries.

History and evolution

Bows and arrows are made of wood, sinew and feathers, which rarely survive, so the earliest archery is read from stone points. At Sibudu Cave in KwaZulu-Natal, South Africa, small stone points about 64,000 years old show impact damage, traces of blood and bone, and remains of the plant-resin glue that held them to a shaft, which suggests they tipped arrows. Researchers have proposed older arrowheads, about 74,000 years old, at Shinfa-Metema 1 in Ethiopia, an interpretation that further work has yet to confirm. In Europe, the earliest likely evidence comes from Grotte Mandrin in southern France: flint points about 54,000 years old, left by modern humans and too small to have been thrown by hand.

The oldest known arrow shafts, of pine, come from Stellmoor near Hamburg and are about 12,000 years old. The oldest complete bow, of elm, was found in the Holmegaard bog in Denmark and dates from about 7000 BC. Ötzi, the man who died in the Alps about 5,300 years ago, carried an unfinished yew stave and a deer-hide quiver holding 14 arrows; only two were finished, with flint heads and feathers fixed with birch tar and plant fibre.

In the steppes of Asia and the Near East, bowyers developed the composite bow, glued from a thin wooden core with horn on the belly and sinew on the back. It is shorter than a self bow of the same power, which suited archers in chariots and on horseback, and it armed the Scythians, the Huns, the Mongols and the Ottoman Turks.

In western Europe, the yew longbow served English armies at Crécy in 1346 and Agincourt in 1415. Henry VIII's warship the *Mary Rose*, which sank in 1545, has given up 172 longbows, each cut from a single piece of yew and up to 2.11 m long. Guns took longer to load, but a soldier learned to use one much faster than an archer could be trained, and through the sixteenth and seventeenth centuries firearms pushed the bow off European battlefields. It remained a hunting weapon in many parts of the world, and archery became a sport, practised today with bows of fibreglass and carbon and with compound bows that use pulleys.

Unstrung, a composite bow curves forward, away from the archer; stringing it bends it back and stores energy even before the draw.

Key figures

Early arrowheads
About 64,000 years ago, Sibudu Cave, South Africa

Oldest complete bow
Holmegaard, Denmark, elm, about 7000 BC

Ötzi's archery kit
Unfinished yew stave of 1.82 m, 14 arrows of which 2 finished

Longbows from the Mary Rose (sank 1545)
172 recovered, estimated draw weights 65 to 175 lb (290 to 780 N)

Sources

1. Indications of bow and stone-tipped arrow use 64 000 years ago in KwaZulu-Natal, South Africa · Antiquity (Lombard and Phillipson, 2010) https://resolve.cambridge.org/core/journals/antiquity/article/abs/indications-of-bow-and-stonetipped-arrow-use-64-000-years-ago-in-kwazulunatal-south-africa/89AF638BE5E64CEAC63363EFDD4D5E8F
2. Surviving a volcanic supereruption may have facilitated human dispersal out of Africa · University of Texas at Austin https://news.utexas.edu/2024/03/20/surviving-a-volcanic-supereruption-may-have-facilitated-human-dispersal-out-of-africa/
3. Earliest likely evidence for bow and arrow use in Europe, 54,000 years ago, found in southern France · Popular Archaeology https://popular-archaeology.com/article/earliest-likely-evidence-for-bow-and-arrow-use-in-europe-54000-years-ago-found-in-southern-france/
4. How old is the bow and arrow? · World Archery https://www.worldarchery.sport/news/166330/
5. Ötzi's equipment · South Tyrol Museum of Archaeology https://www.iceman.it/en/equipment/
6. The longbows of the Mary Rose · Mary Rose Trust https://maryrose.org/ship/bows1.htm
7. Standardised Equipment or Specialist Groups? The Role of Archery Aboard Mary Rose · University of Southampton (Parkes, PhD thesis, 2024) https://eprints.soton.ac.uk/id/eprint/500151/
8. On the Mechanics of the Bow and Arrow · Rijksuniversiteit Groningen (Kooi, PhD thesis, 1983) https://www.bio.vu.nl/thb/users/kooi/thesis.pdf

Fact-checked on 2026-10-12

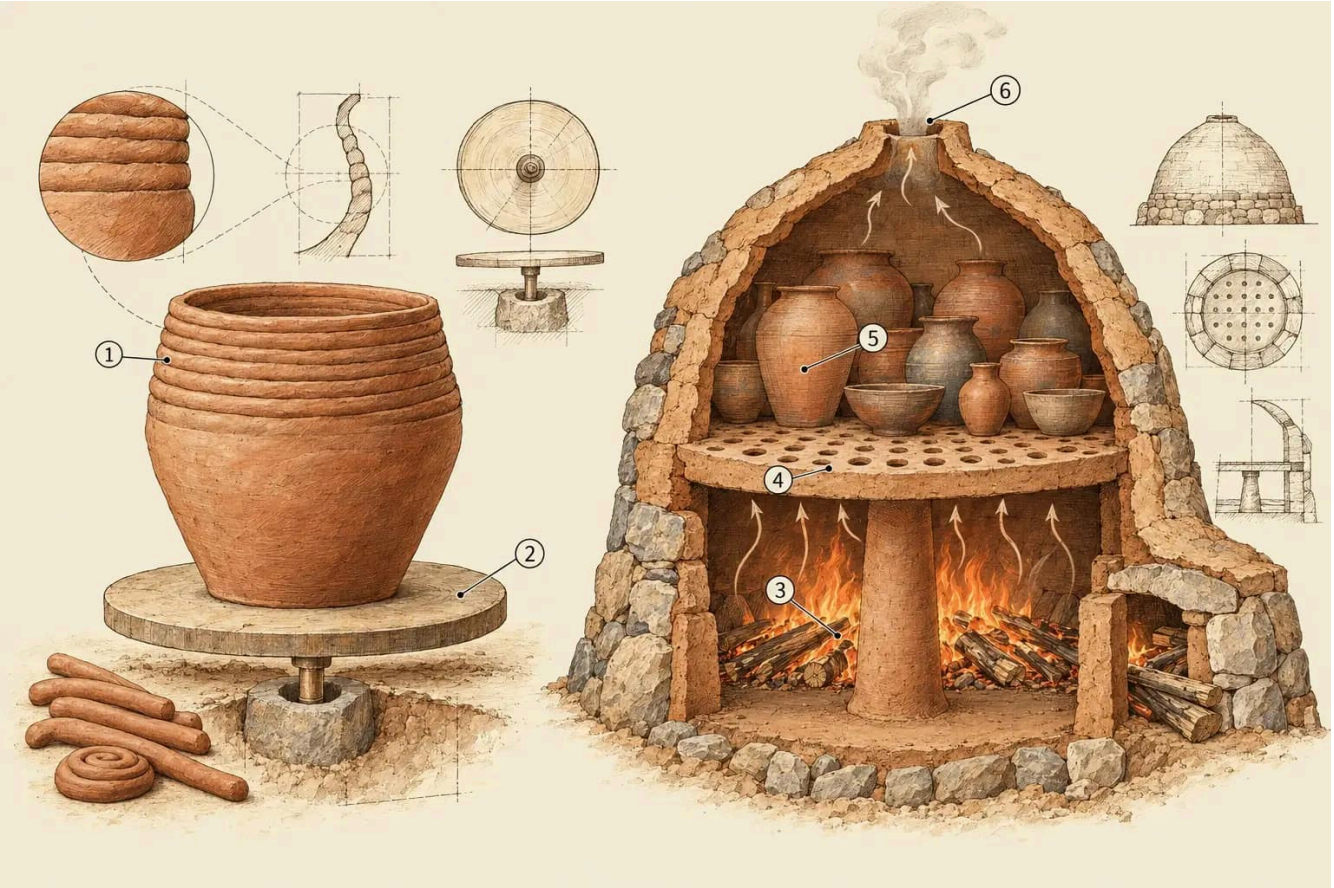
Pottery

Clay turned to stone by fire

18,000 years ago · Prehistory · Settlement

Requires: Control of Fire (p. 9)

Leads to: Beer (p. 74), Bronze (p. 120), Cheese (p. 55), Distillation (p. 169), Drinking Water (p. 34), Dyeing (p. 66), Glass (p. 129), Measures and standards (p. 124), Paper (p. 165), Potter's Wheel (p. 116), Salting & Curing (p. 47), Soap (p. 90), Writing (p. 82)



1 Clay coils 2 Turntable 3 Firebox 4 Perforated floor 5 Pots in the firing chamber 6 Vent

Pottery is clay shaped while wet and then fired until it changes for good into a hard, stone-like material. Foragers in southern China were making clay pots, probably for cooking, about 20,000 years ago, long before farming.

What it is

Pottery covers every object made of clay and hardened by fire, from cooking pots and jars to lamps and roof tiles. Potters sort their wares into three groups by clay body and firing temperature: porous earthenware, dense stoneware, and white, glassy porcelain.

A pot of coarse, well-tempered clay can be heated slowly over a fire, so food can be boiled and stewed as well as roasted, and lidded jars kept in a dry place hold grain away from mice.

The plate shows how a pot is shaped and fired: built by hand from coils of clay, then baked in a simple updraft kiln.

How it works

Clay is made of microscopic flat crystals, mostly silicates of aluminium. Wet, the flakes slide over each other on films of water, so the clay can be shaped and holds its shape. As it dries, the flakes pack together and the pot shrinks by several per cent. Dried clay is firm but would turn back to mud in the rain.

An early Japanese Jōmon pot, its surface marked by rolling twisted cord over the wet clay.

In the fire, between about 450 and 650 °C depending on the clay, the water bound inside the crystals is driven off and their structure breaks down; the clay can never be softened in water again. Hotter still, the grains start to fuse where they touch. Earthenware stays porous. At stoneware temperatures part of the body melts into glass that fills the pores, so the pot holds water without a glaze. Porcelain, made from a white, kaolin-rich body fired at high temperature, becomes hard and slightly translucent.

An open firing: pots are buried in fuel and fired on the ground, without a kiln.

Potters mix temper into the clay, such as sand, crushed shell or ground-up old pots. It opens the body so steam can escape, and reduces cracking as the pot dries and heats.

The first pots were fired in bonfires or shallow pits at 600 to 900 °C. A kiln holds the heat in. In the updraft kiln on the plate, the fire burns in a firebox below and the hot gases rise through holes in a clay floor, around the stacked pots and out of a vent at the top. The pots no longer sit in the burning fuel, so the heat is more even and easier to control, and fewer pots crack.

How to build

Good earthenware can be made with clay dug from the ground, a few simple tools and a bonfire. The steps below are an outline.

Find and prepare clay. Roll a thin sausage and bend it into a ring: if it does not crack, the clay is plastic enough. Soak it to a slurry, let stones settle, pour off the top and dry it until it can be kneaded. Knead in sand or crushed fired pottery, starting with about a quarter of the clay's volume, and fire a few small test pieces to adjust the mix.

Build with coils. Flatten a disc for the base. Roll coils as thick as a finger and lay them on top one at a time, pinching and smoothing each one into the last on the inside and outside. Work on a board or turntable so you can rotate the pot. Thin and even the walls with a wooden paddle against a stone held inside.

Dry slowly. Keep the pot out of sun and wind for a week or more. When it is leather-hard, you can rub the surface with a smooth pebble to burnish it. Fire it only when it is bone dry and no longer cool to the touch.

Fire. Warm the pots beside the fire for an hour or two, turning them. Then stack them on embers, cover them with wood and dung, and build the fire up over several hours. Let everything cool slowly in the ashes before you lift the pots out.

> **Safety.** Fire only outdoors, away from buildings: clear the ground, keep water at hand, watch the wind and stay out of the smoke. Damp clay can burst and throw sharp fragments, and hot ashes stay dangerous for hours. Dry clay dust contains fine silica that damages the lungs: wet-clean rather than sweep. Treat pots made this way as experimental and keep them away from food unless the clay and the finished ware have been tested. Never use glazes of unknown composition: lead can leach into food.

History and evolution

Fired clay is older than pots. People at Dolní Věstonice, in what is now the Czech Republic, made figurines of fired clay between about 29,000 and 25,000 BCE but made no vessels.

The oldest known pots come from Xianrendong Cave in Jiangxi province, China. In 2012 a team led by Wu Xiaohong and Ofer Bar-Yosef dated the earliest sherds, some with soot and scorch marks that suggest cooking, to about 20,000 to 19,000 years ago, at the height of the last ice age. Some researchers think the cave's layers are too disturbed for certainty, but early pottery from elsewhere in East Asia confirms that ice-age foragers made pots. At Ōdai Yamamoto in northern Japan, sherds with charred food residue have been dated to between about 16,500 and 15,000 years ago, depending on the study. In the Near East it was the other way round: the first farming villages managed without pots for more than two thousand years.

The earliest known pottery kiln in the Middle East, at Yarim Tepe in northern Iraq, dates from about 6000 BCE or a little earlier. Slow turntables helped Near Eastern potters shape coiled pots by about 3500 BCE, and the fast wheel, heavy enough to keep spinning while the potter raised a pot from a lump of clay, followed in the third millennium BCE.

Chinese kilns could reach about 1,000 °C before 2000 BCE, and climbing dragon kilns built on hillsides reached 1,300 °C. That made stoneware possible and, by the Tang dynasty (618–907), white porcelain.

An early potter's wheel: a heavy wooden head turning on a pivot set in a stone.

Key figures

Oldest known pots
Xianrendong Cave, China, c. 20,000–19,000 years ago

Earliest known pottery kiln in the Middle East
Yarim Tepe, Iraq, c. 6000 BCE or a little earlier

Point of no return
About 450–650 °C, depending on the clay: it no longer softens in water

Firing ranges
Earthenware 600–1,200 °C, stoneware 1,100–1,300 °C, porcelain up to 1,400 °C

Sources

1. Pottery · Wikipedia https://en.wikipedia.org/wiki/Pottery
2. Kiln · Wikipedia https://en.wikipedia.org/wiki/Kiln
3. Potter's wheel · Wikipedia https://en.wikipedia.org/wiki/Potter%27s_wheel
4. Oldest pottery comes from Chinese cave · Science News https://sciencenews.org/?p=8772
5. The First Pots (Top 10 Discoveries of 2012) · Archaeology Magazine https://archaeology.org/issues/january-february-2013/collection/top-10-2012-neolithic-china-pottery/top-10-discoveries-of-2012/
6. Firing Clay: The Lowdown on the Ceramic Firing Process · Ceramic Arts Network https://ceramicartsnetwork.org/daily/article/Firing-Clay-The-Lowdown-on-the-Ceramic-Firing-Process
7. Quartz Inversion · Digitalfire Reference Library https://digitalfire.com/glossary/quartz+inversion
8. Water Smoking · Digitalfire Reference Library https://digitalfire.com/glossary/water+smoking
9. Red heat · Wikipedia https://en.wikipedia.org/wiki/Red_heat

Fact-checked on 2026-10-11

Bread

Ground grain, water and heat

12,400 years ago · Prehistory · Settlement

Requires: Control of Fire (p. 9)

Leads to: Beer (p. 74)

1 Saddle quern 2 Risen dough 3 Oven dome 4 Baking floor 5 Embers 6 Peel

Bread is a dough of ground grain and water, often leavened, baked until it sets. Hunter-gatherers in Jordan were already baking flatbread about 14,400 years ago, before anyone farmed cereals.

What it is

Bread is flour mixed with water, shaped, and cooked by dry heat. Salt is almost always added. Most breads are also leavened, filled with small gas bubbles by yeast or by a sourdough culture, so they rise and bake to an airy crumb. Unleavened flatbreads skip that step and bake in minutes on a hot stone or the wall of an oven.

Cooked grain keeps poorly and raw grain is hard to digest. Bread turns cereals into a food that is easy to carry and keeps for days, and in many diets it supplies most of the calories. The plate follows the old sequence: grain ground on a saddle quern, dough left to rise in a wooden trough, loaves baked on the floor of a domed oven.

Einkorn, emmer and barley, the cereals of the first breads in the Near East.

How it works

Wheat flour holds two families of proteins, glutenins and gliadins. When water is added and the dough is kneaded, they link into gluten, an elastic network that can stretch and hold gas. Rye and barley proteins do not build the same elastic network; rye bread holds together mainly through its starch and gums, which is why such breads are dense.

Yeasts, single-celled fungi present on grain and in the air, feed on the sugars released from starch. They give off carbon dioxide and a little alcohol. The gas collects in tiny pockets trapped by the gluten, and the dough swells. A sourdough culture combines wild yeasts with lactic bacteria, which add a sour taste and help the bread keep.

In the oven, the gas and the water in the dough expand and the loaf rises fast for the first few minutes. Between about 60 and 80 °C the starch absorbs water and swells, and the proteins set; the soft foam becomes a firm crumb. At the surface, where the dough dries and gets much hotter, sugars and proteins react and brown into a crust. A loaf is done when the centre approaches 100 °C.

A wood-fired oven works by stored heat. The fire burns inside the dome until the masonry is hot through, then the embers are raked aside or pulled out and the loaves go in on a peel. The thick walls give back heat for an hour or more.

How to build

You need wheat, a way to grind it, a starter and an oven. The steps below make two wheat sourdough loaves; rye and barley need different recipes.

Make flour. Grind clean, dry wheat or spelt between two stones. Sift out the coarse bran for a lighter loaf.

Start a culture. Mix equal weights of wholemeal flour and water in a jar, cover it loosely and keep it warm. Each day keep about 100 g of it, throw the rest away and feed it with 100 g of flour and 100 g of water, at 20 to 27 °C. After five to ten days it should bubble and double within a few hours of feeding.

Mix and knead. For two loaves take 1 kg of flour, 650–700 g of water, 20 g of salt and about 200 g of active starter. Knead for ten minutes until the dough is smooth and springs back.

Let it rise. Leave the dough covered for four to eight hours depending on warmth, divide it in two, shape each half into a tight round and let it rise again in a floured basket or cloth for one to three hours, until it has grown by about half and a fingertip dent springs back slowly.

Heat the oven. Burn dry hardwood in a clay or brick dome for one to two hours, until the soot on the inside of the dome has burned off and the masonry looks pale. Rake out the embers, wipe the floor with a damp cloth, then slide in the loaves with a peel. Bake for about 40 minutes; the base should sound hollow when tapped.

> **Safety.** Oven floors and walls burn skin badly: use a long peel and thick gloves, and never lean into the mouth. Work in the open air, because a smouldering fire in a closed room gives off carbon monoxide. Throw away grain that is mouldy or carries black, horn-shaped ergot bodies, which are poisonous. Keep the starter jar clean; if any mould appears, throw the whole starter away and scald the jar.

History and evolution

A carbonised loaf buried by Vesuvius in 79 CE, scored into eight portions before baking.

In 2018 a team led by Amaia Arranz-Otaegui described charred crumbs from two fireplaces at Shubayqa 1, a site in north-eastern Jordan used by Natufian hunter-gatherers about 14,400 years ago. Under the electron microscope they proved to be a flatbread-like food of wild cereals such as einkorn, mixed with ground club-rush tubers, made some 4,000 years before farming began in the region.

Ancient Egypt made bread from emmer wheat, which had to be pounded to free the grain from its husks before being ground on saddle querns. The archaeobotanist Delwen Samuel examined desiccated loaves under the microscope and found preserved yeast cells in bread from about 1400 BCE, the earliest direct evidence of yeast in baking.

In Rome baking became a trade. Archaeologists have documented 39 bakeries at Pompeii, with stone mills turned by donkeys and domed ovens, and loaves carbonised in the eruption of 79 CE survive. Pliny the Elder noted that the Gauls and Iberians used the froth from beer to raise a lighter bread.

A Pompeian mill: the hourglass upper stone turns over a fixed cone and grinds the grain between them.

For centuries most people ate coarse breads of rye, barley or mixed grain; fine white wheat bread was a luxury. Roller mills in the nineteenth century made white flour cheap, and commercial baker's yeast replaced the leftover dough and brewers' barm. In 1961 the Chorleywood process in Britain replaced the long first fermentation with a few minutes of intense mechanical mixing, and most British factory bread is still made that way.

Key figures

Oldest known bread
Shubayqa 1, Jordan, c. 14,400 years ago

Earliest direct evidence of yeast in bread
Egyptian loaves, c. 1400 BCE

Typical dough
100 parts flour, 60–75 water, about 2 salt

Bake
About 40 minutes at 220–250 °C for a loaf of about 900 g

Sources

1. Bread · Wikipedia https://en.wikipedia.org/wiki/Bread
2. Flatbread Baked 14,400 Years Ago Found in Jordan · Sci.News https://www.sci.news/archaeology/natufian-flatbread-jordan-06210.html
3. 3500 year old bread and beer from the New Kingdom Egypt · UCL Researchers in Museums https://blogs.ucl.ac.uk/researchers-in-museums/2017/02/09/3500-year-old-bread-and-beer-from-the-new-kingdom-egypt
4. Digging Deeper into Pompeii's Past · Archaeology Magazine https://archaeology.org/issues/july-august-2019/collection/pompeii-industry-bakeries/digging-deeper-into-pompeiis-past/
5. Adjusting Bake Times in New Ovens · BAKERpedia https://bakerpedia.com/?p=39416
6. Yeast Kill · BAKERpedia https://bakerpedia.com/processes/yeast-kill/
7. Relating Bread Baking Process Operating Conditions to the Product Quality: a Modelling Approach · Chemical Engineering Transactions https://doi.org/10.3303/CET1439289

Fact-checked on 2026-10-11

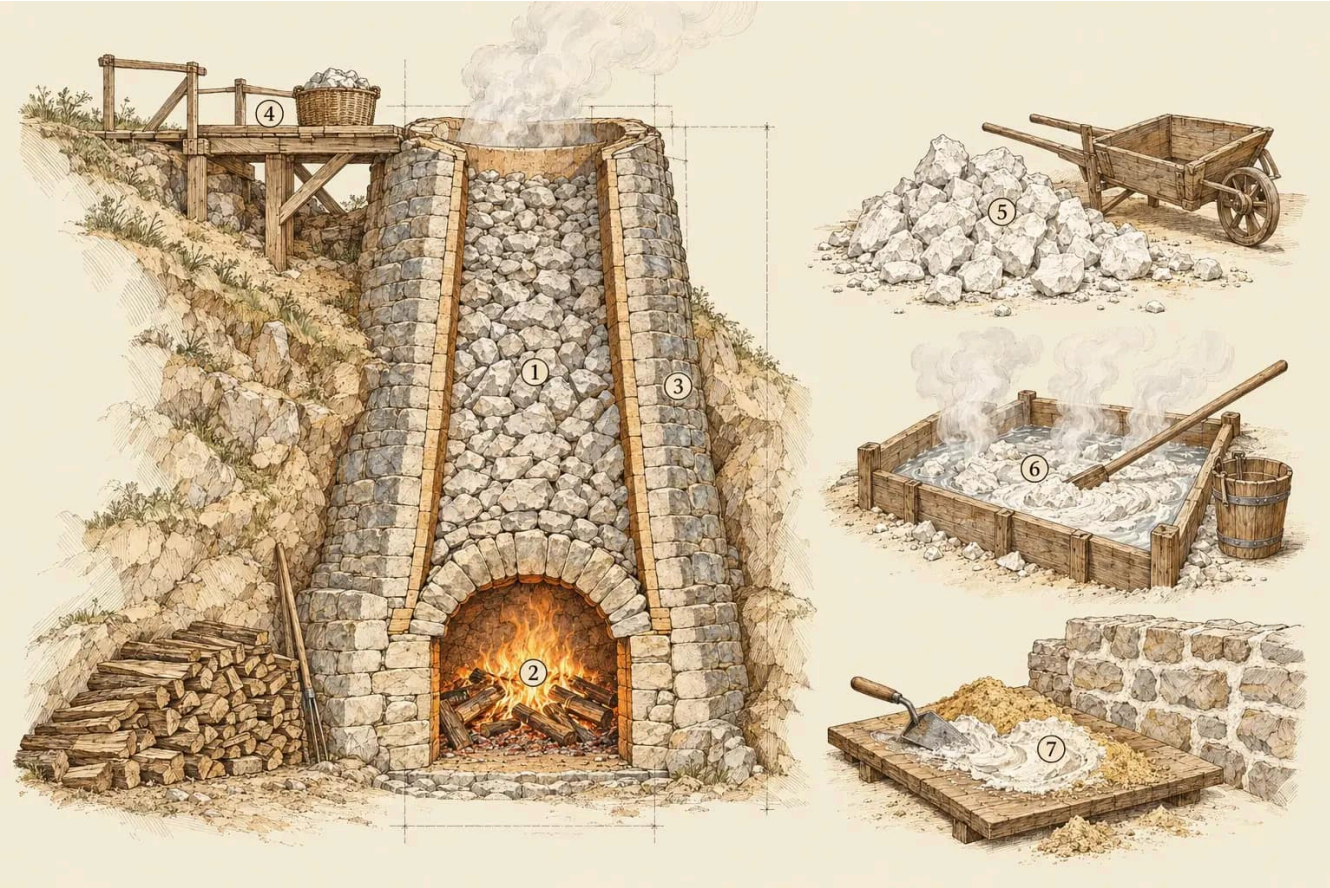
Lime and lime mortar

Burnt stone that turns back to stone

10,000 years ago · Prehistory · Settlement

Requires: Control of Fire (p. 9), Stone Tools (p. 5)

Leads to: Aqueduct (p. 141), Portland Cement (p. 250), Roman Concrete (p. 161)



1 Charge of limestone 2 Wood fire under the arch of stones 3 Thick kiln wall with its inner lining 4 Loading platform at the top
5 Quicklime drawn from the kiln 6 Slaking pit: water, steam and putty 7 Mortar of putty and sand, laid in a wall

Lime is limestone burnt in a kiln until it gives off carbon dioxide, then slaked with water into a white putty or powder. Mixed with sand, it has made mortar and plaster for thousands of years, and it sets by taking carbon dioxide back from the air and turning into stone again.

What it is

Lime is a white binder made from limestone, chalk or shells, all forms of calcium carbonate. Burnt, the stone becomes quicklime; with water, quicklime becomes slaked lime, as a soft putty or a dry powder. Mixed with sand, slaked lime makes mortar to bed stones and bricks, and plaster for walls and floors.

Once in place, the mortar slowly takes carbon dioxide from the air and turns back into calcium carbonate, the substance it started from. Builders call this round trip the lime cycle, and the plate follows it from the kiln on the left to the wall on the right.

How it works

Burning. Above roughly 700 °C, and quickly at about 900 °C, calcium carbonate breaks down into calcium oxide and carbon dioxide, which leaves with the smoke. Pure limestone loses 44% of its weight, yet the lumps keep their shape and come out light, porous and chalky. Vitruvius noticed the loss and put it at a third.

In a traditional kiln the burner builds a vault of large stones over the fire channel, then fills the shaft with smaller and smaller pieces. Fire is fed through the opening at the foot for two or three days. Cato, writing about 160 BCE, gives the signs that the burn is done: the top stones are burnt through, the charge sinks at the bottom, and the flame comes out with less smoke. The kiln then cools for several days before it is emptied.

Slaking. Quicklime reacts with water to form calcium hydroxide and gives off a great deal of heat. The water can boil, and the lumps swell and burst into a fine white mass. With plenty of water the result is lime putty; with just enough, a dry powder, the hydrated lime sold in bags. Putty improves with keeping: until the mid-nineteenth century it matured in a pit or a wooden box for several weeks or up to a year, kept covered so that the air could not harden it.

Slaking: the lumps swell, crack and fall apart while the water heats up.

Setting. In a wall, the sand forms the body of the mortar and the lime fills the gaps between grains. As the water dries out, the calcium hydroxide takes carbon dioxide from the air and becomes calcium carbonate again. This carbonation starts at the surface and moves inward slowly. Mortar that dries too fast stays weak.

Pure lime mortar is usually softer and more permeable than the stones or bricks it binds, so a wall can settle a little and still dry out through its joints. Limestone containing clay gives a hydraulic lime, which also sets under water.

How to build

Buy lump quicklime from a supplier for building conservation, slake it, then mix mortar and lay a short garden wall of stones. With ready-made lime putty, skip the slaking and go straight to the mix.

Slake the lime. Half fill a steel tub with water. Wearing goggles, gloves and long sleeves, add the quicklime to the water a little at a time, never the water to the lime, and stand back as it heats. Stir with a long wooden paddle. Once cool, sieve it into a lidded bin, let the putty settle under a few centimetres of water and leave it for at least a few weeks.

Mix the mortar. Use clean, sharp sand with grains of many sizes, one part of putty to three of sand by volume. Beat and chop the mix with a larry or a shovel for a long time, adding as little water as you can: long working makes lime mortar plastic and cohesive, while extra water makes it shrink and crack.

Lay and cure. Build only when it is at least 5 °C and rising, with no frost forecast for weeks. Dampen the stones so they do not draw the water out of the joints. Bed each stone in mortar and press the joints full. Keep the work damp and shaded under hessian for at least a week, misting it when it turns pale, and cover it with insulating sheets if frost threatens. Never dry lime work with a heater.

Mixing by hand: the larry, a hoe pierced with holes, works the putty into the sand.

> **Safety.** Quicklime and slaked lime are caustic: they burn skin and can blind. Wear sealed goggles, gloves, long sleeves and boots, and a dust mask for powder. If lime gets in the eyes, rinse at once with plenty of clean water, holding the lids open, for at least 15 minutes, and get medical help. Slaking can make water boil and spit, and quicklime that meets moisture has set wood and straw on fire: keep it dry, sealed and away from anything that burns, and never add water to it in a closed container. Do not build a kiln without local permission and experienced help, keep away from its top while it burns, and never climb onto or into a warm kiln. Keep children away.

History and evolution

The oldest burnt lime comes from foragers in the Levant: in Sinai, about 16,000 years ago, it seems to have helped fix small flint blades to their hafts. At Nahal Ein Gev II, near the Sea of Galilee, eight people were buried about 12,000 years ago under a layer of lime plaster some 40 cm thick, which means lime was already being made in quantity.

In the early farming villages that followed, from about 10,000 years ago, lime plaster covered floors and walls at many sites, and a kiln sunk into the ground at Nesher-Ramla in Israel dates from about 10,400 years ago. At ʼAin Ghazal, near Amman, people modelled 32 statues and busts in lime plaster over reed frames; calibrated radiocarbon dates place them around 7700 to 7500 BCE, while older publications give about 6700 to 6500 BC in uncalibrated years.

A plaster statue from ʼAin Ghazal: lime modelled over bundles of reeds tied with twine.

Roman writers left practical instructions. Cato's kiln was 10 feet across, 20 feet high and 3 feet wide at the top. Vitruvius advised three parts of pit sand to one of lime, or two of river or sea sand.

After Rome, many mortars were lime putty and local sand, about one to three; others were hot mixes of quicklime slaked in damp sand, and recipes varied from region to region. Quicklime was slaked on the building site until the mid-nineteenth century. Portland cement, patented in Britain in 1824, gradually took over, and by the 1930s most American masons mixed it into their mortar. Conservation builders have gone back to lime for old buildings, because a hard, dense cement mortar can keep moisture in the masonry and speed the decay of the stone.

Key figures

Burning temperature
About 900 °C; the change begins above roughly 700 °C

Weight lost in the kiln
44% for pure limestone; Vitruvius put it at a third

Traditional mortar
1 part lime putty to 3 parts sand by volume

Heat of slaking
Quicklime reacting with moisture has reached 800 °C and set wood and straw alight

Oldest large-scale lime plaster
Nahal Ein Gev II, Israel, about 12,000 years ago

Sources

1. Lime plaster cover of the dead 12,000 years ago: new evidence for the origins of lime plaster technology (Friesem, Abadi, Shaham and Grosman, Evolutionary Human Sciences, 2019) · Cambridge University Press, via PubMed Central https://pmc.ncbi.nlm.nih.gov/articles/PMC10427327/
2. A 10,400-year-old sunken lime kiln from the Early Pre-Pottery Neolithic B at the Nesher-Ramla quarry (el-Khirbe), Israel (Toffolo et al., 2017) · Journal of Archaeological Science: Reports, record at CENIEH https://investigacion.cenieh.es/documentos/65872833e6e23719147fb5c7?lang=fr
3. 'Ain Ghazal "Monumental" Figures: A Stylistic Analysis (Denise Schmandt-Besserat) · University of Texas at Austin https://sites.utexas.edu/dsb/ain-ghazal/ain-ghazal-monumental-figures-a-stylistic-analysis/
4. Lime Plaster Statue from Ain Ghazal · World History Encyclopedia https://www.worldhistory.org/image/8522/lime-plaster-statue-from-ain-ghazal/
5. Cato, On Agriculture, chapters 1–52 (chapters 16 and 38: the lime kiln), translated by W. D. Hooper and H. B. Ash · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Cato/De_Agricultura/A*.html
6. Vitruvius, The Ten Books on Architecture, Book II, chapters 4–5 (sand and lime), translated by Joseph Gwilt · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/2*.html
7. Introduction to lime: lime and its production · Tŷ-Mawr Lime https://lime.org.uk/knowledge-base/introduction-to-lime-lime-and-its-production
8. Some dos and don'ts in the use of lime mortars · Building Limes Forum https://www.buildinglimesforum.org.uk/some-dos-and-donts-in-the-use-of-lime-mortars/
9. Technical Advice Guide: Introduction to Lime in Traditional Buildings · Scottish Lime Centre Trust https://scotlime.org/documents/15/Technical_Advice_Guide_Introduction_to_Lime_in_Traditional_Buildings_1.pdf
10. Preservation Brief 2: Repointing Mortar Joints in Historic Masonry Buildings (Mack and Speweik, 1998) · U.S. National Park Service https://www.nps.gov/orgs/1739/upload/preservation-brief-02-repointing.pdf
11. A case study in lime production no. 1: traditional batch techniques at Chenkumbi, Malawi · Practical Action https://kolibri.teacherinabox.org.au/modules/en-practical_action/Construction/Cement%20and%20binders/KnO-100090_Lime_production_traditional_Chenkumbi_Malawi.pdf
12. Lime production: traditional batch techniques in Patarra, Costa Rica · Practical Action https://samplecontents.library.ph/en-practical_action/Construction/Cement%20and%20binders/KnO-100089_Lime%20production%20-%20Traditional%20batch%20techniques%20in%20Patarra%20%20Costa%20Rica,%20case%20study/page2.html
13. Calcium oxide: chemical datasheet (with NIOSH Pocket Guide first aid) · CAMEO Chemicals, U.S. National Oceanic and Atmospheric Administration https://cameochemicals.noaa.gov/chemical/311

Fact-checked on 2026-10-13

Drinking Water

Draw, settle, filter, boil

c. 8,400 BCE · Prehistory · Settlement

Requires: Control of Fire (p. 9), Pottery (p. 22), Rope & Cordage (p. 13)

Leads to: Hygiene & Antisepsis (p. 290), Oral rehydration (p. 360)

1 Stone-lined well shaft 2 Headwall, cover and windlass 3 Sloping apron and drain 4 Settling jar
5 Fine sand bed with its biological layer 6 Gravel and outlet pipe 7 Pot at a rolling boil

Safe drinking water starts with a protected source, such as a lined and covered well dug uphill and well away from latrines and animal pens. When the water is doubtful, settling, slow sand filtration and boiling remove or kill most of the germs behind diarrhoea, cholera and typhoid, but none of them takes out dissolved chemicals.

What it is

Most water that makes people ill looks clean. The danger lies in bacteria, viruses, protozoa and worm eggs, nearly all of them from human or animal faeces. Cholera, typhoid, dysentery and the diarrhoea that still kills young children travel this way.

Safe water comes from a chain of habits: a source kept clean, doubtful water cleared by settling or slow sand filtration and then boiled, and careful storage, since a dirty cup or hand can spoil clean water again.

How it works

Rain washes excreta from fields and yards into streams and ponds. Liquid from a pit latrine seeps through the soil towards shallow groundwater, faster through gravel or fissured limestone than through clay.

Groundwater is usually cleaner than surface water because the soil holds back particles and microbes. A well keeps that advantage when its mortared upper lining, headwall, cover and sloping apron stop runoff and spills from entering the shaft.

Many germs cling to particles of silt and clay. When cloudy water stands still for some hours, the particles sink and take part of the load with them. Settling alone does not make water safe.

A slow sand filter is mostly a living system. Water creeps down through fine sand at a few tenths of a metre per hour. Over the first weeks a layer of bacteria, algae and tiny organisms settles in the top centimetres. Particles stick there, the microbes of the layer feed on many of the trapped pathogens, and others die before they get through. Some bacteria and many viruses still pass, so the filter improves water without making it safe on its own.

Boiling kills by heat. According to the WHO, bringing water to a rolling boil is enough to inactivate pathogenic bacteria, viruses and protozoa. Heat does nothing to chemicals.

How to build

Choose and guard the source. Prefer protected groundwater or a captured spring, then rain from a clean roof, and only then rivers and ponds. Site a well uphill of any latrine, at least 30 m away and further in gravel or fissured rock, and fence animals out at about 15 m, as the WHO suggests. Wash clothes and water livestock downhill.

Dig and line the well. Dig a shaft at least a metre across and line it with stone or brick as you go down. The WHO recommends making at least the top 3 m watertight with mortared joints, while the lining below the water level stays open to let groundwater in. Raise a headwall, fit a cover, and build a watertight apron at least 1 m wide, joined to the headwall and sloping to a channel that leads spilt water downhill. Keep one rope and bucket for the well and never set them on the ground. A new or flooded well must be disinfected and, where possible, its water tested; until then, boil it. Digging or cleaning a deep well is work for experienced well diggers, never for one person alone.

Settle and strain. Let cloudy water stand in a covered jar for several hours, then pour off the clear upper part without stirring the sediment. Strain it through clean cotton cloth folded into several layers. In Bangladeshi villages, sari cloth folded to eight layers cut cholera by almost half.

A cloth folded several times holds back silt and the plankton that cholera bacteria cling to.

Build a sand filter. These figures give the principle; a tested design such as CAWST's biosand filter specifies sand grading and flow. Take a watertight container about 0.9 m tall. Put gravel at the bottom around the end of an outlet pipe, then coarser sand, then at least half a metre of fine washed sand. Bring the pipe up the outside so that its end sits about 5 cm above the sand surface; once the flow stops, check that about 5 cm of water still covers the sand. A perforated plate or flat stone on top stops pouring from digging into the sand. Pour in one batch at a time and let the filter rest for at least an hour, and no more than two days, between batches. When the flow becomes too slow, lightly swirl the very top of the sand with the palm of the hand, without mixing it deeper, and scoop out the dirty water.

A lid, a raised base and a ladle keep hands and dirt out of the stored water.

Boil and store. Boil all water from a doubtful source before drinking it, even after settling and filtering. Bring it to a rolling boil; the CDC advises keeping it there for 1 minute, or 3 minutes above about 2,000 m. Let it cool covered, then pour it into a clean jar with a narrow neck and a lid. Serve with a clean ladle or by pouring, never by dipping a cup or a hand.

> **Safety.** Boiling and filtering deal with germs, not chemicals. Nitrate from manure and latrines, arsenic, fluoride, lead, salt, fuel and pesticides stay in the water, and boiling concentrates nitrate as water evaporates. If a source may be chemically polluted, find another. Settling and sand filters do not remove every germ: boil the water as well. Keep every latrine at least 30 m from a well and downhill of it, with the bottom of the pit at least 1.5 m above the water table at its highest, in the rainy season. Boiling water scalds: keep the pot stable and children away. Do not climb down into a well: the air at the bottom can lack oxygen and the walls can collapse, and a rope protects against neither. Cover every well so that no child or animal can fall in.

History and evolution

The oldest securely dated wells are in Cyprus: at Kissonerga-Mylouthkia, a shaft cut through limestone around 8400 BCE reached water at 8 m.

Filtered public supplies grew out of an experimental filter built at a Scottish bleachworks in 1804. In 1829 James Simpson, engineer of the Chelsea Waterworks Company in London, brought into use a filter bed of about an acre of brick, gravel and sand for water taken from the Thames.

In 1849 John Snow argued that cholera travelled in water fouled by sewage, while most doctors blamed bad air. When cholera struck Soho on 31 August 1854, he linked the deaths to the Broad Street pump: of 73 deaths he looked into in the streets around it, 61 were of people known to have drunk its water. The parish removed the handle on 8 September, when the outbreak was already waning. A local clergyman, Henry Whitehead, later traced the likely origin to a cesspool at No. 40, into which the water from a sick baby's nappies had been emptied. Snow also compared two water companies serving the same streets: houses supplied from below London's sewer outlets had about 315 cholera deaths per 10,000 houses, against 37 for the company drawing upstream.

Broad Street, September 1854: without its handle, the pump could no longer be used.

In 1908 Jersey City became the first American city to chlorinate its supply routinely; the chlorine left in the water keeps protecting it in the pipes.

Key figures

Boiling

A rolling boil inactivates bacteria, viruses and protozoa (WHO); CDC advises 1 minute, 3 minutes above about 2,000 m

Household sand filter

In the laboratory, with a mature biological layer: 99.98% of protozoa and 90–99% of bacteria removed, viruses less reliably (CDC)

Oldest dated well

About 8400 BCE, Kissonerga-Mylouthkia, Cyprus, 8 m deep through limestone

Latrine and well

At least 30 m apart, pit bottom at least 1.5 m above the water table (MSF)

Folded cloth

Sari cloth folded to 8 layers strains out particles above about 20 µm; 48% less cholera in Bangladeshi villages (2003)

Sources

1. Boil water (technical brief WHO/FWC/WSH/15.02) · World Health Organization https://www.who.int/publications/i/item/WHO-FWC-WSH-15.02
2. How to Make Water Safe in an Emergency · Centers for Disease Control and Prevention https://www.cdc.gov/water-emergency/about/index.html
3. How to Create and Store an Emergency Water Supply · Centers for Disease Control and Prevention https://www.cdc.gov/water-emergency/about/how-to-create-and-store-an-emergency-water-supply.html
4. Household Water Treatment: Slow Sand Filtration · Centers for Disease Control and Prevention https://stacks.cdc.gov/view/cdc/41390/cdc_41390_DS1.pdf
5. Biosand Filter Manual: Design, Construction, Installation, Operation and Maintenance (2009) · CAWST (Centre for Affordable Water and Sanitation Technology) https://www.ctahr.hawaii.edu/hawaiirain/Library/Guides%26Manuals/CAWST%20files/Biosand%20Filter%20Manual_Version%2010_Sep%2009%5B1%5D.pdf
6. Technical Fact Sheet: Dug well with a hand pump (draft, 2020) · World Health Organization https://www.who.int/docs/default-source/wash-documents/sanitary-inspection-packages/2-tfs-dug-well-with-hand-pump-d-200506.pdf
7. Appendix 14. Excreta pit (stools and vomit) · Médecins Sans Frontières, Medical Guidelines https://medicalguidelines.msf.org/en/viewport/CHOL/english/appendix-14-excreta-pit-stools-and-vomit-32409860.html
8. Introduction to Excreta Disposal, Drainage and Hand Washing Facilities · Red Cross Red Crescent, Southeast Asia https://www.rcrc-resilience-southeastasia.org/wp-content/uploads/2018/03/5-Introduction-to-Excreta-Disposal-Drainage-and-Hand.pdf
9. Private Water Supplies Technical Manual, 6.5 Filtration · Drinking Water Quality Regulator for Scotland https://dwqr.scot/media/jl0ddz3x/pws-technical-manual-section-6-water-treatment-processes-65-filtration-larger-scale.pdf
10. Reduction of cholera in Bangladeshi villages by simple filtration (Colwell et al., 2003) · Proceedings of the National Academy of Sciences https://pmc.ncbi.nlm.nih.gov/articles/PMC298724
11. All About DWEE: Keeping Your Well Water Safe and Sound · Nebraska Department of Water, Energy, and Environment https://dwee.nebraska.gov/node/5495
12. Well · Wikipedia https://en.wikipedia.org/wiki/Well
13. London's water supply and the introduction of sand filtration (Chelsea) · Institute of Water https://instituteofwater.org.uk/all/londons-water-supply-and-the-introduction-of-sand-filtration-chelsea/
14. John Snow: Cholera & the Broad Street pump · London Museum https://www.londonmuseum.org.uk/collections/london-stories/john-snow-cholera-broad-street-pump/
15. Dr John Snow and Reverend Whitehead · Cholera and the Thames (Westminster City Archives) https://www.choleraandthethames.co.uk/cholera-in-london/cholera-in-soho/
16. Snow & the pump handle · Cholera in St. James, Michigan State University https://johnsnow.matrix.msu.edu/broadstpump/snow-the-pump-handle/
17. Snow's "Grand Experiment" · Adhikari, DeNero and Wagner, Computational and Inferential Thinking https://inferentialthinking.com/chapters/02/2/snow-s-grand-experiment/index.html
18. History of Drinking Water Treatment · Centers for Disease Control and Prevention https://archive.cdc.gov/www_cdc_gov/healthywater/drinking/history.html
19. Reductions of E. coli, echovirus type 12 and bacteriophages in an intermittently operated household-scale slow sand filter (Elliott et al., 2008) · Water Research https://doi.org/10.1016/j.watres.2008.01.016
20. Investigation of E. coli and virus reductions using replicate, bench-scale biosand filter columns and two filter media (Elliott et al., 2015) · International Journal of Environmental Research and Public Health https://pmc.ncbi.nlm.nih.gov/articles/PMC4586611
21. Slow Sand Filtration (Huisman and Wood, 1974) · World Health Organization https://www.susana.org/knowledge-hub/resources?id=4263
22. Giardiasis (DPDx, laboratory identification of parasites) · Centers for Disease Control and Prevention https://www.cdc.gov/dpdx/giardiasis/index.html

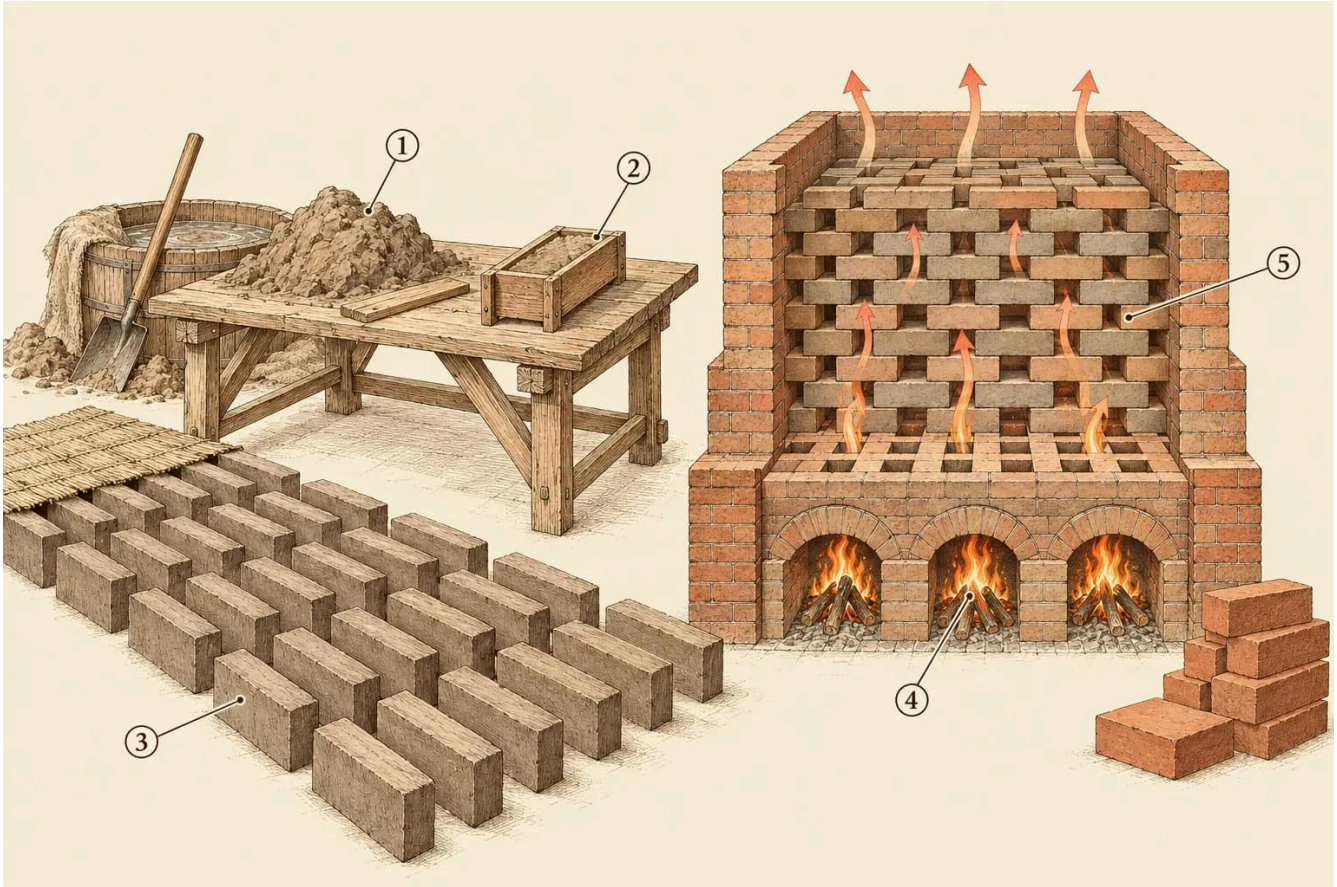
Fact-checked on 2026-10-13

Bricks

Standard blocks of earth

c. 7,500 BCE · Prehistory · Settlement

Leads to: Aqueduct (p. 141), Arch and Vault (p. 70), Roman Concrete (p. 161)



1 Prepared clay 2 Wooden mould 3 Green bricks drying 4 Fire tunnel 5 Bricks set in the kiln

A brick is a block of clay shaped to a set size, dried in the sun or fired in a kiln, so that walls can be built from identical, easily handled units. Shaped mud bricks were in use in the Near East before 7500 BCE; fired bricks came thousands of years later and went on to carry cities, aqueducts and factory chimneys.

What it is

A brick is a small block of earth made to a regular shape and size. Mud bricks are only dried in the sun; fired bricks are baked in a kiln until the clay turns to a hard ceramic. Both are laid in courses with mortar, and because every brick has the same size, the builder can work out quantities in advance and keep the courses level.

The plate shows the work of a hand brickyard before machines: clay prepared beside a moulding table, green bricks drying in rows, and a small updraft kiln shown in section.

How it works

Clay is made of tiny flat mineral grains. Wet, they slide over each other and the mass can be shaped; as it dries, the water between them leaves, the grains pack together and the block hardens and shrinks. Pure clay shrinks so

much that it cracks, so brickmakers mix in sand, crushed pottery or chopped straw. In ancient Mesopotamia straw or dung was the usual temper, and one estimate puts the need at about 60 kg of straw per hundred bricks.

A sun-dried brick stays soft enough to return to mud if it is soaked, so mud-brick walls need a stone footing, wide eaves and regular repair. Firing changes the clay itself. The clay minerals first lose the water bound inside them, and towards 900 to 1,000 °C their grains begin to fuse together. The fired brick will no longer soften in water, and its colour, usually red, comes from the iron in the clay.

In an updraft kiln like the one drawn, fires burn in tunnels at the base. The hot gases rise through a perforated floor and through the gaps left between the green bricks, which are set in an open lattice, and leave at the top. Firing has to start slowly. Water still trapped in the clay turns to steam, and a brick heated too fast can crack or burst.

A bottomless wooden mould, sanded inside, gives every brick the same size.

How to build it

Sun-dried bricks need nothing more than suitable earth, water, straw, a mould and a few dry weeks.

Test the earth. Dig below the topsoil, which holds roots and humus. Make a few trial bricks: if they crack as they dry, the earth has too much clay and needs sand; if they crumble at the corners, it needs more clay.

Mix and temper. Break up the earth, soak it, and tread chopped straw into it until it forms a stiff paste with no lumps. A bucket of loose straw to five of earth is a reasonable first trial; adjust it after the test bricks, since some good soils need little or no straw. Leave the mix covered for a day so the water spreads evenly.

Make the mould. Join four planks into a bottomless frame, for example 30 × 15 × 10 cm inside, with handles at the ends. Wet it and dust it with sand so the clay will release.

Mould the bricks. Set the mould on flat sanded ground, throw in a lump of clay hard enough to fill the corners, strike off the top with a wet stick, and lift the mould straight up. Place the next brick a finger's width away.

Dry them. Keep the bricks out of strong sun and rain for the first days, then stand them on edge so air reaches every face. Depending on the weather they need one to four weeks before they can be stacked; break a test brick to check that no darker, damp core remains. For fired bricks, take a few small, bone-dry samples to a pottery studio and fire them in its kiln.

> **Safety.** A soaked mud brick weighs several kilograms: lift with bent knees and keep stacks low and stable. Dry clay dust contains fine silica, so dampen the earth before breaking it up, clean up with water rather than by sweeping, and wear a well-fitting P2 or P3 dust mask whenever dust cannot be avoided. Fence or fill any pit you dig, as water collects in it. Kiln firing involves high heat and fumes; leave it to someone trained, and never fire bricks that are still damp.

History and evolution

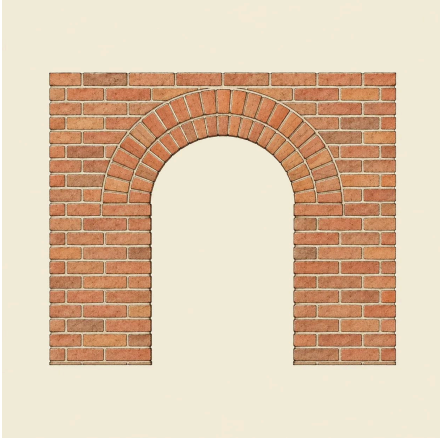
Sun-dried earth was already used for walls in the Near East in the ninth millennium BCE, and among the oldest shaped mud bricks are those of Tell Aswad in Syria, from before 7500 BCE. At Nemrik in northern Iraq, eighth-millennium walls were built of long cigar-shaped bricks about 51 cm long. The bricks of Jericho, from the eighth and seventh millennia BCE, were shaped by hand and pressed with rows of thumbprints that helped the mortar grip.

A hand-shaped brick from Jericho: the thumbprints gave the mortar something to hold.

Bricks made in rectangular wooden moulds spread across Mesopotamia in the sixth millennium BCE. Fired bricks came later and were at first kept for special uses, because fuel was scarce: in Mesopotamia they appear in the Uruk period of the fourth millennium BCE, though some writers date the first ones earlier, and they were made in China at Chengtoushan around 4400 BCE. A Sumerian text of about 2100 BCE describes Gudea, ruler of Lagash, pouring clay into the mould and lifting out the first brick of a new temple. Cities of the Indus valley built with fired bricks of regular size from the third millennium BCE; many are close to a ratio of 1:2:4 for thickness, width and length, although excavators recorded several sizes.

Rome produced standard fired bricks in great numbers by the first century CE, and after a long gap northern Europe took up brick again in the Middle Ages, where good building stone was rare.

Industrial brickmaking began in the nineteenth century with machines that pressed clay into moulds. In 1858 Friedrich Hoffmann patented a ring kiln that never had to go cold: the fire moved from one chamber to the next, while the hot gases dried and warmed the bricks ahead of it. In the kiln at Palmerston North in New Zealand, the fire took about six weeks to travel round its fourteen chambers. The standard metric British brick measures 215 × 102.5 × 65 mm.



In an arch, each brick is set on end so that every joint points to the centre and the load passes from brick to brick.

Key figures

Among the oldest shaped mud bricks
Tell Aswad, Syria, before 7500 BCE

Standard metric British brick
215 × 102.5 × 65 mm

Firing temperature
About 900 to 1,000 °C for common fired brick

Continuous kiln
Patented by Friedrich Hoffmann in 1858

Sources

1. The Appearance of Bricks in Ancient Mesopotamia (Hnaihen, Athens Journal of History 6/1, 2020) · Athens Institute for Education and Research https://www.athensjournals.gr/history/2020-6-1-4-Hnaihen.pdf
2. Thumb-pressed brick, Tell al-Sultan (Jericho) · Queen's University Library, Museum of Near Eastern Archaeology https://virtual-exhibits.library.queensu.ca/museum-of-near-eastern-archaeology/thumb-pressed-brick/
3. Hoffman Oblong Continuous Kiln, Palmerston North · Heritage New Zealand Pouhere Taonga https://www.heritage.org.nz/list-details/194/Listing
4. Brick · Wikipedia https://en.wikipedia.org/wiki/Brick
5. Technical Note 9: Manufacturing of Brick · Brick Industry Association https://www.gobrick.com/media/file/9-manufacturing-of-brick.pdf
6. ABCs of Making Adobe Bricks (Guide G-521) · New Mexico State University, Cooperative Extension Service https://pubs.nmsu.edu/_g/G521/
7. Shrinkage rates · Valentine Clays https://valentineclays.co.uk/pages/shrinkage-rates
8. Drying shrinkage · Digitalfire Reference Library https://digitalfire.com/glossary/drying+shrinkage
9. Hands-on archaeology: how to make adobe bricks · Archaeology Southwest https://www.archaeologysouthwest.org/2018/11/04/hands-on-archaeology-how-to-make-adobe-bricks/
10. Stamford bricks: the hand-made process (Talking about technology) · Bournemouth University https://histru.bournemouth.ac.uk/Oral_History/Talking_About_Technology/building%20conservation%20technology/stamford_bricks_hand_made_process.htm
11. Material behaviour of unstabilised earth block masonry and its components under compression at varying relative humidity (Wiehle and Brinkmann, Case Studies in Construction Materials 17, 2022) · Elsevier https://doi.org/10.1016/j.cscm.2022.e01663

Fact-checked on 2026-10-12

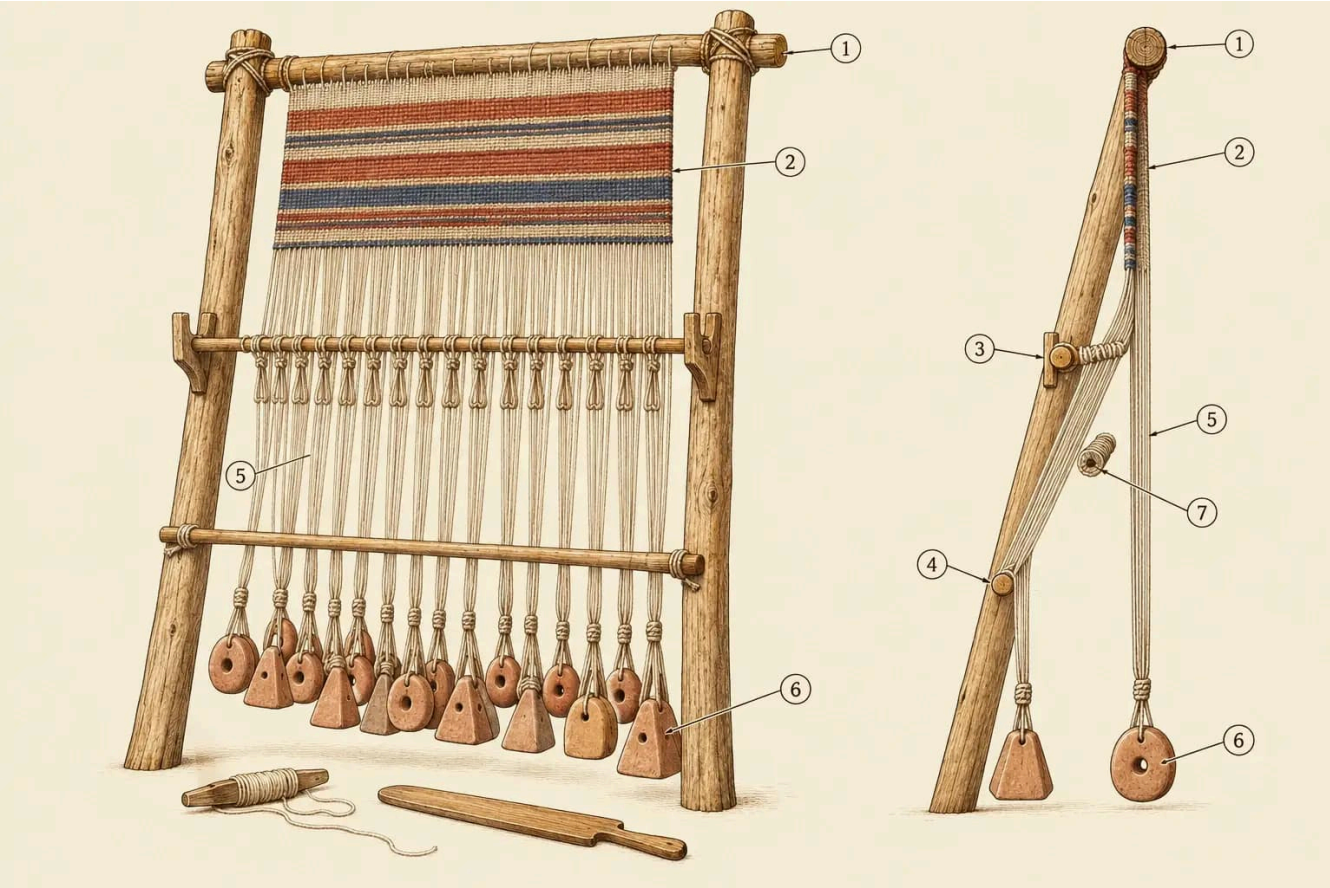
Weaving

Threads crossed into cloth

c. 6,700 BCE · Prehistory · Settlement

Requires: Rope & Cordage (p. 13)

Leads to: Hot-Air Balloon (p. 225), Sail (p. 86), Sewing Machine (p. 262)



1 Upper beam 2 Woven cloth 3 Heddle rod 4 Shed rod 5 Warp 6 Loom weights 7 Weft in the open shed

Weaving makes cloth by passing a thread, the weft, over and under a set of stretched threads, the warp, row after row. The loom keeps the warp taut and opens it so that the weft crosses in one pass; the warp-weighted loom drawn here goes back to the Neolithic and lasted in northern Europe into the Middle Ages; it survives in a few places.

What it is

Weaving makes cloth from two sets of threads crossed at right angles. The warp is stretched lengthwise on a frame, the loom. The weft goes across it. In the simplest structure, plain weave, it passes over one warp thread and under the next, and each new row does the opposite. Friction holds the crossings together, so the cloth needs no glue or knots and still drapes.

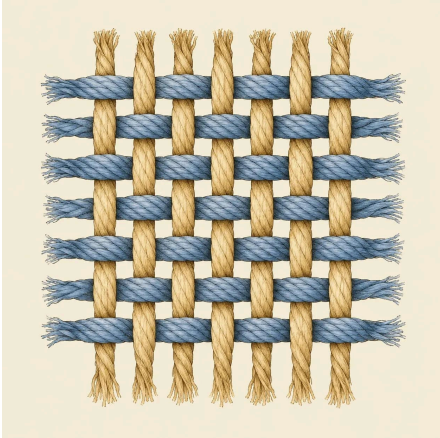
People twisted cords and plaited mats long before they wove. A loom keeps hundreds of threads at an even tension and lifts a whole set of them at once, so the weft crosses the whole width in one movement instead of being worked over and under each warp thread by hand.

The plate shows a warp-weighted loom, used in the Near East and Europe from the Neolithic, and in northern Europe until the Middle Ages: two posts lean against a wall, the warp hangs from a beam across their tops, and clay weights keep it taut.

How it works

The weft passes through an opening in the warp, the shed, which two rods make on this loom. The shed rod (4) is fixed low across the posts, with every other warp thread in front of it and the rest behind. Because the posts lean, the front threads slope out over the rod while the back ones hang straight down, and a gap opens between the two layers by itself: the natural shed.

The heddle rod (3) sits higher up, in front of the warp. A loop of string, a heddle, runs from it to each back thread. When the weaver pulls the rod forward and rests it in forked brackets on the posts, the back threads come forward past the front ones and a second opening forms, the countershed. Passing the weft (7) through the shed, then back through the countershed, gives plain weave. More heddle rods, tied to other sets of threads, make twills and patterns.



Plain weave: from one row to the next, the weft swaps which warp threads it covers.

Weaving starts at the top. The weaver lays each weft in a loose arc, so it does not pull the edges in, and beats it upwards against the cloth with the fingers, a comb or a flat wooden sword beater. Finished cloth (2) can be rolled onto the upper beam (1), so the loom can make a piece longer than its own height.

Each loom weight (6) carries a bundle of warp threads (5). In tests at the Centre for Textile Research in Copenhagen, wool yarn spun with a 4 g whorl needed about 13 g of tension per thread, and thicker yarn from an 8 g whorl about 19 g. The weights must hang side by side at one level, or they tangle and wear the threads.

How to build

Most of the labour goes into the yarn: at six warp threads and ten weft threads per centimetre, a square metre of cloth takes at least 1.6 km of it, plus waste and the extra length the threads take as they bend over and under each other.

Spin the yarn. A drop spindle is a stick about 25 cm long with a weighted disc, the whorl, near one end. Set it turning, let the twist run into fibres drawn from a bundle of wool or flax, and wind the yarn on when the spindle nears the floor. Warp yarn must be strong, since it carries the weights.

Make the frame. Cut two straight posts about 2 m long, a round beam to sit in notches at their tops, a shed rod, a heddle rod and two forked brackets. Bore a few holes round one end of the beam: a peg pushed through one of them and lashed to a post stops it turning, and comes out when you roll up the cloth. Lean the posts against a solid wall at a gentle angle, wedge their feet and tie their tops to the wall or a roof beam, so the loom cannot come forward when you pull the heddle rod. Lash the shed rod and the brackets firmly to the posts.

Make the weights. Shape pierced rings or pyramids of clay, dry them right through, until they no longer feel cool to the touch, and have them fired in a kiln or bonfire by someone who knows how; stones with a natural hole avoid the firing. Keep them as equal as you can; a few hundred grams each is usual. The yarn decides how many threads each weight carries: at about 15 g a thread, a 300 g weight holds some twenty. Each row of weights should be about as wide as the warp.

Set up the warp. On a small band loom or with tablets, weave a narrow band as long as the cloth will be wide, carrying its weft out on one side in loops as long as the warp you need: these loops become the warp. Sew it to the upper beam and let the threads fall. Pass every other one behind the shed rod. Tie the front threads and the back threads to separate weights, in equal bundles, and hang the weights of each row side by side at one height. Then tie a heddle loop from the heddle rod to each back thread. For a piece longer than the loom, wind spare warp into a small bundle above each weight and let some out each time you roll up the cloth.

Weave. Pass the weft through the natural shed, just under the edge of the cloth, and beat it up. Bring the heddle rod forward into the brackets, pass the weft back, beat again and return the rod. To finish, weave a closing band or knot the warp ends into a fringe.

> **Safety.** A loaded loom is top-heavy: tie it to a sound wall, block its feet and keep children off it. A falling weight can break a toe, so wear closed shoes. Damp clay can burst in the fire: fire only weights that are fully dry, outdoors or in a ventilated kiln, and stand well back.

History and evolution

Cloth seldom survives, but its tools do: loom weights and spindle whorls are common finds on ancient sites.

Weaving may be older than farming. At Pavlov and Dolní Věstonice in Moravia, fired clay lumps more than 26,000 years old carry some eighty prints that Olga Soffer and James Adovasio read as plant-fibre cords, twined fabrics and plain weaves. They are impressions, not cloth, and nobody knows whether a loom made them.

The oldest woven cloth to survive in the Near East and Europe comes from Çatalhöyük in Anatolia, from about 6700–6500 BCE: plain weave, preserved because it was charred. Long taken for linen, several of its samples proved in 2021, under the microscope, to be oak bast, the inner bark of the tree; others were too charred to tell. The date given for weaving in this catalogue follows this cloth: the Moravian prints are older but uncertain.

Clay loom weights, which outlast the wood, show the warp-weighted loom spreading through Neolithic Europe. In the Americas, weavers used the backstrap loom, stretched between a tree or post and a strap round the weaver's waist. The upright loom with two beams, pictured in Egyptian tombs, probably reached Europe from Egypt.

From about the eleventh or twelfth century the horizontal treadle loom, which opens the shed with the feet, gradually replaced the warp-weighted loom in Europe, later in the Nordic countries. The older loom is still worked at Fitjar in western Norway, and at Manndalen in the north, where Sami weavers revived it after 1945 for heavy wool blankets.

On a backstrap loom the weaver leans back to tighten the warp and forward to slacken it.

Key figures

Oldest textile impressions

Pavlov and Dolní Věstonice (Moravia), more than 26,000 years ago

Warp tension

About 13–19 g per wool thread in tests at the Centre for Textile Research, Copenhagen

Still in use

Warp-weighted looms at Fitjar and Manndalen, Norway

Oldest preserved woven cloth

Çatalhöyük (Anatolia), about 6700–6500 BCE, in plain weave

Loom weights

245 to 870 g in a set of seven found at Voss, Norway

Sources

1. Experimental Archaeology, Part 3: Loom weights (technical report, 2007) · Centre for Textile Research, University of Copenhagen https://ctr.hum.ku.dk/research-programmes-and-projects/previous-programmes-and-projects/tools/technical_report_3__experimental_archaeology.pdf
2. Oppstadvev · Store norske leksikon https://snl.no/oppstadvev
3. Çatalhöyük – The oldest textiles at the TRC · Textile Research Centre, Leiden https://www.trc-leiden.nl/trc/index.php/en/blog/1794-catalhoeyuek-the-oldest-textile-at-the-trc
4. Upper Palaeolithic fibre technology: interlaced woven finds from Pavlov I, Czech Republic, c. 26,000 years ago · Antiquity (Adovasio, Soffer and Klíma, 1996) https://www.cambridge.org/core/journals/antiquity/article/upper-palaeolithic-fibre-technology-interlaced-woven-finds-from-pavlov-i-czech-republic-c-26000-years-ago/CD78BC4A39E2DD6958ACA29BA1BA30DA
5. Ice Age clothing said to be more advanced than previously thought · ScienceDaily / University of Illinois https://www.sciencedaily.com/releases/2000/02/000203074853.htm
6. Backstrap looms · Sam Noble Museum, University of Oklahoma https://samnoblemuseum.ou.edu/collections-and-research/ethnology/mayan-textiles/weaving-technology/backstrap-looms
7. Understanding the Archaeological Record: Reconstructing a Warp-Weighted Loom · EXARC Journal https://exarc.net/ark:/88735/10351

Fact-checked on 2026-10-13

Salting & Curing

Drawing water out to stop decay

c. 6,050 BCE · Prehistory · Settlement

Requires: Pottery (p. 22)

1 Coarse sea salt 2 Pork legs buried in dry salt 3 Herring packed in salt and brine 4 Cured hams drying 5 Salt cod drying on a rack

Salting preserves meat, fish and vegetables by drawing water out of them and out of the microbes that would spoil them. People were boiling brine for salt in eastern Europe by the sixth millennium BCE, and salted pork, herring and cod fed armies, sailors and cities until refrigeration.

What it is

Salting, or curing, is one of the oldest ways of keeping food. Meat or fish is rubbed with dry salt or soaked in brine until it holds so little free water that spoilage bacteria cannot grow. Often the food is then dried, smoked or left to mature. Vegetables can be salted lightly instead, so that useful lactic bacteria ferment and sour them, as in sauerkraut.

The plate gathers the methods of a European larder before refrigeration: coarse salt, pork legs buried in a salting trough, herring packed in a barrel, hams hanging to dry, and split cod drying on a rack.

How it works

Every microbe needs water it can use. Food scientists measure that with water activity, which is 1.0 for pure water and falls as salt or sugar binds water. The limit differs from one microbe to another, and some food-poisoning bacteria still grow at fairly low values, but the great majority of microbes stop multiplying below about 0.90. A saturated salt brine sits near 0.75.

When salt touches meat or fish, water flows out of the tissue towards the more concentrated salt solution, while salt slowly moves in. Bacteria on the surface lose water the same way: their cell contents shrink away from the wall and they stop growing or die. The deeper the salt goes and the more water leaves, the longer the food keeps. Heavily salted cod or ham can last for months or years, but has to be soaked in fresh water, in the refrigerator, before cooking.

Rock salt grows in cubes; a crystal that grows faster along its edges than across its faces becomes a stepped "hopper".

Salt does not sterilise. Some dangerous bacteria tolerate it well, Staphylococcus aureus among them, and Clostridium botulinum, which grows without air, survives as spores in poorly cured meat and fish. Most modern meat cures therefore contain nitrite, which slows the growth of botulinum and keeps cured meat pink. Older recipes used saltpetre, which bacteria in the cure turn into nitrite.

Light salting works differently. With about 2 to 2.5% salt, cabbage keeps enough water for lactic acid bacteria, which tolerate salt better than most spoilers. They turn its sugars into lactic acid, and the acidity preserves the food.

How to build it

Curing meat at home safely needs a tested recipe, measured curing salt and a cool, controlled room. The safest place to start is with salt and cabbage: sauerkraut.

Prepare the cabbage. Take firm, fresh heads, remove the outer leaves and the cores, and shred finely, about 5 mm wide. Weigh it.

Salt it. For every 2.25 kg of cabbage, mix in 3 tablespoons of canning or pickling salt (salt without iodine or anti-caking agents), about 2 to 2.5% by weight. Pack it hard into a clean crock or wide jar, a handful at a time, pressing until the salt draws out the juice.

Cover and weigh it down. The cabbage must stay under its own brine at all times. If the juice does not cover it, add brine at once, made with 1½ tablespoons of salt for every 950 ml (one US quart) of boiled and cooled water. Lay a plate on top with a weight, such as a sealed bag of brine, and cover with a cloth.

Let it ferment. At 21 to 24 °C the cabbage takes about three to four weeks, at 15 to 18 °C five to six weeks. Below 15 °C it may not ferment; above 24 °C it can turn soft. A thin white film may form on the surface: skim it off. The kraut is ready when the expected time has passed, the bubbling has stopped and the cabbage tastes clearly sour throughout. It then keeps for months in the refrigerator.

> **Safety.** Keep vegetables under the brine at all times and use clean equipment. Throw the whole batch away if fuzzy or coloured mould appears anywhere, or if the kraut turns slimy, pink or dark, or smells rotten. Do not improvise cured meat or fish: botulism is rare but deadly, and nitrite curing salt is poisonous in excess. Use only the curing product, dose and weighing precision a tested recipe specifies, label it and keep it away from children. Cured foods carry a lot of salt; anyone told to limit salt should soak them well or avoid them.

History and evolution

Briquetage: brine was boiled in coarse clay troughs over a fire, and the troughs were broken to free the salt cakes.

Salt was being made long before writing. At Poiana Slatinei near Lunca, in north-eastern Romania, a brine spring about six times as salty as seawater is surrounded by a mound of ash and burnt earth some three metres high, left by people who boiled the brine with fire from about 6050 BCE. The excavators do not know whether that salt went to preserving food, to livestock or to trade, so the date marks the oldest known salt-making, not the first salted food.

In later prehistoric Europe, brine was boiled in coarse clay vessels set on clay props over a fire, a method called briquetage. The vessels were broken to free the salt cakes, and heaps of their fragments still mark the sites. At Hallstatt in Austria, people mined rock salt from the Bronze Age, and in the 13th and 12th centuries BCE they salted pork on a large scale in timber vats sunk into the ground, eight of which are now known.

The Greeks salted fish as tarichos and the Romans called salted meat and fish salsamentum; in the second century BCE, Gaul sent salt pork to Rome in large quantities. In Catholic Europe, salted fish, and dried salt cod above all, became the everyday food of Fridays and Lent, when meat was forbidden.

Cod from Newfoundland was already being salted for European markets in the sixteenth century, and in the seventeenth, cheap salt from southern Europe made salting worthwhile for the fishing nations of the north; salt cod became one leg of the Atlantic trade. Canning, from the early nineteenth century, and refrigeration in the twentieth took over much of the work, yet ham, bacon and salt fish are still cured with salt, and sauerkraut is still fermented in its own brine.

Salt cod, beheaded, split and dried, keeps for years and must be soaked in the refrigerator for a day or more before cooking.

Key figures

Earliest known salt production
Poiana Slatinei, Lunca, Romania, about 6050 to 5500 BCE

Water activity of saturated brine
About 0.75 (pure water: 1.0)

Most microbes stop multiplying
Below a water activity of about 0.90

Bronze Age meat curing at Hallstatt
Timber curing vats of the 13th to 12th century BCE, mainly for pork

Sources

1. The earliest salt production in the world: an early Neolithic exploitation in Poiana Slatinei-Lunca, Romania (Weller and Dumitroaia, 2005) · Antiquity https://www.antiquity.ac.uk/projgall/weller306/
2. Bronze Age meat curing vats · Naturhistorisches Museum Wien https://www.nhm.at/hallstatt/en/trading_hub/meat_processing_industry/meat_curing_vats
3. Is there a common water-activity limit for the three domains of life? (Stevenson et al., ISME Journal, 2015) · PubMed Central https://pmc.ncbi.nlm.nih.gov/articles/PMC4438321/
4. Sauerkraut · National Center for Home Food Preservation, University of Georgia https://nchfp.uga.edu/how/ferment/recipes/sauerkraut/
5. Curing (food preservation) · Wikipedia https://en.wikipedia.org/wiki/Curing_(food_preservation)
6. Dried and salted cod · Wikipedia https://en.wikipedia.org/wiki/Dried_and_salted_cod
7. One-directional modelling to assess the mechanistic actions of power ultrasound on NaCl diffusion in pork (McDonnell et al., Ultrasonics Sonochemistry 40, 2018) · Elsevier https://doi.org/10.1016/j.ultsonch.2017.06.025
8. The physics behind ham production (Parnovsky and Varlamov, 2026) · arXiv https://arxiv.org/abs/2607.18173
9. Interactive comment on Rose et al.: water activity of aqueous NaCl after Archer's evaluation (Clegg, 2007) · Atmospheric Chemistry and Physics Discussions https://acp.copernicus.org/preprints/7/S4180/2007/acpd-7-S4180-2007.pdf
10. Water Activity of Foods (MF3674) · K-State Research and Extension https://bookstore.ksre.ksu.edu/download/water-activity-of-foods_MF3674
11. Hazard Analysis and Risk-Based Preventive Controls for Human Food, Appendix 3: Bacterial Pathogen Growth and Inactivation (Table 3-A) · US Food and Drug Administration https://www.fda.gov/media/99598/download

Fact-checked on 2026-10-12

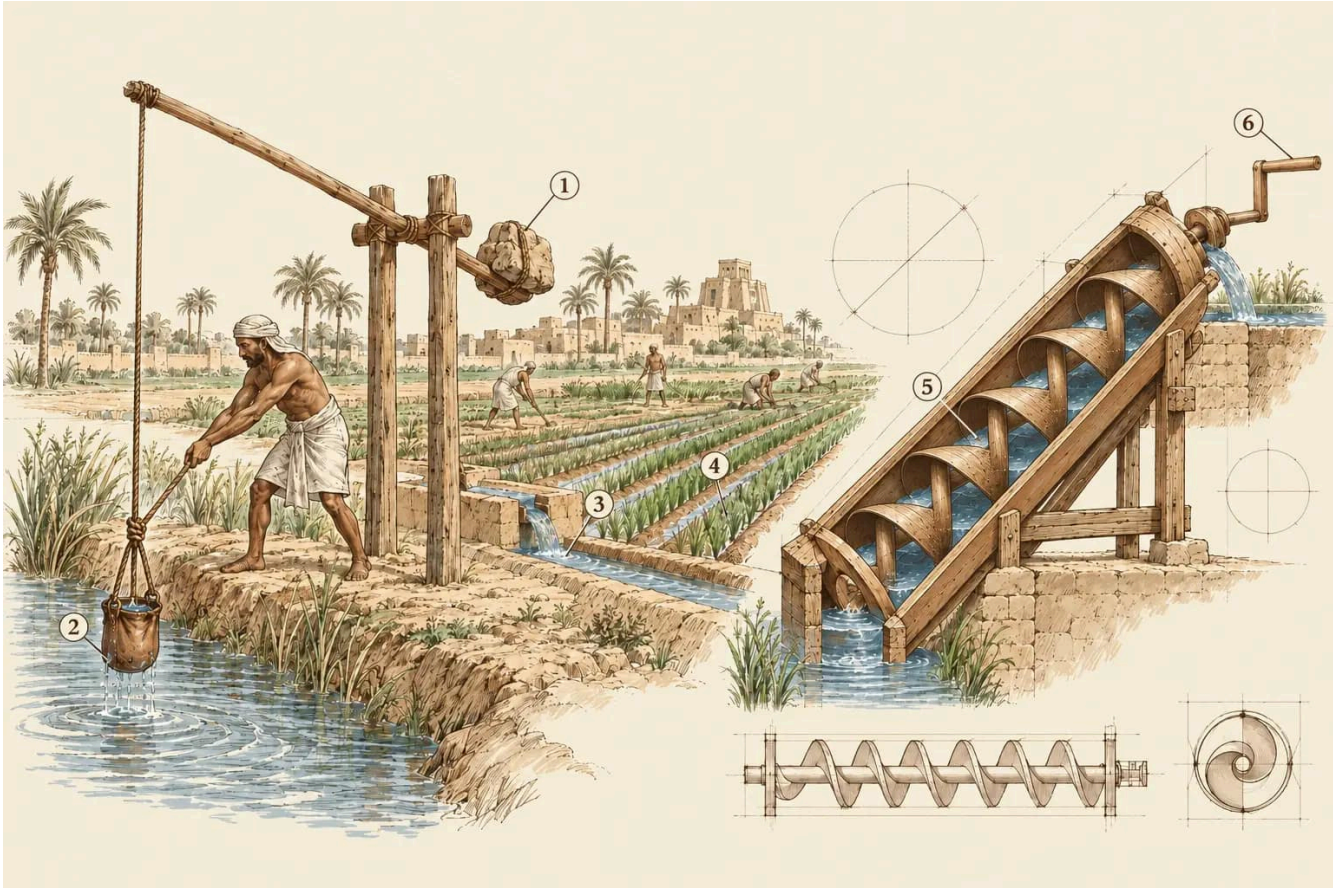
Irrigation

Leading water to the crops

c. 6,000 BCE · Prehistory · Settlement

Requires: Stone Tools (p. 5), Rope & Cordage (p. 13)

Leads to: Aqueduct (p. 141)



1 Counterweight of the shaduf 2 Leather bucket 3 Feeder canal 4 Furrows between the crop rows 5 Helical flight of the screw 6 Crank

Irrigation brings water to crops that rain alone cannot feed, either by letting it run down gently sloping canals or by lifting it from a river or a well. The earliest known canals were dug on the dry plains of Mesopotamia about eight thousand years ago, and the same plains showed early on that a field watered without drainage can slowly turn salty.

What it is

Irrigation gives crops water when they need it instead of waiting for rain. In southern Iraq or in Egypt's Nile valley there is no farming without it; elsewhere it raises yields and allows a second crop in the dry months.

If the source lies higher than the field, gravity does the work: a canal leaves the river upstream and follows a gentle slope down to the land. If the water lies lower, between high banks or at the bottom of a well, someone has to lift it. The plate shows a shaduf feeding a canal and its furrows, and an Archimedes screw.

How it works

On a bed that is too flat, water slows down, drops its silt and lets reeds grow; on one too steep, it scours the bed and breaks the banks. A small earth canal often falls little more than a metre per kilometre, and FAO recommends a furrow slope between 0.05 % and 0.5 %. Canals therefore follow the contours and lose height slowly.

In the field, water either floods a level basin closed by low earth banks and soaks in, or runs along furrows between the rows and seeps sideways into the ridges.

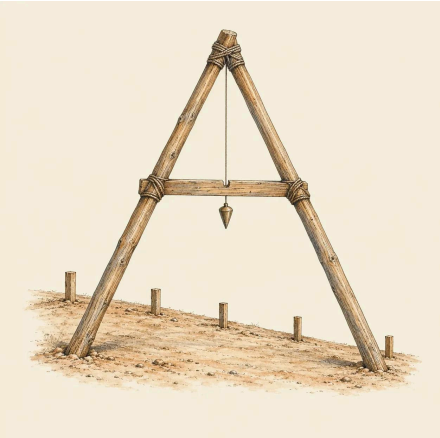
Lifting a cubic metre of water by one metre takes at least 9.8 kilojoules, and friction adds to that; a device only makes the work easier to supply. The shaduf is a lever with a bucket at the long end and a stone or a lump of dried mud at the short end. The farmer pulls the empty bucket down into the water, which raises the weight, and the weight brings the full bucket up. In field measurements in Chad, one person lifted between 39 and 130 litres a minute over heights of 1.8 to 6.2 m. For the same effort, a higher lift means less water.

The shaduf: once the farmer lets go, the counterweight lifts the full bucket.

The Archimedes screw is a helix turning inside a tube tilted at about 30°. Water stays at the low point of each turn, and as the screw rotates that low point moves up, carrying a pocket of water. It moves large volumes a few metres up; the steeper the screw, the smaller each pocket.

All irrigation water carries some dissolved salt. Plants and the sun take the water and leave the salt behind. Leaks from canals and fields also raise the water table, and salty groundwater then rises into the root zone. A field stays healthy only if extra water washes the salt down from time to time and drainage, natural or dug, carries it away. Otherwise salt builds up, sometimes as a white crust, and yields fall.

How to build it



The A-frame: when the plumb line hangs on the mark, both feet are at the same height.

Make an A-frame level. Lash two poles about 2.8 m long together at the top, with their feet 4 m apart, and fix a crossbar about 1 m above the ground. Hang a plumb line from the apex. Mark where it crosses the bar with the frame on two pegs, turn it round and mark again: halfway between is level.

Lay out the canal. Walk the frame from the intake, driving a stake at each foot. To set a fall, put a block under the downhill foot and move that foot until the line hangs on the level mark, then drive the stake: a 1 cm block on a 4 m frame gives 0.25 %. Dig along the stakes and tamp the spoil into a bank on the downhill side.

Cut the furrows. Lead them off the canal on the same gentle fall, 30 to 60 cm apart on sandy soil and 75 cm to 1.5 m on clay, each opened by a notch in the bank. Let water run until the soil at the far end is moist to root depth, then close the notch, and lead the furrow ends into a drain ditch so that surplus water leaves the field.

Build a shaduf. Set two posts firmly at the water's edge, with a crossbar on which a pole three to four metres long pivots a quarter of its length from one end. Hang a bucket from the long end and a stone or bag of earth from the short end, adjusted until a full bucket rises with a light push.

Or wind a small screw. Wind a flexible tube round a pole, each turn advancing about as far as the pole is thick. Mount the pole at about 30° on two bearings, low enough that the mouth of the tube dips under water for part of each turn, and fit a crank at the top. Turn it so the mouth scoops water as it goes in. If nothing comes up, try the other direction first, then lower the angle or tighten the turns.

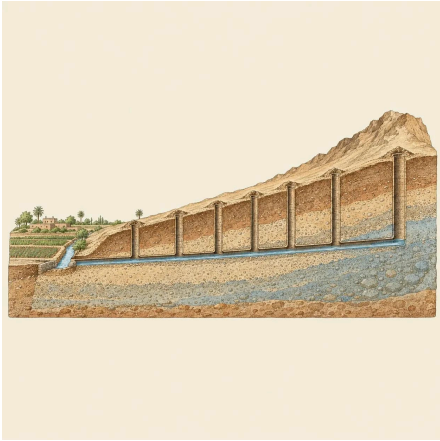
> **Safety.** People drown even in narrow canals with steep, slippery banks: never work alone at the water and keep children away. Keep channels shallow, no deeper than the knee, and never enter a deeper trench: its walls can collapse without warning. Keep spoil back from the edge. Keep clear of the swinging shaduf weight. Drain standing water within a few days, as it breeds mosquitoes. Where bilharzia occurs, its parasites live in fresh water, still or flowing, and enter through the skin: avoid any skin contact with canal water. Irrigation water is not drinking water.

History and evolution

At Choga Mami, in eastern Iraq near the Iranian border, excavators found channels of about 6000 BCE that they read as irrigation ditches; some put them nearer 5500 BCE. The cities of Sumer later lived on canals from the Tigris and Euphrates; texts from Lagash describe full networks by about 2400 BCE.

In Egypt, earth banks divided the floodplain into basins. During the flood, sluices let the water in; it stood about a month, then drained away before sowing. The shaduf, shown on a Mesopotamian seal of about 2200 BCE, reached Egypt in the second millennium BCE.

Greek writers credit Archimedes, in the third century BCE, with the water screw used in Egypt; the Assyriologist Stephanie Dalley reads an inscription of Sennacherib, around 700 BCE, as describing bronze screws at Nineveh, a reading still debated. Qanats, tunnels that carry groundwater for kilometres, are usually traced to Iran in the first millennium BCE, though they are hard to date; about 37,000 were still in use there in 2015.



A qanat taps groundwater under the hills and brings it to the surface through a tunnel.

In 1958 Thorkild Jacobsen and Robert Adams argued that rising salt pushed Sumerian farmers from wheat to hardier barley; Marvin Powell challenged that theory in 1985. Drip irrigation, developed in Israel by the engineer Simcha Blass and made by Netafim from 1965, now feeds water to the foot of each plant.

Key figures

Earliest known canal irrigation
Choga Mami, eastern Iraq, about 6000 BCE (some estimates 5500 BCE)

Archimedes screw angle
Usually about 30°; Vitruvius used a 3-4-5 triangle, about 37°

Share of farmland
About 18% of the world's arable land was irrigated in 2000 (FAO)

Shaduf output, one person
39–130 litres a minute, for lifts of 1.8–6.2 m (field measurements in Chad)

Furrow slope
0.05–0.5 %, that is 0.5 to 5 m of fall per kilometre (FAO)

Sources

1. Choga Mami · Wikipedia https://en.wikipedia.org/wiki/Choga_Mami
2. Dating Ancient Canal Systems Using Radiocarbon Dating and Archaeological Evidence at Tello/Girsu (Egberts et al., 2023) · Radiocarbon 65(4), Cambridge University Press https://www.cambridge.org/core/journals/radiocarbon/article/dating-ancient-canal-systems-using-radiocarbon-dating-and-archaeological-evidence-at-tellogirsu-southern-mesopotamia-iraq/DFCB7F569B744396C9E4BDA923A8EB07
3. Evolution of Water Lifting Devices (Pumps) over the Centuries Worldwide (Yannopoulos et al., 2015) · Water 7(9), MDPI https://www.pumpfundamentals.com/pumps%20historical.pdf
4. Shadoof · Wikipedia https://en.wikipedia.org/wiki/Shadoof
5. The Ten Books on Architecture, Book X (water screw, ch. 6) · Vitruvius, LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/10*.html
6. Archimedes' screw: optimal design · Chris Rorres, New York University https://math.nyu.edu/Archimedes/Screw/optimal/optimal.html
7. The mystery of the Hanging Garden of Babylon (Stephanie Dalley) · Oxford University Press https://blog.oup.com/2013/06/mystery-hanging-garden-babylon/
8. Ancient Egypt water engineering · University of Wisconsin–Madison, Ancient Engineering Technologies https://ancientengrtech.wisc.edu/ancient-egypt-water-engineering
9. Qanat · Wikipedia https://en.wikipedia.org/wiki/Qanat
10. Irrigation Water Management: Irrigation Methods, ch. 2 Basin irrigation · FAO http://www.fao.org/4/s8684e/s8684e03.htm
11. Irrigation Water Management: Irrigation Methods, ch. 3 Furrow irrigation · FAO http://www.fao.org/4/s8684e/s8684e04.htm
12. Canals, Annexes 2 and 3: How to construct a canal; How to determine the slope of a canal alignment · FAO http://www.fao.org/4/ai585e/ai585e07.pdf
13. Simple methods for aquaculture: contour levelling methods (A-frame level) · FAO https://www.fao.org/fishery/static/FAO_Training/FAO_Training/General/x6707e/x6707e06.htm
14. Irrigation Water Management: Introduction to Irrigation, ch. 7 Salinity · FAO https://www.fao.org/4/R4082E/r4082e08.htm
15. The Challenge of Salinization · Soil Science Society of America https://soils4teachers.org/files/s4t/know-soil-challenge-of-salinization.pdf
16. Salt and Silt in Ancient Mesopotamian Agriculture (Jacobsen and Adams, 1958) · Science 128, KeiBi catalogue, University of Tübingen https://keibi.uni-tuebingen.de/Record/KEI00116827
17. Salt, Seed, and Yields in Sumerian Agriculture. A Critique of the Theory of Progressive Salinization (Powell, 1985) · Zeitschrift für Assyriologie 75, KeiBi catalogue, University of Tübingen https://keibi.uni-tuebingen.de/Record/KEI00062118
18. Water factsheet · FAO https://www.fao.org/fileadmin/user_upload/faowater/docs/FAOWfactsheet.pdf
19. What Israeli drips did for the world · The Times of Israel https://www.timesofisrael.com/what-israeli-drips-did-for-the-world/
20. Schistosomiasis fact sheet · World Health Organization https://www.who.int/news-room/fact-sheets/detail/schistosomiasis
21. The Turn of the Screw: Optimal Design of an Archimedes Screw (Rorres, 2000) · Journal of Hydraulic Engineering 126(1), ASCE https://math.nyu.edu/Archimedes/Screw/optimal/screw.pdf
22. Water Lifting Devices (Fraenkel), 3.6.3 Archimedean screw and open screw pumps · FAO Irrigation and Drainage Paper 43 https://www.fao.org/4/ah810e/AH810E06.htm
23. Water Lifting Devices (Fraenkel), 4.2 Human power · FAO Irrigation and Drainage Paper 43 https://www.fao.org/4/ah810e/AH810E08.htm

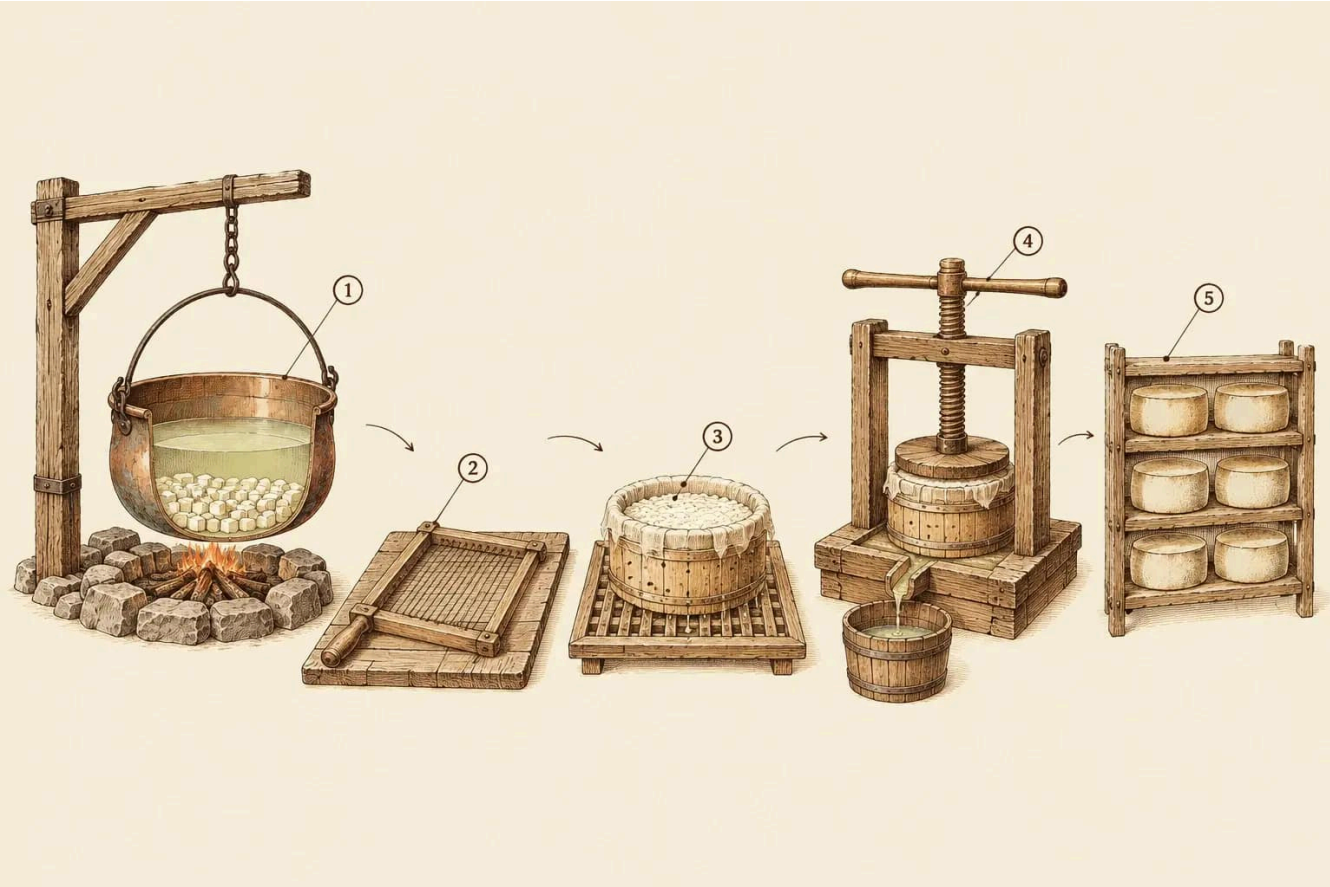
Fact-checked on 2026-10-14

Cheese

Milk that keeps for months

c. 5,500 BCE · Prehistory · Settlement

Requires: Pottery (p. 22)



1 Copper vat with cut curd in whey 2 Curd harp 3 Cloth-lined cheese mould 4 Screw press 5 Ripening shelves

Cheese is milk whose protein has been curdled, drained of its whey and often salted and ripened, so that it keeps far longer than fresh milk. Milk-fat residues in perforated Neolithic pots show that farmers in Europe were making it more than 7,000 years ago.

What it is

Cheese is a solid food made from milk by curdling its protein and draining off the watery part, the whey. Fresh cheeses are eaten within days; hard cheeses are pressed, salted and ripened for months or years. Either way, most of the water leaves, and with it much of the lactose, the milk sugar that many adults digest poorly.

The plate follows a farmhouse cheese of the eighteenth century through its stages: curd cut in a copper vat over the fire, the wire harp that cut it, a cloth-lined mould, a screw press and the shelves where the wheels ripen.

How it works

Milk is mostly water holding fat droplets, lactose and proteins. About four fifths of the protein in cow's milk is casein, which floats in tiny clusters called micelles. Each micelle carries a hairy outer layer of one casein, kappa-

casein, that keeps the clusters apart.

Rennet, traditionally taken from the stomach of a young calf, contains the enzyme chymosin. It cuts kappa-casein at one precise point and shaves off the hairy layer. Helped by the calcium in the milk, the bare micelles then stick together into a soft gel, the curd, which holds the fat inside it. Cheesemakers usually add rennet to milk at about 30 to 32 °C. Acid can also curdle milk, often helped by heat: paneer is made by adding lemon juice or citric acid to hot milk.

Cutting the curd: the smaller the cubes, the more whey runs out and the harder the cheese.

Once the gel is firm, the maker cuts it into cubes. Whey seeps out of every cut face. Stirring and gentle heating squeeze out more, and the size of the cubes decides how dry the cheese will be. The curd is then gathered in moulds and pressed, salted on the surface or in brine, and left to ripen. During ripening, bacteria and enzymes break proteins and fats into smaller molecules that give flavour and change the texture. Salt draws water out of the surface, slows unwanted microbes and helps form a rind.

How to build it

The simplest cheese to make at home is paneer, curdled by heat and acid and eaten fresh. You need 2 litres of pasteurised whole cow's milk, about 5 g of citric acid dissolved in 250 ml of water (or the strained juice of two lemons), a heavy pot, a thermometer, a colander, cheesecloth, a board and a weight of 2 to 3 kg.

Heat the milk. Bring the milk to 85 to 90 °C, stirring so it does not catch on the bottom, then take it off the heat and let it cool to about 70 °C. Curdling much hotter makes a hard, dry cheese; much cooler leaves it wet.

Curdle it. Pour in the acid little by little, stirring gently, until white curds separate and the whey turns clear and greenish-yellow. You may not need all of it. Leave the pot still for ten minutes.

Drain and press. Line the colander with cheesecloth, pour in the curds and let the whey run off. Fold the cloth over, set the board and the weight on top and press for 30 to 60 minutes, until the block holds together.

Chill and store. Cut the block into pieces and soak them in iced water for an hour or two to firm them. Keep the paneer in the refrigerator at 4 °C or below and eat it within three days. Two litres of cow's milk give about 350 g.

Pressed rennet cheeses that ripen for weeks need a measured starter, checks of acidity at each stage and a cellar kept at the right temperature and humidity. Learn them from a complete, tested recipe or a course before trying.

> **Safety.** Use pasteurised milk: raw milk can carry Listeria, E. coli and other dangerous bacteria, and soft raw-milk cheeses are a known source of listeriosis, a serious risk in pregnancy. Hot milk scalds and boils over easily, so keep children away from the pot. Clean every tool, chill the cheese as soon as it is made, and do not rely on smell or appearance to judge safety: throw away any cheese kept too long, too warm, or that smells or looks wrong.

History and evolution

Most adults in the first farming communities could not digest lactose, although children could. Draining off the whey removes most of the lactose from cheese, and in yogurt bacteria break down part of it. On the Dalmatian coast of Croatia, milk residues appear in pottery about 7,700 years ago, and residues of fermented dairy, soft cheese or yogurt, about 7,200 years ago.

A Neolithic pottery sieve of the kind that held milk fats in Kuyavia, Poland: probably a cheese strainer.

In Kuyavia, in central Poland, a team led by Mélanie Salque of the University of Bristol analysed 50 fragments from 34 perforated pots of the first farmers of central Europe, about 7,000 to 7,500 years old, and found abundant milk fats. No molecule is unique to cheese, but straining curd from whey is the obvious use for such sieves, and the 2012 study counts them as the oldest direct evidence of cheesemaking.

The oldest surviving cheese itself is about 3,600 years old, on mummies of the Xiaohe cemetery in Xinjiang. The Roman writer Columella, around 65 CE, described rennet curdling, pressing, salting and ageing much as they are practised now.

The round eyes of some Alpine cheeses are bubbles of carbon dioxide made by bacteria during ripening.

Medieval monasteries kept and refined many cheeses, and records of Roquefort at the abbey of Conques go back to 1070. In the United States cheese stayed a farm product until 1851, when Jesse Williams in Oneida County, New York, began making it from the pooled milk of neighbouring farms, the first cheese factory in the United States. Commercial rennet extract appeared in the 1860s and 1870s, and pure bacterial cultures followed, which made production far more consistent. Most rennet used today is chymosin made by microbes.

Key figures

Earliest direct evidence
Milk fats in pottery sieves, Kuyavia, Poland, about 7,000 to 7,500 years ago

Share of milk protein that curdles
Caseins, about 80% of the protein in cow's milk

Usual renneting temperature
About 30 to 32 °C

First cheese factory in the United States
Jesse Williams, Oneida County, New York, 1851

Sources

1. Say cheese! Central European farmers did, 7,500 years ago · NBC News https://www.nbcnews.com/id/wbna50177947
2. Evidence of 7,200-year-old cheese making found on the Dalmatian Coast · Penn State University https://www.psu.edu/news/research/story/evidence-7200-year-old-cheese-making-found-dalmatian-coast
3. Extent of κ-casein hydrolysis during renneting of bovine milk (Kayihura, Food Science & Nutrition, 2024) · PubMed Central https://pmc.ncbi.nlm.nih.gov/articles/PMC10916671/
4. Technology of paneer · INFLIBNET e-PG Pathshala (Technology of Milk and Milk Products) https://ebooks.inflibnet.ac.in/ftp04/chapter/technology-of-paneer/
5. History of cheese · International Dairy Foods Association https://www.idfa.org/news-views/media-kits/cheese/history-of-cheese
6. Cheese · Wikipedia https://en.wikipedia.org/wiki/Cheese

Fact-checked on 2026-10-12

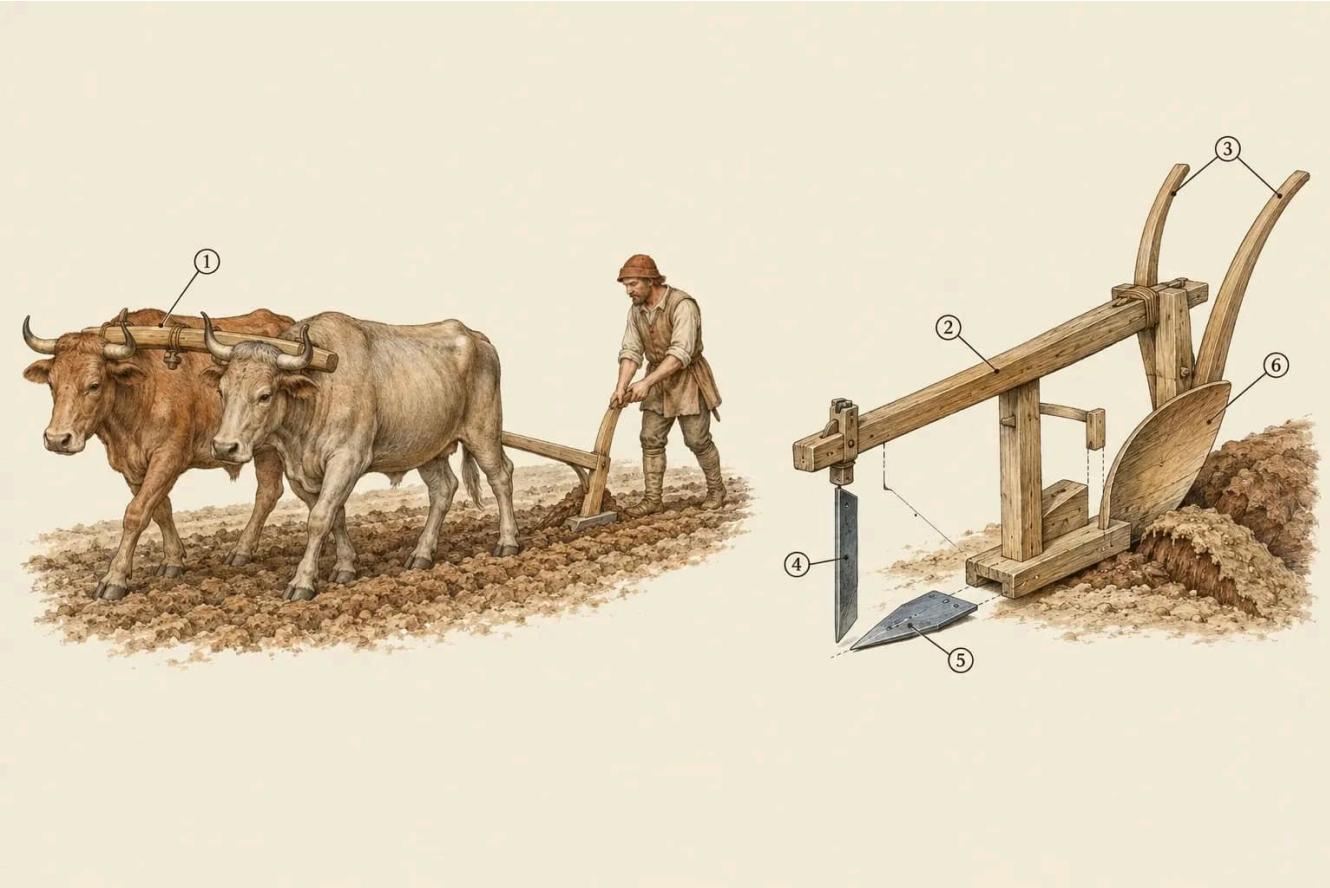
Plough

Opening the soil for seed

c. 5,000 BCE · Prehistory · Settlement

Requires: Stone Tools (p. 5), Rope & Cordage (p. 13)

Leads to: Crop Rotation (p. 106)



1 Yoke 2 Beam 3 Handles (stilts) 4 Coulter 5 Share 6 Mouldboard

A plough is pulled through the ground to cut and loosen the soil before sowing. The first ards only scratched a furrow; the mouldboard plough, which turns the soil over, opened up the heavy, wet lands of northern Europe.

What it is

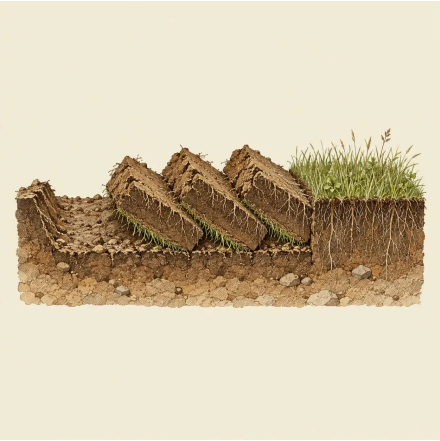
A plough is a blade dragged through the earth by people, animals or an engine. It breaks up the top layer of soil, buries weeds and the remains of the last crop, and loosens the ground so that a harrow can then break the clods into a seedbed. With a plough and a pair of oxen, one family could farm far more land than with a hoe or a digging stick.

The ard, or scratch plough, has a pointed share that drags through the soil and opens a shallow groove without turning it over. The mouldboard plough cuts a slice of soil and turns it upside down. The plate shows both: an ox team pulling an ard on the left, and the parts of a mouldboard plough on the right.

An ard made entirely of wood.

How it works

An ard is a wedge. The share runs at a shallow angle, a few centimetres below the surface, and pushes the soil up and to both sides. It loosens the soil without inverting it, which suits light, dry ground where moisture must be kept. Farmers often ploughed a field twice, the second time at right angles to the first, so ard fields tended to be square.



Turned furrow slices lie against one another, grass side down.

In a mouldboard plough three parts work in turn. The coulter, a vertical knife hanging from the beam, slices the ground ahead. The share, a flat blade near the bottom, cuts the slice free underneath. The mouldboard, a curved board behind the share, lifts the slice, twists it and lays it upside down against the previous one. Weeds and stubble end up buried, and the soil underneath is exposed to air and frost.

A fixed mouldboard always throws soil to the same side. Medieval ploughmen worked each long strip round its centre line, so every pass turned soil toward the middle and the strip slowly rose into a ridge, which helped drain wet clay.

A light ard needs one or two animals. Medieval heavy ploughs on clay could need teams of up to eight oxen. Today a tractor pulls several bodies side by side, each turning a slice 20 to 30 centimetres deep.

How to build

A simple ard can be made from wood alone, with an axe, a knife and an auger. The steps below are an outline, without measured drawings.

Find the timber. Look for a hardwood branch, ash or oak for example, with a natural bend where a thick limb meets a smaller one. The long arm becomes the beam; the short one, cut to about 40 centimetres, becomes the share and sole. A crook grown in one piece is far stronger than a joint.

Shape the share. Trim the short arm to a blunt point, flat on the underside. It should meet the ground at about 30 degrees when the beam is raised to the height of the yoke. Bare wood wears quickly, so carve a spare tip; a tip of iron lasts far longer.

Add the handle. Bore a hole through the beam just above the share and fit an upright handle, wedged tight, so the ploughman can steer and press down.

Make the yoke. A neck yoke is a beam shaped to sit in front of the oxen's withers, with wooden bows or straps around each neck. Tie the far end of the plough beam to the middle of the yoke with rope or a wooden peg.

Plough. Use only oxen already trained to the yoke, with an experienced driver at their heads. Start with short runs on moist, not wet, soil, and lean on the handle to keep the share in the ground.

> **Safety.** Oxen are strong and can panic. Never stand between an animal and the plough, keep a quick-release knot on the hitch, and give the team rest and water. Stop at once if a yoke rubs: a badly fitted yoke causes sores and injuries. Keep your feet clear of the share.

History and evolution

The ard came after cattle had been tamed to pull, though nobody knows exactly when. The oldest plough marks found so far, scratches sealed under river silt at Sion in Switzerland, date from 5100 to 4700 BCE; younger ones in northern Italy, Denmark and at Prague-Bubeneč date from about 4300 to 3500 BCE. No plough marks survive from the Near East, where it may be older still. Seal impressions and texts from Mesopotamia show ploughs in the third millennium BCE, some with a funnel that dropped seed straight into the furrow. A ploughed field at Kalibangan, in north-west India, dates from about 2800 BCE.

Around 1000 BCE ploughs in the Near East gained a detachable, replaceable share, and Chinese farmers used iron shares by about 500 BCE. Under the Han dynasty, in the first and second centuries CE, Chinese workshops cast curved iron mouldboards that turned the soil cleanly with a small team.

In Europe, finds from late Roman Britain suggest ploughs that could turn the soil, although their exact form is debated. The heavy plough with coulter and mouldboard spread across the clay plains of the north from the seventh century, often on wheels and pulled by large ox teams. With it, more land came under cultivation and the long strip fields of the medieval village took shape.

In the eighteenth century English makers built lighter ploughs. The Rotherham plough, patented in England in 1730 by Joseph Foljambe, had a triangular frame and iron on its mouldboard, and two horses could pull it. In the American Midwest, sticky prairie soil clogged cast iron. John Lane in 1833 and John Deere in 1837 made ploughs with smooth steel blades that cleaned themselves as they cut.

Steam engines hauled ploughs on cables from the 1850s, and tractors took over in the twentieth century. Bare, turned soil blows away in drought and washes off in rain, as the American Dust Bowl of the 1930s showed. Many farmers now plough less or not at all and sow directly into the stubble.

A self-scouring steel plough: sticky prairie soil slides off the polished metal.

Key figures

Oldest plough marks found
Sion, Switzerland, 5100–4700 BCE

Heavy iron mouldboard plough
Han China, 1st–2nd century CE

Working depth of a modern mouldboard plough
20–30 cm

Self-scouring steel plough
Illinois, 1833–1837

Sources

1. Plough · Wikipedia https://en.wikipedia.org/wiki/Plough
2. Ard (plough) · Wikipedia https://en.wikipedia.org/wiki/Ard_(plough)
3. Europe's oldest plow marks discovered at Anciens Arsenaux site · Archaeology Magazine (archaeologymag.com) https://archaeologymag.com/2024/03/europes-oldest-plow-marks-discovered-at-anciens-arsenaux-site/
4. When was the plough invented? · Joe Roe (archaeologist) https://joeroe.io/2025/08/24/ploughing.html
5. Tillage (chapter 10), D. Franzen · North Dakota State University Extension https://www.ndsu.edu/agriculture/sites/default/files/ebook/Franzen/PDFs/Franzen_Ch10.pdf
6. Development of the Plough: the Rotherham Plough to Now · Farmland Museum and Denny Abbey https://dennyfarmlandmuseum.org.uk/?p=1138
7. Oldest evidence of ploughing in the Czech lands (Bubeneč) · Stone Pages Archaeo News https://www.stonepages.com/news/archives/004695.html
8. Estimating Tillage Draft (TechGuide 2G-210) · Tillers International https://tillersinternational.org/wp-content/uploads/2025/01/EstimatingTillageDraftTechGuide.pdf
9. Matching tillage implements to draught animal potential (F. Inns) · FAO https://www.fao.org/4/w0613t/w0613T0g.htm

Fact-checked on 2026-10-11

Charcoal

Wood cooked slowly under earth

c. 4,500 BCE · Prehistory · Settlement

Requires: Control of Fire (p. 9), Stone Tools (p. 5)

Leads to: Bronze (p. 120), Gunpowder (p. 177), Iron Smelting (p. 133), Steel (p. 137)

1 Central chimney between stakes 2 Wood already turned to charcoal 3 Layer of leaves, straw and turf
4 Cover of earth and charcoal dust 5 Air hole at the foot 6 Wood not yet charred

Charcoal is wood heated with so little air that it chars instead of burning, leaving a light, black fuel made mostly of carbon. Used by metalworkers since at least the fifth millennium BCE, and later made in earth-covered clamps and pits, it gave smiths the heat and the reducing gas they needed to win copper and iron from their ores.

What it is

Charcoal is what remains of wood heated with too little air to burn. Water and most of the volatile matter leave as smoke, and a black, brittle, light solid stays behind, made largely of carbon.

Weight for weight, it holds roughly twice the heat of air-dried wood. It burns with almost no flame or smoke, and with a bellows it reaches temperatures a wood fire struggles to hold. In a furnace it also forms carbon monoxide, the gas that takes oxygen out of metal ores. For some six thousand years it was the fuel of copper, bronze and iron.

The plate shows the earth-covered clamp that European colliers built in the woods until the twentieth century: a dome of wood stacked around a central chimney, wrapped in leaves and earth, and left to smoulder for days.

The same wood before and after: charcoal shrinks and cracks but keeps the grain of the tree.

How it works

Heated wood first dries at 100 °C or a little below, then warms to about 280 °C. Both steps take energy, supplied by burning a small part of the charge. Above about 280 °C the wood breaks down on its own and gives off heat. Water, acids, tars and flammable gases escape, and charcoal is left.

A pit kiln works the same way: the wood chars in a hole in the ground under leaves and earth.

Without outside heat the reaction peaks at about 400 °C, and the charcoal keeps around 30% of tarry matter. Taken to 500 °C, it reaches about 86% fixed carbon, but heat costs yield: oven-dry wood gives about 42% of its weight as charcoal at 300 °C and 33% at 500 °C, not counting the wood burned for heat.

The earth cover acts as the furnace wall. It admits only the air the collier lets in through holes at the foot. A little wood burns, uses up that oxygen, and its heat cooks the rest. In a clamp the fire is lit in the central chimney and spreads slowly outward through the pile to the foot. The smoke tells how far it has gone: dense and white while the wood dries, bluish later, almost clear when a zone is done. As the wood shrinks the mound sinks and the cover cracks, and every crack must be closed at once, or the charcoal burns to ash.

How to build

This is the outline of a small clamp. You need a few cubic metres of seasoned hardwood such as oak, beech or hazel, split so that no piece is thicker than about 20 cm, plus straw or leaves, sandy soil or loam, a shovel, a rake and about 100 litres of water.

Prepare the hearth. Clear a level, well-drained circle about 6 m across down to bare earth, away from overhanging branches and buildings.

Stack around the chimney. Drive three or four stakes in the centre to frame a shaft. Lay a grid of small logs on the ground so that gas can pass under the pile. Stand the billets upright against the shaft, leaning slightly inward and packed tight, and fill the gaps with small wood. A village mound is typically about 4 m across and 1 to 1.5 m high.

Cover it. Lay leaves, straw or turf over the wood, then 10 to 20 cm of earth, mixed with charcoal dust if you have some. Avoid sticky clay, which cracks as it dries. Leave six to ten holes around the foot.

Light and tend. Drop a shovel of embers down the chimney and feed them with dry kindling until the core of the pile is alight. When thick white smoke rises steadily, partly close the top. From then on someone watches the mound day and night, sealing cracks with damp earth, closing any vent that glows red and opening new ones on the side that lags. A small clamp can finish in a day or two; traditional stacks of medium size took twelve to fourteen days.

Seal, cool and open. When the smoke turns thin and blue, close every hole and add earth. Wait until the mound is cold right through, which takes two or three days for a small one, then open it a section at a time, rake the charcoal out and smother any smouldering piece with sand or a little water. Hot charcoal can catch fire again in the open air, so keep watching.

> **Safety.** A clamp can start a forest fire: check the local rules on open fires, keep the hearth bare, and have water, sand and a shovel ready. The smoke is rich in carbon monoxide, which has no smell and kills. Stay upwind, never lean over a vent or the chimney, and never burn, cool or store warm charcoal in a closed space. Never climb onto the mound: as the wood shrinks, the cover can give way over a glowing hollow and cause deep burns. Wear leather gloves and boots and keep children away.

History and evolution

Charcoal is as old as the use of fire: every ancient hearth leaves some, and archaeologists date hearths by it. At the Chauvet cave in France, painters drew animals with pine charcoal about 37,000 to 34,000 years ago.

Metal created the first large demand for it, although nobody knows when people first made it on purpose. In the fifth millennium BCE, smelters in the southern Levant and on the Iranian plateau heated copper ore with charcoal in crucibles and small furnaces. At Horvat Beter, near Beersheba, the ore came from Wadi Faynan, over 100 km away. An estimate published in 1982, drawn from later records and experiments, puts copper at 20 to 40 kg of charcoal per kilogram of metal. At 100 kg of charcoal for a 5 kg smelt, and seven parts of wood for one of charcoal, that is some 700 kg of wood. In China the oldest charcoal kilns found so far, at Xiwubi in Shanxi, lay beside copper-smelting remains of the Erlitou period, around 1900 to 1600 BCE.

Iron, by the same estimate, needed no more than 10 kg of charcoal per kilogram, forging included, but it was made in far larger amounts, and charcoal burning became a woodland trade. In England's Weald and in the Carranza valley of the Basque Country, colliers supplied ironworks and forges for centuries, working from spring to autumn and living with their families in huts beside the mounds.

Colliers lived beside their clamps in huts of poles and turf, so the burn was never left alone.

By the eighteenth century an English furnace needed about eight tonnes of wood, turned into two tonnes of charcoal, for each tonne of pig iron. In 1709 Abraham Darby smelted iron with coke made from coal at Coalbrookdale, and coke slowly took over. Charcoal survived elsewhere: in 2011 it still made about 30% of Brazil's pig iron, against less than 1% worldwide, from eucalyptus plantations but also from native forest. It also remains the barbecue fuel, the artist's willow stick and, once activated, the carbon in filters.

Key figures

Self-sustaining charring

From about 280 °C; good charcoal is finished near 500 °C

Carbon content

About 68% fixed carbon when charred at 300 °C, about 86% at 500 °C

Oldest charcoal kilns found in China

Xiwubi, Shanxi, c. 1900–1600 BCE, beside copper-smelting remains

Yield of an earth mound

1 t of charcoal from 4 t of air-dry wood with good practice, 1 from 6 more often

Fuel for copper (estimate)

About 20–40 kg of charcoal per kilogram of copper, from later records and experiments

Sources

1. Simple technologies for charcoal making, chapter 4: Carbonisation processes (FAO Forestry Paper 41) · Food and Agriculture Organization of the United Nations https://www.fao.org/4/x5328e/x5328e05.htm
2. Simple technologies for charcoal making, chapter 6: Making charcoal in earth mounds (FAO Forestry Paper 41) · Food and Agriculture Organization of the United Nations https://www.fao.org/4/X5328E/x5328e07.htm
3. Simple technologies for charcoal making, chapter 5: Earth pits for charcoal making (FAO Forestry Paper 41) · Food and Agriculture Organization of the United Nations https://www.fao.org/4/x5328e/x5328e06.htm
4. Fuel for the Metal Worker (Lee Horne, Expedition 25.1, 1982) · Penn Museum https://www.penn.museum/sites/expedition/fuel-for-the-metal-worker/
5. Charcoal Burning: Keeping an Ancient Craft Alive · Weald & Downland Living Museum https://www.wealddown.co.uk/museum-news/charcoal-burning/
6. Charcoal burning in the valley of Carranza (Bizkaia) · Labayru Fundazioa https://labayru.eus/en/basque-ethnography-at-a-glance/charcoal-burning-in-the-valley-of-carranza-bizkaia
7. Charcoal Burning (Wyre Forest) · Revolutionary Players, History West Midlands https://revolutionaryplayers.org.uk/?p=2368
8. The Chauvet cave: 30 years since its discovery. Contribution from radiocarbon dating · Laboratoire des Sciences du Climat et de l'Environnement (LSCE) https://www.lsce.ipsl.fr/en/the-chauvet-cave-30-years-since-its-discovery-contribution-from-radiocarbon-dating/
9. Archaeologists Unearth 6,500-Year-Old Copper-Smelting Workshop in Israel · Sci.News https://www.sci.news/archaeology/copper-smelting-workshop-horvat-beter-israel-08923.html
10. Shanxi discovers earliest charcoal kiln relics in China · China Daily https://regional.chinadaily.com.cn/shanxi/2021-08/23/c_654303.htm
11. Invention of Coke Smelting · EBSCO Research Starters https://www.ebsco.com/research-starters/history/invention-coke-smelting
12. Sustainable charcoal (Pesquisa FAPESP 189, 2011) · Pesquisa FAPESP https://revistapesquisa.fapesp.br/en/carvao-vegetal-sustentavel/

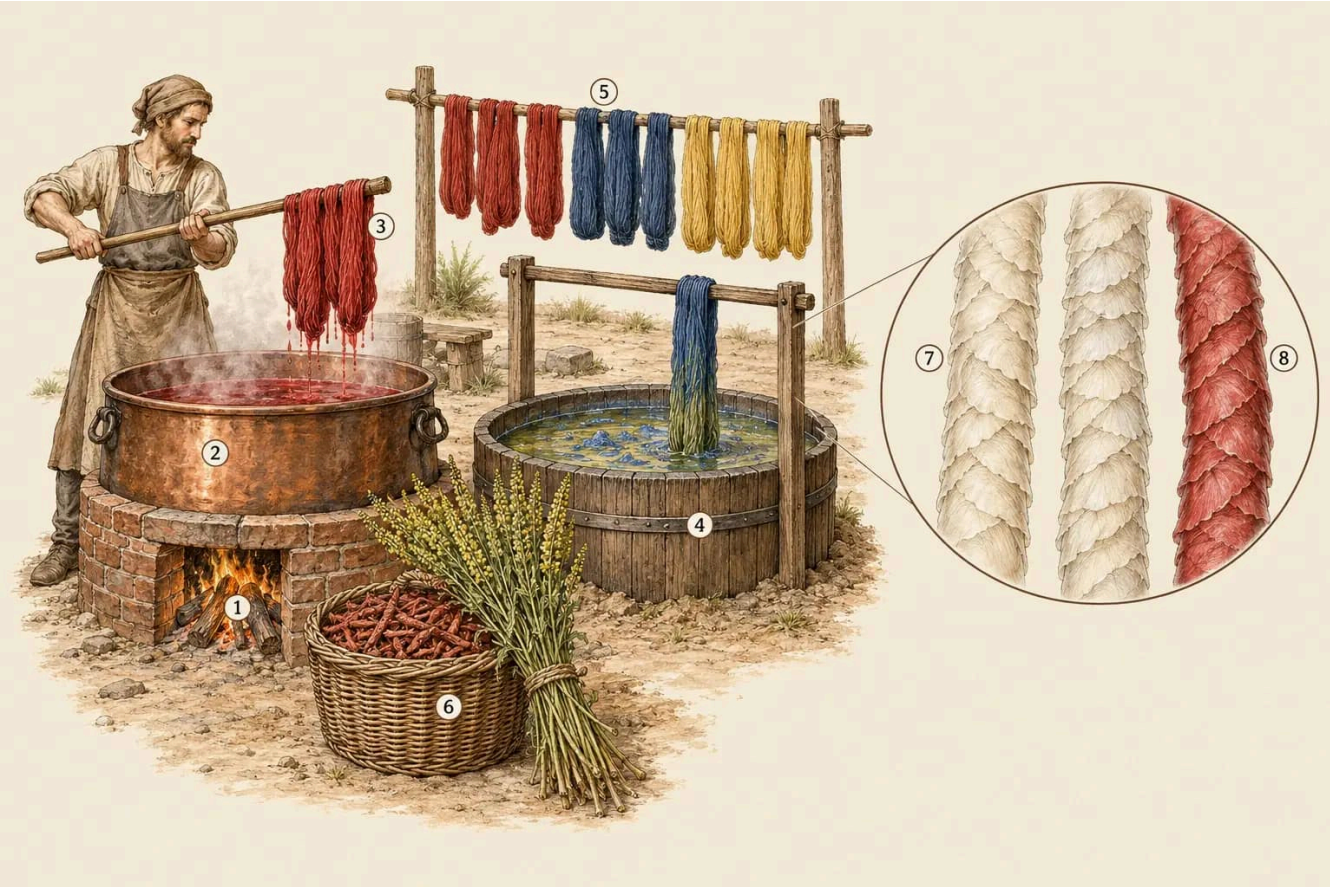
Fact-checked on 2026-10-13

Dyeing

Colour fixed in the fibre

c. 4,200 BCE · Prehistory · Settlement

Requires: Rope & Cordage (p. 13), Pottery (p. 22), Control of Fire (p. 9)



1 Fire under the kettle 2 Copper kettle with the madder bath 3 Skeins lifted on a stick 4 Indigo vat
5 Drying pole with red, blue and yellow skeins 6 Madder roots and weld 7 Raw wool fibre 8 Fibre mordanted and dyed red

Dyeing makes colour part of a fibre: the dye enters the yarn or cloth and stays through washing. Most plant dyes, such as madder and weld, give stronger and faster colours with a mordant, usually alum, while indigo is made soluble in a vat and turns blue again in the air.

What it is

Paint sits on the surface of a cloth and can rub off; a dye enters the fibre dissolved in water and stays through washing. Most dyes came from plants, a few from insects and sea snails.

On bare wool, madder root, the classic red, and weld, the classic yellow, give weaker colours that fade and wash out more easily. Dyers fixed them with a mordant, a metal salt put on the fibre first, to which the dye binds; for most of history it was alum. Indigo, the blue, does not dissolve in water at all and must be changed chemically in a vat before it can enter the yarn.

The plate shows a late medieval dyer's yard: a madder bath in a copper kettle (2) over a fire (1), skeins lifted on a stick (3), the indigo vat (4), yarn drying on a pole (5) and dyestuffs (6). Magnified in the circle, a raw wool fibre (7)

sits beside one mordanted with alum, still pale, and one mordanted and dyed (8).

How it works

Madder's red comes from compounds in its roots, mainly alizarin and purpurin. Alone they give wool a weaker, duller orange that fades more readily. Simmered first in alum, a sulphate of aluminium and potassium, the wool takes up aluminium; in the dye bath the madder molecules bind to it and form a coloured compound that no longer dissolves, held inside the fibre. The mordant also sets the shade: madder gives red with alum and purple-browns with iron, weld bright yellow with alum and olive with iron.

Indigo forms from compounds in the leaves of tropical Indigofera plants and, in Europe, of woad. In an alkaline vat with no oxygen, the insoluble blue molecule gains hydrogen and becomes leucoindigo, a soluble yellow-green form that soaks into the fibre. Out of the vat, oxygen in the air turns it back into blue indigo, now trapped in the fibre. Each dip adds a layer; dark blues take many.

Before industrial chemicals, bacteria did the reducing. Woad or indigo was kept warm in water with an alkali, wood-ash lye or slaked lime, and bran to feed them; as they fermented, they used up the oxygen and turned the indigo into leucoindigo. Greens came from blue dyed over with yellow.

Out of the vat the yarn is yellow-green; the air turns it blue.

How to build

Madder, woad and weld: the red, the blue and the yellow of European dyers.

This outlines the traditional method for wool, not a tested recipe. You need wool yarn, alum, dried madder and weld, and stainless-steel or sound enamel pots, sticks and a thermometer kept only for dyeing.

Prepare the fibre. Wind the yarn into loose skeins tied in several places so the dye reaches every strand. Wash out the grease in warm water with mild soap. Always enter fibre wet, and change temperature slowly: heat shocks and rubbing felt wool.

Mordant. Maiwa, a Canadian supplier of natural dyes, gives alum at 15 per cent of the dry weight of wool. Dissolve it in hot water, add the wool, bring it slowly to about 90 °C, just below a simmer, and hold it there about an hour. Let it cool and rinse.

Dye red or yellow. Soak chopped madder overnight, then heat it gently with the mordanted wool for an hour or more, turning slowly. For European madder, Maiwa advises staying below about 72 °C: hotter baths dull the red towards brown. Weld is steeped overnight, heated and strained; the mordanted wool then spends about an hour in the liquid, also kept below about 71 °C, since more heat dulls the yellow. Cooling in the bath deepens the shade.

Dye blue. A traditional woad or indigo vat, set with alkali and bran, was kept warm for days until the yellow-green liquid showed a coppery skin and blue froth. The yarn goes in wet and slowly, without splashing, since air spoils the vat; after a dip that the method sets, often 20 minutes to an hour for wool, it is lifted, squeezed, left to turn blue and dipped again. Modern vats use other reducing agents, and wool needs a less alkaline bath than cotton (Maiwa gives pH 9–10 against 11–12): follow a tested method written for wool and check the pH.

Rinse and wash. After madder or weld, let the yarn cool in the bath, rinse it gently until the water runs clear and dry it in the shade; wash it with mild soap only later. After indigo, let the blue develop fully in the air, rinse in plain water, then soak the yarn in diluted vinegar to neutralise the alkali left in the wool. Wash it last, and check that no blue rubs off on a white cloth.

> **Safety.** Hot baths scald: use a stable fire or stove and keep children and animals away. Alum irritates and must not be swallowed; iron salts are harmful in strong solution. Slaked lime and lye burn skin and eyes, and lye attacks aluminium pots; reducing agents can release toxic fumes, above all with acids. Wear goggles and gloves, and store these chemicals dry and labelled. Fermenting vats give off foul gases, so work outdoors or with good ventilation. Never use cooking pots or utensils, and never return dye tools to the kitchen. Chrome and tin mordants, once common, are toxic: do not use them. Spent baths are not harmless: mordant and iron baths and vat sludge hold metal salts or alkali. Never pour them into streams, wells or storm drains; ask the local waste service how to dispose of them.

History and evolution

Layers over 30,000 years old in Dzudzuana Cave, Georgia, held coloured fibres that the excavators read as flax dyed with local plants; the dyeing is an interpretation, and the flax identification has been disputed.

The oldest known indigo, identified by chemical analysis, colours cotton from Huaca Prieta, Peru, about 6,200–6,000 years old. The oldest confirmed madder colours an Egyptian leather quiver of about 2124–1981 BCE.

Sea snails gave the purple linked with Tyre: shell heaps show production on Crete early in the second millennium BCE and at Ugarit, in Syria, in the 15th–14th centuries BCE. Kermes, a scale insect, gave crimson; American cochineal, which reached Europe in the 16th century, gradually displaced it.

Each snail gave only a few drops of dye; commercial dyeing needed many thousands.

Medieval dyers formed guilds that guarded recipes and policed quality; London's, recorded in 1188, gained in 1471 a charter to search workshops and fine bad dyeing.

In 1856 William Henry Perkin, an 18-year-old London student trying to make quinine, obtained mauveine from coal-tar chemicals, the first synthetic dye to succeed commercially. In 1868 Carl Graebe and Carl Liebermann synthesised alizarin, and madder growing soon dwindled; Adolf von Baeyer published a synthesis of indigo in 1880, and BASF put it on the market in 1897.

Key figures

Oldest known indigo dye
On cotton from Huaca Prieta, Peru, about 6,200–6,000 years old

Older coloured fibres
Fibres from Dzudzuana Cave, Georgia, over 30,000 years old; flax disputed, dyeing inferred

Madder in Egypt
Identified on a leather quiver of about 2124–1981 BCE

London dyers' guild
First recorded in 1188; royal charter in 1471

First commercial synthetic dye
Mauveine, made by William Henry Perkin, aged 18, in 1856

Sources

1. 30,000-year-old wild flax fibers: testimony for fabricating prehistoric linen (Science, 2009) · Kvavadze, Bar-Yosef et al., Harvard DASH https://dash.harvard.edu/handle/1/4270521
2. Early pre-Hispanic use of indigo blue in Peru (Science Advances, 2016) · Splitstoser, Dillehay, Wouters and Claro https://pmc.ncbi.nlm.nih.gov/articles/PMC5023320/
3. The matter of madder in the ancient world · J. Paul Getty Museum https://www.getty.edu/publications/mummyportraits/part-one/3/
4. The Minoan origin of Tyrian purple (Biblical Archaeologist, 1994) · Robert R. Stieglitz, republished by Keftiu https://www.keftiu.com/magazine/the-minoan-origin-of-tyrian-purple/
5. The Dyers' Company and dyeing · The Worshipful Company of Dyers, London https://www.dyerscompany.co.uk/?p=4304
6. Graebe, Carl · Neue Deutsche Biographie https://www.deutsche-biographie.de/118877364.html
7. William Henry Perkin · Science History Institute https://www.sciencehistory.org/historical-profile/william-henry-perkin
8. História da BASF, 1865–1901 · BASF https://www.basf.com/br/pt/who-we-are/organization/history/1865-1901
9. Response to comment on "30,000-year-old wild flax fibers" (Science, 2010) · Kvavadze et al., Hebrew University of Jerusalem https://cris.huji.ac.il/en/publications/response-to-comment-on-30000-year-old-wild-flax-fibers/
10. Natural dye instructions: scouring, mordanting and dyeing · Maiwa https://naturaldyes.ca/instructions
11. Madder: dyeing instructions · Maiwa https://naturaldyes.ca/madder
12. Weld: dyeing instructions · Maiwa https://naturaldyes.ca/weld
13. Indigo: vat instructions · Maiwa https://naturaldyes.ca/indigo

Fact-checked on 2026-10-13

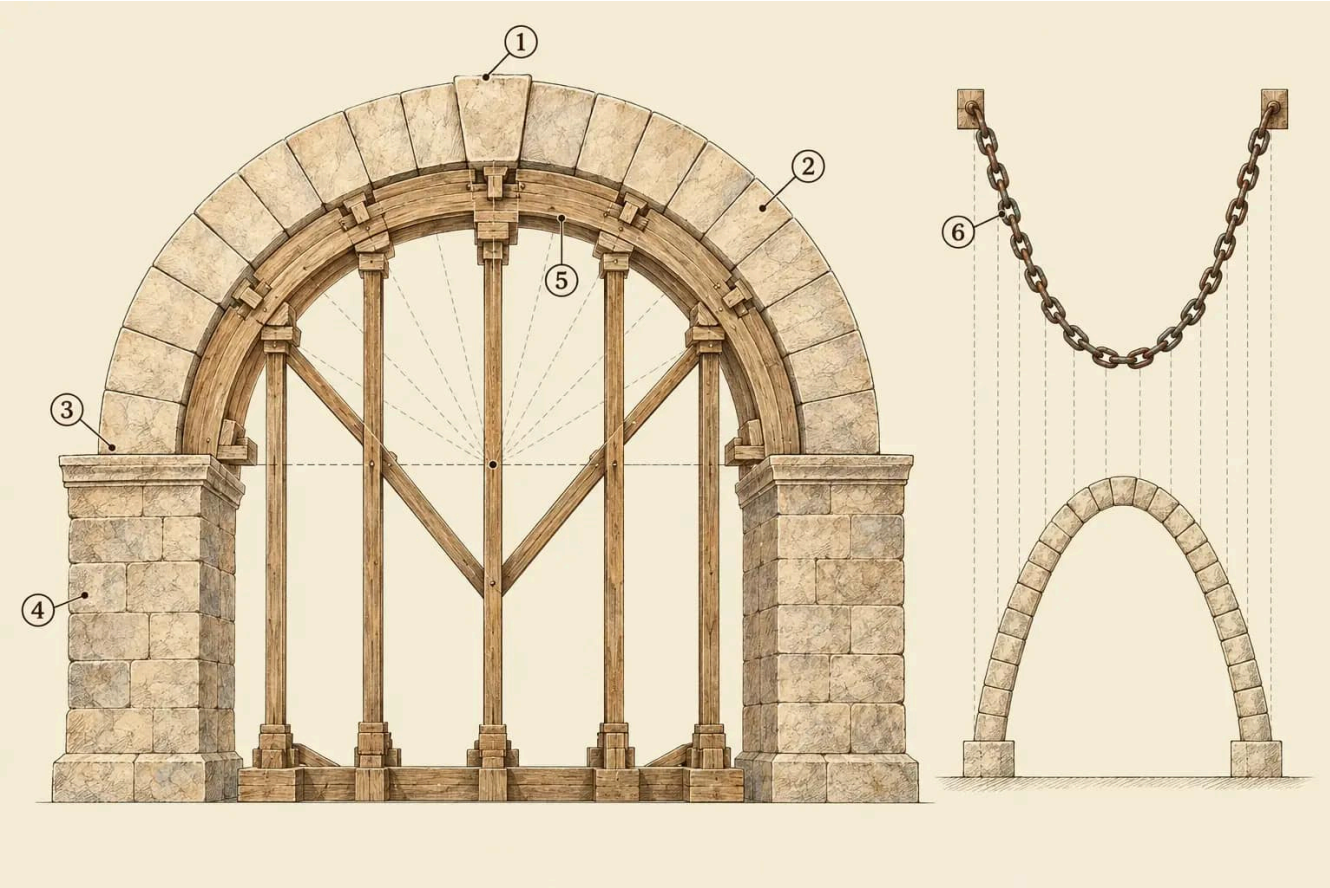
Arch and Vault

Stones that hold each other up

c. 3,500 BCE · Prehistory · Settlement

Requires: Bricks (p. 39), Stone Tools (p. 5)

Leads to: Aqueduct (p. 141)



1 Keystone 2 Voussoir 3 Springer 4 Abutment (pier) 5 Timber centering 6 Hanging chain (Hooke's model)

An arch spans an opening with wedge-shaped blocks that press on one another, so the whole curve works in compression and pushes outward on its supports. Drawn out in depth it becomes a vault, turned about its axis a dome: the forms that roofed tombs, bridges, aqueducts and cathedrals for over five thousand years.

What it is

An arch carries the load above an opening on a curve of wedge-shaped blocks called voussoirs. Each block presses on its neighbours, so the whole ring works in compression and no joint has to hold in tension. Stone and brick resist crushing well but break when bent, which is why a stone lintel cracks over a span that an arch of the same stone crosses easily.

In a corbelled arch, each course is laid flat and projects a little beyond the one below until the two sides meet; each stone stays in place because the masonry behind it weighs down its back end. Courses laid this way can roof a passage or even a round chamber, held in by the earth or masonry around them. In a true arch the joints are set

square to the curve, so in a round arch they all point to its centre; the blocks lean on one another, and the ring pushes outward on its supports.

The top block is the keystone. The lowest blocks on each side are the springers, which sit on the piers or walls that carry the arch, called abutments.

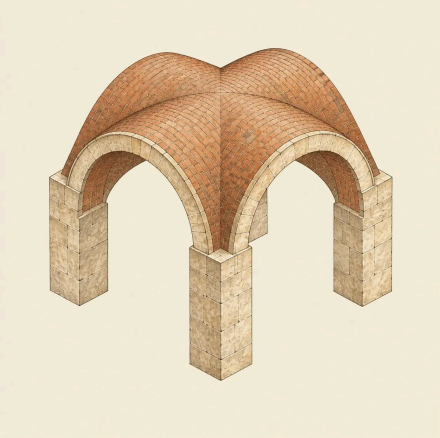
A corbelled opening: every joint is horizontal, and each stone is held down by the wall behind it.

How it works

Weight from above presses each voussoir down. Its faces are slanted, so it cannot drop without forcing its neighbours apart, and the load passes from block to block down to the springers. There the force presses down and also pushes outward. This horizontal push is the thrust: if an abutment leans or slides, the span widens, the crown sinks and the arch can fall. The flatter the arch, the larger the thrust.

The path of this force through the stones is the line of thrust. Since the 1960s, following Jacques Heyman, engineers analyse masonry as if it carried no tension, did not slide and did not crush. Stresses in most arches stay low, so crushing rarely governs failure. An arch then stands if at least one line of thrust fits inside its thickness. Where the line reaches the edge of a joint, the joint can open like a hinge, and once enough hinges form, usually four, the ring collapses.

In 1675 Robert Hooke gave the ideal shape in a Latin anagram: hang a chain and turn its curve upside down. A chain can only pull, so it settles into the curve its loads require; inverted, that curve carries them in pure compression.



A groin vault: where two barrel vaults cross, the thrust gathers at the four corners.

A barrel vault is an arch drawn out in depth. It pushes outward along its whole length, so its side walls must be thick. Two barrel vaults crossing at right angles form a groin vault, whose thrust collects at the corners, and the walls between them can be opened with windows. A dome is an arch turned about its vertical axis; its horizontal rings hold one another, so it can be left open at the top. Most vaults and domes cannot hold themselves until they are closed, so they are built on centering, a temporary timber formwork cut to the curve of the underside.

How to build it

A brick arch of about 60 cm span, standing on the ground as a practice piece, is a good first try for two people. You need bricks, hydraulic lime mortar, planks, battens, nails, two pairs of hardwood wedges, a level and a string.

Set the abutments. On a firm, level base, build two solid blocks of brickwork, each at least 30 cm long and a brick length wide, no more than four courses high. Pack heavy stones or rammed earth against their outer faces, so that

their feet cannot slide or tip outward.

Make the centering. Draw the semicircle full size with the string pinned at its centre. Cut two plank ribs to that curve, less the batten thickness, and nail battens across them. Stand it on props with folding wedges under each, level with the tops of the abutments.

Lay the ring. Set each brick on edge with its length running through the arch, so the ring is about 10 cm deep and a brick length thick. Start at both springers and climb each side in turn, so the centering is loaded evenly. Check with the string that every joint points to the centre, and let the mortar joints take the taper, thicker on the outside. Set the keystone last with a firm push, not hard blows.

Wait, then strike. Cover the fresh work against sun, rain and frost, and keep it damp as the mortar maker advises. Leave the centering at least a week, longer in cold or damp weather: taking the support away too early is a common cause of collapse. Then ease the wedges a few millimetres at a time, alternating sides. If the crown drops or a joint opens, stop, wedge the centering back up under the ring and find the cause before trying again.

Test a model first. Hang a fine chain on an upright board and trace its curve. Saw small blocks from a plank, each a slight wedge with both joints square to the traced line, and assemble them on a card cut to the same curve, with a stop at each foot. Slide the card out: if the blocks are cut true, the arch stands without glue.

> **Safety.** Lift bricks and stones close to the body with bent knees, and share heavy pieces. Wear gloves and safety glasses. Avoid cutting brick or stone, whose dust contains silica; if you must, cut outdoors with a wet saw or a hand chisel and wear a fitted FFP3 respirator. Lime mortar is caustic: protect skin and eyes and rinse splashes at once. Never stand or reach under the arch while you strike the centering; work from the side with a long stick and keep everyone clear. Any larger or higher arch, or one meant to carry a wall, a path or people, needs a design checked by a builder or engineer.

History and evolution

True arches appear in Mesopotamia and Egypt in the fourth millennium BCE, in mud brick, often in drains and tombs. From the First Dynasty, around 3000 BCE, Egyptians built vaults without centering by laying the bricks in leaning rings set against an end wall, a method still used in Nubia. At Tel Dan, in northern Israel, one of the oldest known arched gates, built of mud brick before about 1700 BCE, still stands with its arch preserved.

Corbelling went on alongside: the Treasury of Atreus at Mycenae, a Late Bronze Age tomb, has a corbelled dome 14.5 m across. Roman builders were the first to raise freestanding arches, in bridges, aqueduct arcades such as the Pont du Gard, and concrete vaults and domes like the Pantheon's, 43.3 m wide.

The pointed arch, already common in Islamic architecture, reached Western Europe in the second half of the eleventh century; it pushes outward less than a round arch of the same span. The choir of Saint-Denis near Paris (1140–1144) joined pointed arches, rib vaults and outside buttresses. From about 1160 builders around Paris added flying buttresses, half-arches that carry the thrust of the high vault across the aisles to outer piers. With the thrust carried outside, the walls between the piers could be thin and filled with glass. At Beauvais the choir vault rose to about 48 m; part of it fell in 1284.

A flying buttress: a half-arch carries the vault's thrust over the aisle to a pier standing outside.

Key figures

Earliest true arches

Mesopotamia and Egypt, fourth millennium BCE, in mud brick

An early arched gate still standing

Tel Dan, mud brick, built before about 1700 BCE

Thinnest semicircular arch, in theory

About 0.107 times its radius, with radial joints and only its own weight to carry

Beauvais choir vault

About 48 m high; part of it fell in 1284

Sources

1. The Origins of the Voussoir Arch (A. Hrychuk Kontokosta, in The Roman Arch, 2025) · Oxford University Press https://academic.oup.com/book/61689/chapter/540990895
2. Mud-Brick (V. L. Emery, UCLA Encyclopedia of Egyptology, 2011) · University of California, Los Angeles https://journalpub.escholarship.org/nelc_uee/article/4007/galley/2583/download
3. The Remarkable Discoveries at Tel Dan (J. C. H. Laughlin, Biblical Archaeology Review 7:5, 1981) · Center for Online Judaic Studies https://cojs.org/the-remarkable-discoveries-at-tel-dan/
4. Brick Brief: Arches · Brick Industry Association https://www.gobrick.com/media/file/brick-brief-arches-may-2012.pdf
5. The effect of stereotomy on the shape of the thrust-line and the minimum thickness of masonry arches (N. Makris and H. Alexakis, 2013) · Archive of Applied Mechanics, Aston University https://research.aston.ac.uk/en/publications/the-effect-of-stereotomy-on-the-shape-of-the-thrust-line-and-the-
6. Arches, vaults and buttresses (S. Huerta, seminar, 2015) · University of Pisa, School of Engineering https://docenti.ing.unipi.it/scuola_dottorato_ingegneria/Seminari2015/2015-Huerta-Seminario1.pdf
7. The stone skeleton (J. Heyman, International Journal of Solids and Structures 2, 1966, pp. 249-279) · Elsevier https://doi.org/10.1016/0020-7683(66)90018-7
8. As hangs the flexible line: equilibrium of masonry arches (P. Block, M. DeJong and J. Ochsendorf, Nexus Network Journal 8:2, 2006) · Springer https://doi.org/10.1007/s00004-006-0015-9
9. Maths in a minute: St Paul's dome · Plus Magazine, University of Cambridge https://plus.maths.org/content/maths-minute-st-pauls-dome
10. Hanging models · Stereotomy Semantic Classification, University of Porto https://ssc.arq.up.pt/semantic-classification/hanging-models/
11. Compound brick vaults by slices in written sources (R. Marín-Sánchez et al., 2021) · Universitat Politècnica de València https://riunet.upv.es/bitstreams/f756ca9a-0877-4029-9a69-dd09bc7f3735/download
12. Treasury of Atreus · J. Siegel, Hampden-Sydney College https://blogs.hsc.edu/drjclassics/?p=379
13. Arch · Wikipedia https://en.wikipedia.org/wiki/Arch
14. Centering (masonry) · Wikipedia https://en.wikipedia.org/wiki/Centering_(masonry)
15. Flying buttress · Wikipedia https://en.wikipedia.org/wiki/Flying_buttress
16. Beauvais Cathedral · Wikipedia https://en.wikipedia.org/wiki/Beauvais_Cathedral

Fact-checked on 2026-10-14

Beer

Grain sugars fermented into alcohol

c. 3,500 BCE · Prehistory · Settlement

Requires: Pottery (p. 22), Bread (p. 26)

1 Malted barley 2 Mash tun 3 Brew kettle 4 Cooler 5 Fermenting vat 6 Casks

Beer is made by turning the starch of sprouted grain into sugar and letting yeast ferment that sugar into alcohol. Chemical traces of barley beer go back to the fourth millennium BCE in western Iran, and brewing has followed farming almost everywhere cereals were grown.

What it is

Beer is a fermented drink made from cereal grain, most often barley, with water, yeast and usually hops. Yeast cannot feed on starch, so the grain is first malted and mashed to turn its starch into sugars that yeast can ferment into alcohol and carbon dioxide.

The plate shows a small brewhouse of the kind used in Europe before steam power, with the vessels set out in the order of the work: malt, mash tun, kettle, cooler, fermenting vat and casks.

How it works

First the barley is malted: it is soaked and left to sprout for several days. As the seed starts to grow, it produces enzymes that will later break down its own store of starch. The maltster then dries the grain in a kiln to stop

growth; the heat also sets the colour and flavour of the malt, from pale to roasted.

In the mash, the malt is crushed and steeped in hot water. Between about 62 and 68 °C the malt's amylases cut the starch into sugars, mainly maltose, in an hour or so. A cooler mash leaves more fermentable sugar and a drier beer; a hotter one leaves more unfermentable sugar and a fuller body. The sweet liquid, the wort, is drained off through the husks, which act as a filter.

Malting: the sprouting grain makes the enzymes that brewing needs, and the kiln stops it before it uses up its starch.

The wort is then boiled for an hour or more. Boiling kills most of the microbes that came in with the grain, stops the enzymes and drives off unwanted aromas. Hops added at this stage give bitter compounds that also slow the growth of many spoilage bacteria; hops added near the end keep more of their scent.

Finally the wort is cooled and yeast is added. Over several days the yeast turns the sugar into ethanol and carbon dioxide, along with the esters and other compounds that shape the taste. Ale yeast works warm and rises to the top; lager yeast works cool and settles to the bottom. A period of storage then lets the beer clear and mature.

How to build it

A small batch of about 10 litres can be brewed in a kitchen with the brew-in-a-bag method. You need 2.5 kg of crushed pale malt, about 25 g of hops, a packet of ale yeast, a 20-litre pot, a large mesh bag, a thermometer, a fermenter with an airlock, a hydrometer, a no-rinse sanitiser, and bottles with new caps.

Mash. Heat 14 litres of water to about 70 °C, put the bag in the pot and stir in the malt. The mash should settle near 66 °C. Turn off the heat, then cover the pot and wrap it in a blanket for an hour, keeping the blanket well clear of the burner. Take the blanket off, lift out the bag and let it drain.

Boil. Bring the wort to a rolling boil for 60 minutes. Add most of the hops at the start for bitterness and the rest in the last ten minutes for aroma. Watch the pot as it comes to the boil, because the foam rises fast. Meanwhile clean and sanitise the fermenter and everything else that will touch the cooled wort; a clean immersion chiller can be sanitised by standing it in the boiling wort for the last 15 minutes.

Cool and ferment. Cool the covered pot to about 20 °C with the chiller or in a sink of cold water. Pour the wort into the fermenter, add the yeast, fit the airlock and keep it at 18 to 20 °C.

Bottle. Fermentation usually takes one to two weeks. Bottle only when the hydrometer gives the same reading on three days running and that reading is close to the expected final gravity, about 1.010 to 1.015 for this recipe: a higher steady reading means a stuck fermentation, not a finished one. Dissolve 5 to 6 g of sugar per litre in a little boiled water, mix it gently into the beer, fill and cap the bottles, and keep them at room temperature for two weeks before chilling.

> **Safety.** A pot of boiling wort can cause severe scalds: keep it on a stable burner, lift it with a second person or not at all, and keep children and pets away. Indoors, use only a hob or cooker made for indoor use; burners sold for outdoor use stay outdoors. Too much priming sugar, or bottling before fermentation has finished, can make bottles burst; use real beer bottles, weigh the sugar, and wear eye protection when handling a batch that seems over-carbonated. Never try to distil the beer. Follow the local law on home brewing and on alcohol.

History and evolution

In Mesopotamia, drinkers shared a jar and sucked the beer through long straws that reached below the floating husks.

Residues in stone mortars at Raqefet Cave in Israel, about 13,000 years old, have been read as traces of a gruel-like brew made by Natufian foragers for funeral feasts; the interpretation is debated. An early and widely cited chemical trace comes from Godin Tepe in western Iran, where grooves inside a jug of the late fourth millennium BCE hold calcium oxalate, the “beerstone” that barley beer deposits in brewing vessels. Calcium oxalate is not unique to beer, so this reading has been questioned too.

Mesopotamian tablets mention beer thousands of times, yet give no recipe. The closest is the Hymn to Ninkasi, the goddess of brewing, written down around 1800 BCE, which describes soaking malt, spreading the mash on reed mats and filling the vats. In Egypt beer was a staple food, and a large brewery from about 3000 BCE has been excavated at Abydos.

Medieval European brewers flavoured beer with gruit, a mix of herbs. Abbot Adalhard of Corbie mentioned hops for beer in 822, and hopped beer, which kept better, spread slowly over the following centuries. On 23 April 1516 the dukes of Bavaria ruled at Ingolstadt that beer could contain only barley, hops and water. Yeast was not on the list, because its part in fermentation was not yet understood; Louis Pasteur showed in the 1850s that fermentation was the work of living cells. At the Carlsberg laboratory in Copenhagen, Emil Christian Hansen found that wild yeasts mixed into the brewers’ yeast caused “beer sickness”. He grew a pure culture from a single good yeast cell, first used for a full-scale brew in November 1883, and lager became far more reliable. Carlsberg gave the yeast to other brewers.

The yellow lupulin glands inside the hop cone hold the bitter resins and the aroma.

Key figures

Early chemical trace of barley beer (debated)
Godin Tepe, Iran, late 4th millennium BCE

Usual mash temperature
About 62 to 68 °C, where the malt's starch-splitting enzymes work best

Bavarian purity law
23 April 1516, Ingolstadt: barley, hops and water only

First pure-culture yeast in production
Carlsberg, Copenhagen, November 1883

Sources

1. Five things I learned about Sumerian beer · University of Chicago Magazine https://mag.uchicago.edu/arts-humanities/five-things-i-learned-about-sumerian-beer
2. Purifying yeast · Carlsberg Group https://www.carlsberggroup.com/pursuit-of-better/scientific-discoveries/purifying-yeast/
3. 500 Jahre Reinheitsgebot: Deutsches Bier, was darf rein und was ist drin · Stiftung Warentest https://www.test.de/500-Jahre-Reinheitsgebot-Deutsches-Bier-was-darf-rein-und-was-ist-drin-4991639-0/
4. The brewing process · Cornell Brewing Program, Cornell University https://blogs.cornell.edu/brewing/?p=116
5. History of beer · Wikipedia https://en.wikipedia.org/wiki/History_of_beer
6. Mashing · Wikipedia https://en.wikipedia.org/wiki/Mashing

Fact-checked on 2026-10-12

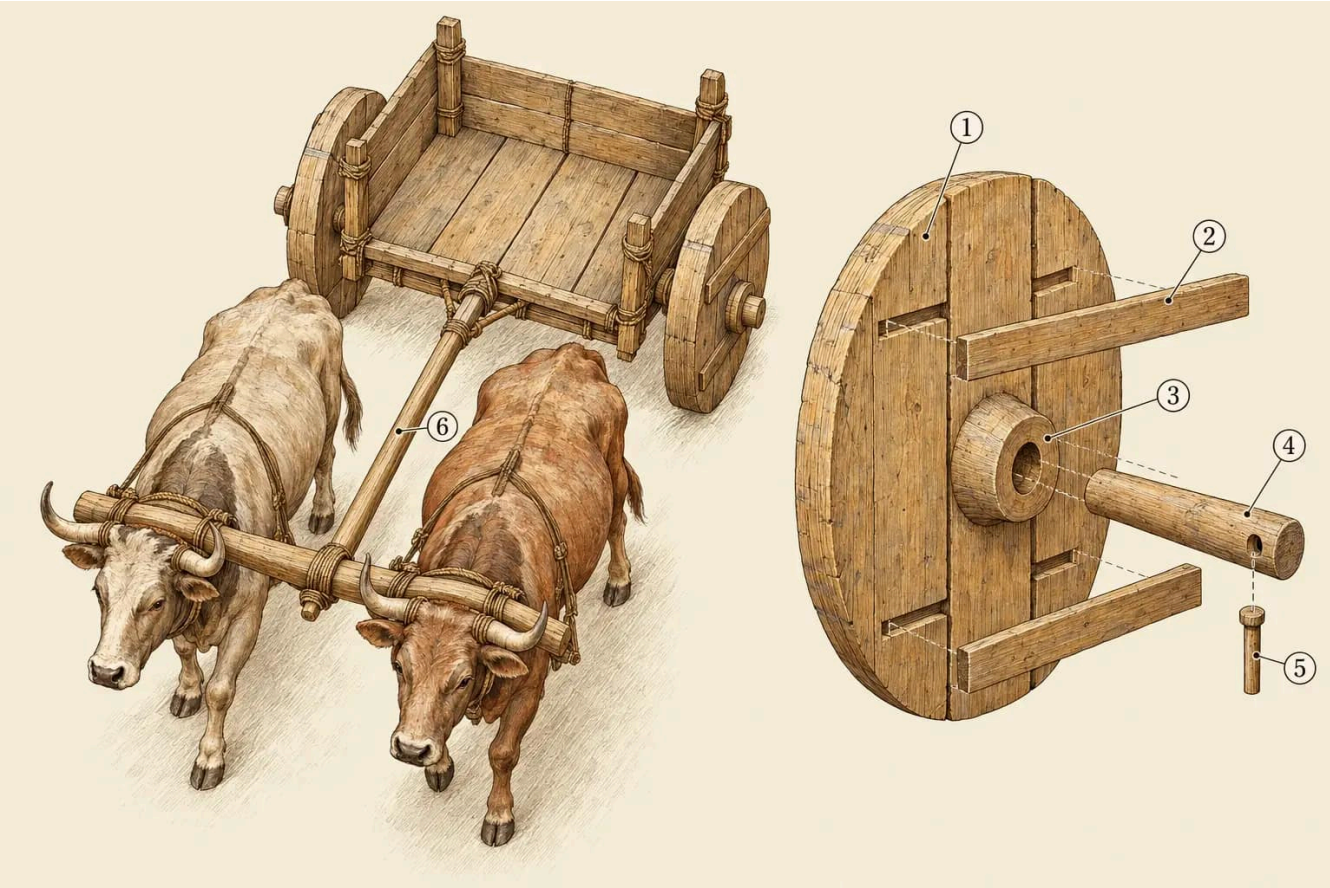
Wheel & Axle

Rolling instead of dragging

c. 3,500 BCE · Prehistory · Settlement

Requires: Stone Tools (p. 5)

Leads to: Bicycle (p. 246), Crane & Pulley (p. 145), Spinning Wheel (p. 185), Steam Locomotive (p. 238), Water Wheel (p. 153)



1 Disc planks 2 Cross-batten 3 Nave (hub) 4 Axle 5 Linchpin 6 Draught pole

A wheel turning on an axle lets a load roll instead of scraping along the ground, so the rubbing moves to a small, greased bearing. Wheeled carts appeared in Mesopotamia and Europe around 3500 BCE, and the same idea later turned winches, mills and waterwheels.

What it is

A wheel and axle is a disc fixed to, or turning on, a shaft. Under a cart it carries a load over the ground. On a well winch or a capstan it multiplies force.

Rollers under a sledge have to be carried round to the front again and again, while a wheel stays under the load. The hard part, which took people a long time, was making the wheel turn smoothly around a fixed axis.

The plate is a reconstruction of an early solid wheel built from three planks, a type found in many excavations in Europe and the Near East, under an ox cart of around 3000 BCE.

How it works

A dragged sledge presses its whole weight on its runners and scrapes over every bump. On wheels the rubbing happens in one small place, between the axle and the hole it turns in, while the rim rolls over the ground.

The gain comes from leverage, because the axle's surface is much closer to the centre than the rim. On a wheel 70 centimetres across turning on an axle 7 centimetres thick, the rim has ten times the leverage, so the pull needed to overcome the axle's friction is about a tenth of that friction. The rim still has to roll over the ground, which adds its own resistance on soft or rough roads. Grease, usually animal fat or tar, lowers the axle friction further.

On rollers a load moves easily, but each roller left behind has to be carried round to the front again.

An axle that is too thin breaks, and one that is too thick adds friction. The hole must be round and smooth, the axle snug without binding. On some early carts the wheels were locked onto the squared ends of the axle and both turned together, the rounded middle of the axle running in supports under the body. Most later carts had a fixed axle, with the wheels turning on its ends and held on by linchpins.

How to build

A solid wheel for a light handcart can be made with hand tools. The steps below are an outline, without measured drawings; a cart for heavy loads or draught animals needs a wheelwright's experience.

Choose the wood. Use a hard, tough, well-seasoned timber such as oak, ash or elm. You need three planks about 5 centimetres thick, the middle one wider than the two side ones.

Cut the disc. Lay the planks edge to edge and mark a circle with a cord and a peg. Cut grooves across the grain and drive in two hardwood battens to lock the planks together, with wooden dowels between the planks. Then saw the outline to the circle.

Make the hub. The centre needs extra thickness to stop the wheel wobbling, so fix a turned block, the nave, on each face with glued hardwood pegs driven right through the disc. Bore the axle hole at right angles to the disc, then smooth it with a rasp or a heated iron rod.

Shape the axle. Hew a straight, knot-free piece of hardwood. Taper the ends to fit the holes with a little play and bore a hole through each tip, just beyond where the hub and washer will sit, for the linchpin. Bolt the axle under the cart bed with wooden blocks or iron straps.

Fit and test. Grease the ends, slide the wheels on, add washers and drive the linchpins home. Each wheel should spin freely and run true without rocking. Load the cart a little at a time and check the joints after each trial.

> **Safety.** Adzes, axes and augers cause deep cuts: keep both hands behind the edge. A loaded cart on a slope can run away and crush whoever stands in front of it, so test on level ground and chock the wheels when you stop. If you burn out the axle hole with hot iron, keep water at hand.

History and evolution

A Bronze Age chariot wheel: six spokes and a rim of bent felloes, far lighter than a solid disc.

Between about 3600 and 3300 BCE, signs of the wheel appear over a wide area. Clay tablets from Uruk in Mesopotamia use a sign for a wagon. A pot from Bronocice in southern Poland is incised with what looks like a four-wheeled cart. Other finds come from the northern Caucasus and the steppes north of the Black Sea. Archaeologists still argue over where the idea began.

The oldest wheel that survives was found in 2002 in the Ljubljana Marshes in Slovenia. It is about 70 centimetres across, made of ash planks held by oak battens, and radiocarbon dates put it between about 3350 and 3100 BCE. Its oak axle, about 1.2 metres long, has square ends that locked into the wheel.

The anthropologist David Anthony has argued that the wheel came late because of tools. Shaping round holes and true axles needed cast copper chisels and gouges, which became common in the Near East only after about 4000 BCE.

Solid wheels were sturdy but heavy, and suited slow ox carts. Around 2000 BCE people of the Sintashta culture, east of the Ural Mountains, built light wheels with spokes and fitted them to two-wheeled chariots pulled by horses. Spoked wheels and chariots spread to Egypt, Greece and China over the following centuries.

In the first millennium BCE, Celtic wheelwrights began to bind the rim with a single iron tyre, fitted hot so that it shrank and pulled the joints tight, a method used into the twentieth century.

The nineteenth century brought wire-spoked wheels in tension, light enough for the bicycle, and then rubber tyres filled with air. A railway axle still works the same way: the load rests on a small, lubricated bearing while the wheel rolls along the rail.

Fitting a tyre: the iron ring is put on hot and shrinks as it cools, binding the wheel tight.

Key figures

Oldest surviving wheel
Ljubljana Marshes, Slovenia, c. 3150 BCE

Spoked wheel
c. 2000 BCE, steppes east of the Urals

Earliest images of wagons
c. 3500–3350 BCE (Uruk tablets, Bronocice pot)

Axle friction felt at the rim
Reduced by the ratio of wheel to axle diameter

Sources

1. Wheel · Wikipedia https://en.wikipedia.org/wiki/Wheel
2. World's oldest wheel found in Slovenia · Government Communication Office of Slovenia https://slovenia.si/art-and-cultural-heritage/worlds-oldest-wheel-found-in-slovenia
3. Replica of the oldest wooden wheel with an axle · City Museum of Ljubljana (MGML) https://mgml.si/en/city-museum/news/667/replica-of-the-oldest-wooden-wheel-with-an-axle-for-the-winner-of-the-26th-tour-of-slovenia/
4. Why It Took So Long to Invent the Wheel · Scientific American https://www.scientificamerican.com/article/why-it-took-so-long-to-inv/
5. Sennacherib's Quarry, 705–681 BCE · Center for Online Judaic Studies https://cojs.org/sennacherib-s_quarry-_705-681_bce/
6. Old Civilization: Layard's Nineveh (1853) · Scientific American https://www.scientificamerican.com/article/old-civilizationlayards-nineveh/
7. Estimating Wagon Draft (TechGuide 2G-213) · Tillers International https://tillersinternational.org/wp-content/uploads/2025/01/EstimatingWagonDraftTechGuide.pdf
8. Friction and Friction Coefficients for various Materials · Engineering ToolBox https://www.engineeringtoolbox.com/friction-coefficients-d_778.html
9. Densities of Solids · Engineering ToolBox https://www.engineeringtoolbox.com/density-solids-d_1265.html

Fact-checked on 2026-10-11

Writing

Knowledge that outlives memory

c. 3,300 BCE · Prehistory · Settlement

Requires: Pottery (p. 22), Stone Tools (p. 5)

Leads to: Positional Numerals (p. 94), Printing Press (p. 200), Electric Telegraph (p. 278)

1 Clay counting tokens 2 Clay envelope broken open, tokens inside 3 Early tablet: number marks, barley and a jar 4 Cut reed stylus 5 Scribe's palette with black and red ink 6 Papyrus roll

Writing records language with visible marks that another person can read back later, far away or long after the writer has died. It arose independently several times; among the earliest examples are tablets from southern Mesopotamia of around 3300 BCE, on which temple accountants pressed and drew signs while the clay was still damp.

What it is

Writing is a set of visible marks, agreed within a community, that stand for the words or sounds of a language. A reader who never met the writer can recover the message, even centuries later.

People kept records long before they wrote. In the Near East, small clay tokens shaped as cones, spheres and discs appear from about 8000 BCE. The archaeologist Denise Schmandt-Besserat reads them as counters for measures of grain, oil or livestock; others, such as Lucy Bennison-Chapman, argue that many had other uses. Around 3500

BCE, accountants sealed tokens inside hollow clay balls and pressed the same shapes on the outside. Such devices tracked quantities but could not record a name or a sentence.

A writing system can note whole words, syllables or single sounds, and many combine these principles.

Each shape of token probably stood for a kind of goods. Sealed in a clay envelope, the tokens could record a debt until it was paid.

How it works

Two ideas turned counting into writing. The first gave quantities and goods separate signs. On the oldest tablets from Uruk, numbers are pressed with the round end of a stylus and the goods are drawn beside them with a pointed tip: five marks and an ear of barley for five measures of barley. The value of a number sign still depended on what was counted, with different systems for grain, animals or land.

The second idea was the rebus, using a sign for its sound. In Sumerian, “arrow” and “life” sounded alike, so the arrow sign could also write “life”, a word hard to draw. Sound signs appear in Mesopotamia by about 3000 BCE.

Pressed at different angles, the corner of a cut reed leaves vertical, horizontal and oblique wedges.

Tracing curves in damp clay drags it into ridges, so scribes came to press the edge of a cut reed instead. Each touch left a wedge, and over the third millennium BCE the pictures became groups of wedges, hence the name cuneiform, from the Latin *cuneus*.

Egyptian scribes chewed the end of a rush stem into a brush and rubbed it on cakes of black or red ink set in a wooden palette. They wrote on papyrus, strips of the plant’s pith laid in two crossed layers, pressed and dried. Alphabets later used signs for single sounds, so a few dozen of them could write any word.

How to build

You need fine clay, water, a dry reed or garden cane as thick as a pencil, a knife and a damp cloth.

Prepare the clay. Potter’s clay works as it is. Riverbank clay must be soaked, poured through a cloth to remove grit, then left to stiffen until it takes a thumbprint without sticking. Knead out the air pockets.

Shape the tablet. Press a ball the size of a small egg into a cushion about 2 cm thick, small enough to hold in one hand.

Cut the stylus. Saw off about 15 cm of reed. Near one end, shave the sides with the knife until the tip is square in section, with flat faces meeting at sharp corners, then cut it straight across: a corner pressed into clay leaves a wedge. Cut the other end through a node, so that the solid partition closes the tube, and round it off; a round

wooden stick also works. Pressed straight down it leaves a circle, and at a slant a D-shaped notch, the two shapes the first scribes used for numbers.

Write. Divide the face into boxes with the long edge of the stylus and put one entry in each box. Press the number with the round end and lift it cleanly. Then draw the sign for what was counted with a corner of the square end, as the first scribes did, or build it from pressed wedges, as later scribes did.

Dry it. Leave the tablet in the shade for several days, turning it once so it does not crack. Dried clay softens again in water; firing in a kiln, as for pottery, makes it permanent.

Try the alphabet. Say ten words aloud and list the sounds you hear, ignoring the letters you would normally spell them with. Give each sound a simple sign, using the old trick: draw something whose name begins with that sound. When no word starts with a sound, invent a sign for it. Add a sign whenever a new word brings a new sound: most alphabets end up with twenty to forty-odd letters.

> **Safety.** Cut away from your body when trimming the reed. Do not sand or sweep dry clay: its dust contains fine silica that harms the lungs, so clean with a damp cloth. Fire tablets only in a proper kiln, and never fire a piece that is still damp, which can burst.

History and evolution

The oldest tablets come from the Uruk IV layer of the city's temple quarter, usually dated about 3350–3200 BCE, by some authors 3200–3100 BCE. Over 6,000 proto-cuneiform tablets and fragments are known from Uruk and other sites, most of them accounts. Cuneiform lasted over three thousand years.

In Egypt, bone and ivory labels from tomb U-j at Abydos, dated to around 3200 BCE, already carry hieroglyphs, some used for their sound. Specialists still debate whether Egypt took the idea from Mesopotamia, as the dates are so close. Chinese writing appears on Shang oracle bones from Anyang around 1200 BCE, already mature. In Mesoamerica, writing was in use in Oaxaca by about 400 BCE, and painted Maya glyphs at San Bartolo date from 300–200 BCE. No contact links China or Mesoamerica with the Near East at those dates: these were separate inventions.

In China the scribe ground an ink stick on a wet stone and wrote with a pointed hair brush.

The alphabet grew out of hieroglyphs. Some forty short texts from the turquoise mines of Serabit el-Khadim, in Sinai, and two from Wadi el-Hol, in Egypt, use only 27 to 29 signs. Their writers, speakers of a Semitic language, gave each Egyptian picture the first sound of its name in their own tongue: a house, *beth*, became b; water, *mem*, became m. Proposed dates run from about 1850 to 1550 BCE. By 1200–1050 BCE the Phoenicians wrote 22 consonant letters from right to left. Greeks adopted them around 800 BCE and added vowels, and the Etruscans passed the alphabet to Rome in the seventh century BCE.

Paper, first made in China in the second century BCE, later became the usual surface for writing and for printed books.

Key figures

Oldest tablets
Uruk, southern Iraq, about 3350–3200 BCE (some authors say 3200–3100)

Separate inventions
Mesopotamia, China and Mesoamerica; Egypt probably, though still debated

Phoenician alphabet
22 consonant letters, about 1200–1050 BCE

Earliest corpus
Over 6,000 proto-cuneiform tablets and fragments, most of them accounts

First alphabet
27 to 29 signs, Sinai and Egypt, between about 1850 and 1550 BCE

Sources

1. The state of decipherment of proto-Elamite (Englund, 2004) · Cuneiform Digital Library Initiative https://cdli.earth/files-up/publications/englund2004c.pdf
2. Seals and signs: tracing the origins of writing in ancient South-west Asia (Kelley, Cartolano & Ferrara, 2024) · Antiquity, Cambridge University Press https://www.cambridge.org/core/journals/antiquity/article/seals-and-signs-tracing-the-origins-of-writing-in-ancient-southwest-asia/B3C2D400F3F80A7A0162D9035C9C2804
3. The Evolution of Writing (Schmandt-Besserat, 2014) · Denise Schmandt-Besserat, University of Texas at Austin https://sites.utexas.edu/dsb/tokens/the-evolution-of-writing/
4. Reconsidering 'Tokens': The Neolithic Origins of Accounting or Multifunctional, Utilitarian Tools? (Bennison-Chapman, 2019) · Cambridge Archaeological Journal, Cambridge University Press https://www.cambridge.org/core/journals/cambridge-archaeological-journal/article/abs/reconsidering-tokens-the-neolithic-origins-of-accounting-or-multifunctional-utilitarian-tools/7E6C04CB040AD8AA0EA84B94D4D275C4
5. Visible Language: Inventions of Writing in the Ancient Middle East and Beyond (Woods, ed., 2010) · Institute for the Study of Ancient Cultures, University of Chicago https://isac.uchicago.edu/sites/default/files/uploads/shared/docs/oimp32.pdf
6. Early Egyptian Writing (1999) · Archaeology, Archaeological Institute of America https://archive.archaeology.org/9903/newsbriefs/egypt.html
7. Oracle bone (50-31) · Nelson-Atkins Museum of Art https://art.nelson-atkins.org/objects/23289/oracle-bone
8. Evidence of Earliest Maya Writing (report on Saturno, Stuart & Beltrán, Science, 2006) · Mesoweb https://www.mesoweb.org/reports/SanBartoloWriting.html
9. Proto-Sinaitic: Progenitor of the Alphabet (Simons, 2011) · Rosetta 9, University of Birmingham https://rosetta.bham.ac.uk/wp-content/uploads/2024/02/Simons_Proto-Sinaitic_Rosetta9.pdf
10. The alphabet · Deutsche Nationalbibliothek, German Museum of Books and Writing https://mediengeschichte.dnb.de/DBSMZBN/Content/EN/SoundsSymbolsScript/01-alphabet-en.html
11. Papyrus · Centre for the Study of Manuscript Cultures, Universität Hamburg https://www.csmc.uni-hamburg.de/profiling-guide/materials/writing-surfaces/papyrus.html
12. Scribal Palette · Institute of Egyptian Art and Archaeology, University of Memphis https://memphis.edu/egypt/exhibit/palette.php
13. The Cuneiform Stylus (on Cammarosano, Mesopotamia 49, 2014) · Book and Sword https://www.bookandsword.com/2022/12/10/the-cuneiform-stylus/
14. What the Earliest Texts Say About the Invention of Writing · Discover Magazine https://www.discovermagazine.com/what-the-earliest-texts-say-about-the-invention-of-writing-692

Fact-checked on 2026-10-14

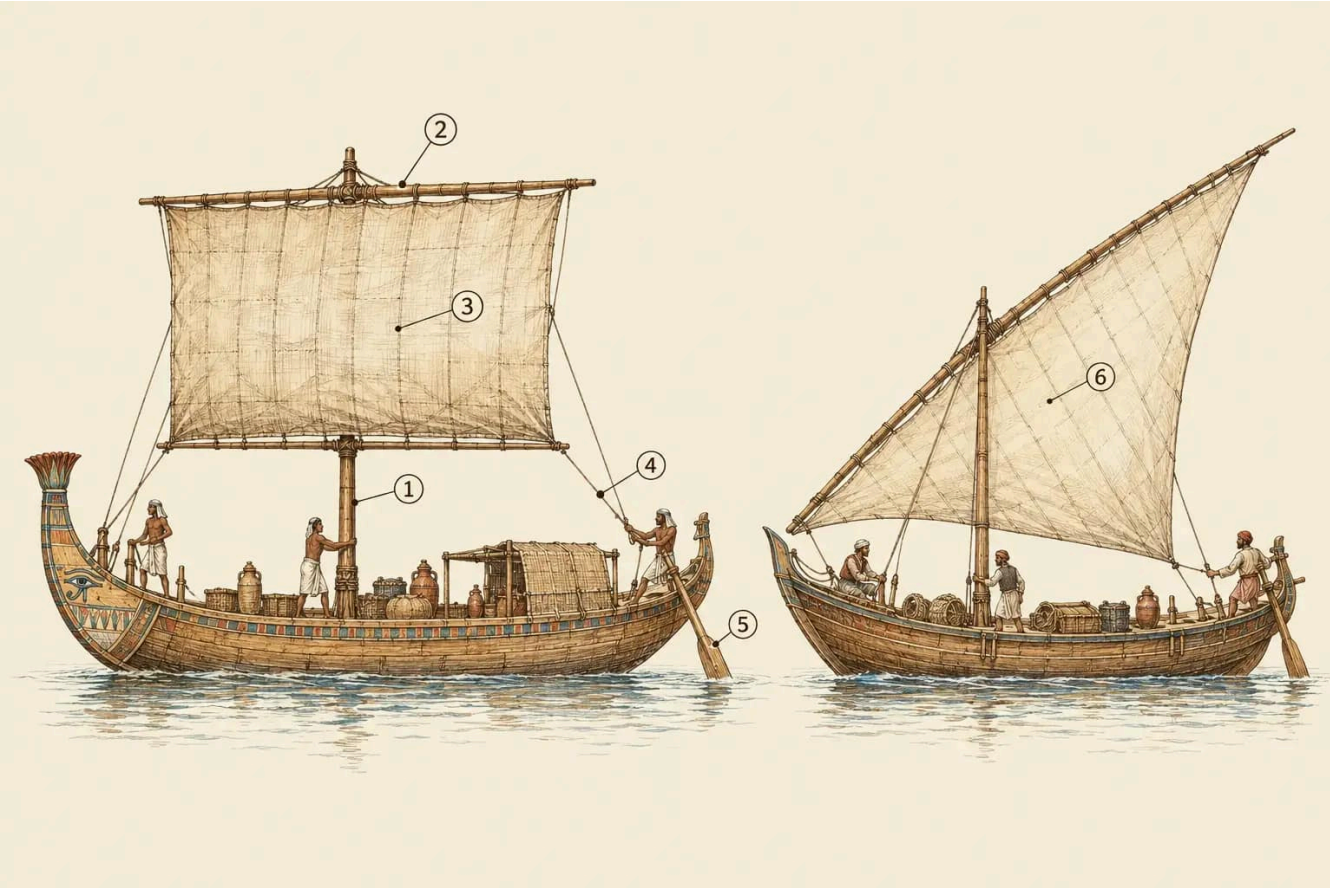
Sail

Catching the wind to move a boat

c. 3,200 BCE · Prehistory · Settlement

Requires: Rope & Cordage (p. 13), Weaving (p. 43)

Leads to: Celestial Navigation (p. 205)



1 Mast 2 Yard 3 Square sail 4 Sheet 5 Steering oar 6 Lateen sail

A sail is a sheet of cloth or matting raised on a mast to catch the wind and move a boat. Set at the right angle, it drives the boat with the wind behind or across it, and by zigzagging, even towards where the wind comes from.

What it is

A sail is a surface spread to the wind to drive a vessel. The earliest were probably mats or skins held up on a pole; later sails were woven from linen, wool or cotton, and today mostly from synthetic fibres. Hung from a mast and adjusted with ropes, a sail moves a boat with no fuel and no rowers.

The plate shows square and fore-and-aft sails. The square sail hangs across the boat from a horizontal spar, the yard, and works best with the wind behind. A fore-and-aft sail lies along the length of the boat. The lateen is a triangular sail hung from a long slanting yard and works well with wind from the side.

How it works

With the wind behind, the principle is simple: the air pushes on the sail as it would on an open hand. On this course a boat cannot go faster than the wind, because the faster it moves, the weaker the wind it feels.

With the wind on the side, the sail works like a wing. Curved and set at a small angle to the wind, it bends the flow of air, and the air pushes back on the sail, mostly sideways and partly forward. The hull, and the keel if there is one, resist sliding sideways because the water pushes back on them, which leaves a forward push. A boat can therefore sail faster across the wind than straight before it.

No sail can drive a boat straight into the wind. A modern sailing boat can hold a course about 40 to 45 degrees off the wind. To reach a point upwind it zigzags, crossing the wind's direction at each turn. Sailors call this tacking.

The crew adjust the sail with ropes. The sheet (4) pulls a lower corner of the sail in or lets it out to set its angle to the wind. The halyard hoists the yard (2) up the mast (1). On a square-rigged ship the braces swing the yard round. In strong wind the crew reduce the sail's area, which is called reefing. The steering oar (5), later the rudder, holds the course.

How to build

This outline describes how a small square sail is made. It is not a measured drawing or a plan for fitting a sail to any small boat. Use a rig designed for the specific boat and checked by a qualified boatbuilder or sailing instructor for hull, sail and steering balance, stability and attachment strength.

Gather the materials. Use the sailcloth, thread, edge rope, yard and fittings specified in the checked rig plan. You also need a sail needle and palm. The mast support and its attachments must follow that plan.

Cut and join the cloths. Lay the canvas strips side by side. Use the seam overlap and stitching specified in the plan for the expected loads.

Hem and rope the edges. Fold and sew the hems as specified in the plan, then sew on the edge rope. The cloth and seams transmit wind loads; the rope reinforces the edges. Reinforce the corners and fit the specified rings or eyes.

The sailmaker's palm lets the hand push a heavy needle through several layers of cloth.

Rig it. Follow the checked plan for attaching the sail to the yard and fitting the halyard and sheets. Check that the yard can be lowered and that the ropes run freely.

Practise before sailing. Have an instructor demonstrate how to lower the sail and reduce its pull with this rig, then practise under supervision before going afloat. Releasing the sheets alone may leave a square sail drawing. Make the first sailing trial in sheltered water with light wind and an instructor aboard.

> **Safety.** A gust can capsize a small boat in seconds. Wear a lifejacket, check the forecast, and sail first in light wind close to shore with someone watching. Never tie the sheet off so that it cannot be released quickly. A swinging yard or boom can strike your head, and cold water exhausts a swimmer fast.

History and evolution

Boats are far older than sails: people paddled, poled and rowed long before they used the wind. When the sail appeared is uncertain, because cloth and matting rarely survive. In Kuwait, remains of sea-going reed boats coated with bitumen date to between 5500 and 5000 BCE. Robert Carter discusses them as evidence of early maritime exchange; boat remains alone do not establish that sails were used.

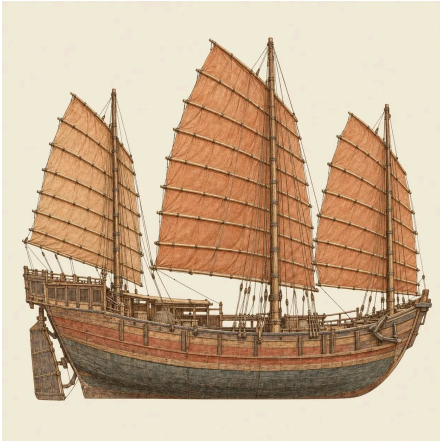
The crab-claw sail, held between two spars, drove Austronesian canoes across the Pacific.

Early possible depictions come from Egypt, around 3200 BCE. A painted Naqada II jar in the British Museum shows a boat with an object on a pole. R. L. Bowen interpreted it as a sail; the alternative reading is a banner. The catalogue uses about 3200 BCE for this possible evidence, not as a known invention date. On the Nile, the current carried boats north and the wind could push them back south.

Square sails were used on Egyptian, Phoenician, Greek and Roman ships, and later on Viking ships, whose sails were often woven from wool. Across the Pacific and the Indian Ocean, Austronesian sailors developed their own rigs. Words for “sail” in their languages go back about five thousand years, and the crab-claw sail carried their outrigger canoes over thousands of kilometres of open sea.

The lateen sail appears in the Mediterranean by the second century CE and becomes common from the fifth. It cost less to make and maintain than the square sail, though it was not clearly faster. Earlier Chinese ship images show square sails. China may have adopted the battened junk sail, stiffened by bamboo poles, around the twelfth century; this does not establish a uniform replacement of square sails.

From the fifteenth century, European shipbuilders used mixed square and lateen rigs on carracks and some caravels. These traditions contributed to later ocean-going sailing ships. Steam took over commercial shipping in the nineteenth and twentieth centuries. Sails survive on yachts and racing boats, now cut from synthetic cloth.



Bamboo battens keep the junk sail flat and stiff.

Key figures

Early possible depictions
Egypt, about 3200 BCE

Closest course to the wind
About 40–45° for a modern sailing boat

Lateen sail
In the Mediterranean by the 2nd century CE

Battened junk sail
Possibly adopted in China around the 12th century CE

Sources

1. Sail · Wikipedia https://en.wikipedia.org/wiki/Sail
2. Junk (ship) · Wikipedia https://en.wikipedia.org/wiki/Junk_(ship)
3. Boat remains and maritime trade in the Persian Gulf during the sixth and fifth millennia BC (R. Carter, 2006) · Antiquity https://www.cambridge.org/core/journals/antiquity/article/abs/boat-remains-and-maritime-trade-in-the-persian-gulf-during-the-sixth-and-fifth-millennia-bc/98224B03E778DE5C9D3EAA806A5ABCF8
4. Egypt's Earliest Sailing Ships (R. L. Bowen, 1960) · Antiquity https://www.cambridge.org/core/journals/antiquity/article/egypts-earliest-sailing-ships/28F7218895B44D2DC9BF36AECD5B3F79
5. The physics of sailing (J. Wolfe) · School of Physics, UNSW Sydney https://newt.phys.unsw.edu.au/~jw/sailing.html
6. The Ship’s Sail · The Viking Ship Museum https://www.vikingeskibsmuseet.dk/en/professions/education/all-about-the-viking-ship/the-ships-sail
7. Seam · UK Sailmakers https://www.uksailmakers.com/encyclopedia/glossary/seam/
8. Carrack (Não) · The Mariners’ Museum and Park https://exploration.marinersmuseum.org/watercraft/carrack-nao/
9. Hypothetical Reconstruction of an Ancient Egyptian Sea-going Vessel from the Reign of Hatshepsut, 1500 BCE (P. Couser, C. Ward and T. Vosmer, 2009) · RINA Historic Ships conference https://www.ancientportsantiques.com/wp-content/uploads/Documents/ETUDESarchivees/Navires/Min%20of%20the%20Desert/Min-Couser2012.pdf
10. Drag Equation · NASA Glenn Research Center https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/drag-equation/

Fact-checked on 2026-10-12

Soap

Fat and ash against germs

c. 2,800 BCE · Antiquity · Settlement

Requires: Control of Fire (p. 9), Pottery (p. 22)

Leads to: Hygiene & Antisepsis (p. 290)

1 Ash hopper (lye barrel) 2 Lye crock 3 Tallow 4 Soap kettle over the fire 5 Mould and cut bars

Soap is made by boiling or mixing fat with a strong alkali, which splits the fat into glycerol and the salts of fatty acids that lift grease and dirt into water. Recipes for soap-like cleaners go back to Mesopotamia in the third millennium BCE; cheap industrial alkali made soap an everyday product in the nineteenth century.

What it is

Soap is a cleaning substance made from fats or oils and an alkali. Each soap molecule has one end that holds on to water and a long tail that holds on to oil, so it can carry grease, dirt and many microbes off the skin and into the rinsing water. Soap made with sodium hydroxide sets into hard bars; potassium soaps stay soft or liquid. The lye that farmers leached from wood ash held potassium carbonate rather than a modern hydroxide, and gave a soft soap.

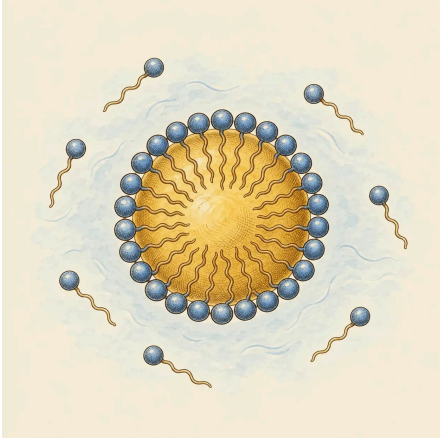
The plate shows soapmaking as it was done on farms in Europe and North America until the nineteenth century: water poured through wood ash to make lye, a crock to catch it, rendered tallow, a kettle boiling over the fire, and

a mould with cut bars drying.

How it works

Fats and oils are triglycerides: three fatty acid chains joined to one molecule of glycerol. A strong alkali breaks those joints. Each fatty acid takes the sodium or potassium of the alkali and becomes a soap molecule, and the glycerol is set free. Chemists call the reaction saponification.

In water, soap molecules gather into tiny spheres called micelles, with their oily tails inside and their water-loving heads outside. A drop of grease is drawn into the core and rinsed away with it. The same tails can wedge into the fatty envelope of some bacteria and viruses, including coronaviruses, and pry it apart. That is why washing with soap and water removes far more germs than water alone, although microbes with tougher coats resist it better.



A micelle: the soap's oily tails hold the grease inside, and their water-loving heads let the rinse carry it away.

On a farm, the alkali came from ashes. Water poured through a barrel of hardwood ash dissolved potassium salts, mainly potassium carbonate, and ran out as a brown lye. Boiled with tallow for six to eight hours, it gave a soft, jelly-like soap that was kept in a barrel and ladled out as needed. Common salt stirred in at the end of the boil made a firmer soap rise as a cake that could be cut into bars, but salt was dear and many farm families did without. Truly hard soda soap needed soda, which came from the ashes of seaweed and coastal plants until Nicolas Leblanc found how to make it from common salt.

How to build it

Small batches of soap are made today by the cold process, with sodium hydroxide bought for soapmaking and a soap calculator. Sodium hydroxide is corrosive and can blind in seconds, so it is a job for adults only, in a calm, uncluttered room.

Gather the kit. You need safety goggles, chemical-resistant gloves and long sleeves, a digital scale reading to the gram, containers of stainless steel or of polypropylene sold as safe for hot lye (never aluminium, which reacts with it), a stick blender, a thermometer, a silicone or lined mould, and pure olive oil or a tested mix of oils.

Calculate. Enter the exact weight of each oil into a saponification calculator with a fat margin of about 5%. For 500 g of olive oil it gives about 64 g of sodium hydroxide and about 170 g of water. Check the result twice: too much alkali makes a soap that burns the skin.

Make the lye. Outdoors or by an open window, weigh the water first, then pour the sodium hydroxide slowly into the water while stirring, never the water onto the alkali. The solution heats up quickly and gives off fumes for a moment; do not breathe them. Let it cool to about 40 °C.

Mix and pour. Warm the oil to a similar temperature, pour in the lye and blend in short bursts until the mixture thickens like thin custard. Pour it into the mould, cover it and leave it for one to two days.

Cure. Unmould after one to two days and cut into bars. A correctly measured batch has finished reacting by then; four to six weeks of curing on edge in a dry, airy place, longer for pure olive soap, let water evaporate so the bars harden and last. Curing cannot rescue a batch made with too much alkali: if a cured bar still stings the skin, throw the batch away.

> **Safety.** Always wear goggles and gloves while handling lye or fresh soap, and keep children and pets out of the room. If lye touches the skin, rinse at once with plenty of running water; if it reaches the eyes, rinse with running water for at least 30 minutes while someone calls emergency services. Label every container, store sodium hydroxide locked away in its original packaging, and never use kitchen utensils again for food once they have held lye. Handle fresh soap with gloves for the first days.

History and evolution

Before soap was common, soapwort was crushed in water to give a mild lather for washing wool and linen.

Soap-like cleaners are old, but the early evidence is thin. Babylonian sources of about 2800 BCE are often cited as the first record, and later accounts describe Mesopotamian recipes of the third millennium BCE that heated oil with wood ash to wash wool, although the tablets themselves are rarely identified. The Egyptian Ebers papyrus, around 1550 BCE, prescribes animal fats or vegetable oils mixed with an alkaline salt as a medicine.

Roman writers treated soap as a foreign product. Pliny the Elder, in the first century CE, credited it to the Gauls, who made it from tallow and ashes and used it to tint their hair; his is the first known use of the word sapo. A century later the physician Galen described soap made with lye and advised washing with it.

Hard soaps of olive oil came from the eastern Mediterranean. The Persian physician al-Razi wrote down soap recipes around 900, and by the thirteenth century soapmaking was a major trade in the cities of Syria and Palestine. In Europe, workshops in Castile and Marseille were turning out olive-oil soap on a large scale by the fifteenth century, while northern soapmakers boiled tallow with ash lye.

Aleppo soap, made with olive and laurel oil, is cut into cubes and stacked in airy towers to cure for months.

Soap became cheap only when its alkali did. In 1791 Nicolas Leblanc patented a process that made soda from salt, sulphuric acid, coal and limestone, so soapmakers no longer depended on plant ash. In 1823 Michel-Eugène Chevreul showed that fats are compounds of glycerol and fatty acids, which explained what happens in the kettle. Factories such as Lever Brothers, founded in 1885 at Warrington, sold soap in wrapped, branded bars. Hygiene followed slowly: in 1847 Ignaz Semmelweis made the staff of his Vienna maternity clinic disinfect their hands with chlorinated lime, and deaths from childbed fever there fell from about 18% to about 1% the next year.

Key figures

Earliest recorded soap-like material
Babylon, about 2800 BCE

The reaction
Fat + alkali → soap + glycerol (saponification)

Chemistry explained
Michel-Eugène Chevreul, 1823

Soda from common salt
Nicolas Leblanc's process, 1791

Sources

1. Why soap works · Yale School of Medicine https://medicine.yale.edu/news-article/why-soap-works
2. Soap making (Dallas Bogan, History of Campbell County, Tennessee) · TNGenWeb https://www.tngenweb.org/campbell/hist-bogan/SoapMaking.html
3. Nicolas Leblanc (1742-1806) · European Route of Industrial Heritage https://www.erih.net/how-it-started/stories-about-people-biographies/biography/leblanc
4. Chevreul et la chimie des corps gras · Encyclopædia Universalis https://www.universalis.fr/encyclopedie/chevreul-et-la-chimie-des-corps-gras/
5. Lever Brothers Limited · Science Museum Group https://collection.sciencemuseumgroup.org.uk/people/cp42536
6. Pioneering hand hygiene: Ignaz Semmelweis and the fight against puerperal fever (Cureus, 2024) · PubMed Central https://pmc.ncbi.nlm.nih.gov/articles/PMC11568873/
7. Codex Standard for Named Animal Fats (CODEX-STAN 211-1999) · FAO/WHO Codex Alimentarius https://www.fao.org/4/y2774e/y2774e05.htm
8. Saponification value of fats and oils as determined from 1H-NMR data: the case of dairy fats (Foods, 2022) · PubMed Central https://pmc.ncbi.nlm.nih.gov/articles/PMC9140812/
9. Soap · Wikipedia https://en.wikipedia.org/wiki/Soap

Fact-checked on 2026-10-12

Positional Numerals

Digits worth what their place says

c. 2,050 BCE · Antiquity · Settlement

Requires: Writing (p. 82)

Leads to: Celestial Navigation (p. 205), Computer (p. 351), Thermometer and barometer (p. 217)

1 Counting board: one line per power of ten 2 Pebble used as a counter 3 Clay tablet: one thousand as 16,40 in base sixty
4 Maya dots and bars: 2 and 10 in base twenty 5 Shell sign for zero 6 One thousand in Indian digits, the ones we use

In a positional numeral system a few digits are enough to write any number, because each digit's value depends on the place it occupies. With a zero to mark an empty place, sums, products and divisions can be worked out in writing, column by column, instead of on a counting board.

What it is

In 707, the first seven counts hundreds and the last counts units. That is the whole idea of positional notation: a short set of signs whose value depends on where each one stands. The ten digits from 0 to 9 can write any whole number, however large, without a new sign.

Older systems added their signs together. Egyptian scribes had one sign for units, another for tens, another for hundreds, and repeated each as often as needed. Roman numerals work the same way with a few subtractions: 1888 is MDCCCLXXXVIII, thirteen signs. Such numbers record a total well but are awkward to calculate with, so Roman and medieval accountants worked on a counting board and wrote down only the result.

A place-value system turns the written number into a counting board on paper, so the calculation itself can be written down and checked. Zero makes this work: it first marked an empty place, then became a number in its own right.

How it works

The base is the number of distinct digits, and each place is worth that many times the place to its right. In base ten, 2748 means 2 thousands, 7 hundreds, 4 tens and 8 units. In 1081 the zero says there are no hundreds; without it, 1081 and 181 would look alike.

A Babylonian number was pressed into wet clay one wedge at a time.

Other bases follow the same rule. Babylonian scribes counted in sixties, with two marks: an upright wedge for one and a corner wedge for ten. One thousand is 16 sixties and 40, written 16,40. The Maya counted in twenties with a dot for one, a bar for five and a shell for zero, and stacked the places from the bottom up. One thousand is 2 four-hundreds, 10 twenties and no units: two dots over two bars over a shell. In calendar dates the third place counted 360 days instead of 400. Computers use base two, where 13 is written 1101: one eight, one four, no two and one unit.

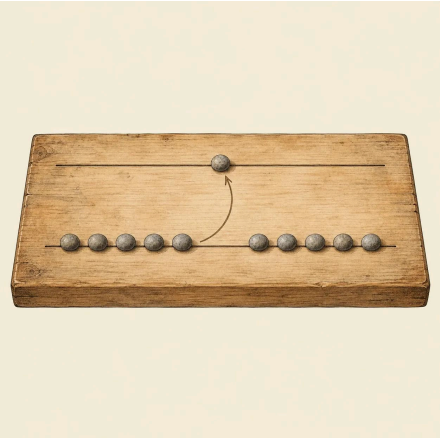
When a column reaches ten or more, you write its units and carry its tens to the next column; when it runs short, you borrow one from the left. Moving a number one place to the left multiplies it by ten, so 47 × 23 is 47 × 3 plus 47 × 20: 141 + 940 = 1081. A table of products up to 9 × 9 is enough to multiply any two numbers. Long division works from the left, one place at a time: guess a digit of the quotient, multiply, subtract, bring down the next digit.

How to build

You need a flat board or a patch of smooth sand, chalk or a stick, about forty pebbles, paper and a pencil.

Draw the board. Draw four parallel lines a hand's width apart: from the bottom, units, tens, hundreds and thousands. Once all carrying is done, no line holds more than nine pebbles.

Lay out a number. For 2748, put 2 pebbles on the thousands line, 7 on the hundreds, 4 on the tens and 8 on the units. A line left empty is a zero.



Carrying on the board: ten counters on one line are exchanged for a single counter on the line above.

Add with carrying. Add 1375 by putting 1, 3, 7 and 5 pebbles on the same lines. The units line now holds 13: take ten off, put one on the tens line, and 3 remain. The tens line then holds 12, so carry again, and do the same with the hundreds. The board reads 4123.

Multiply. Clear the board. For 47 × 23, lay out 47 three times, carrying as you go: 141. Then lay out 47 twice more with every pebble one line higher, which adds 940. Carry and read 1081.

Write it on paper. Do the same sums in columns, the carried figure written small above the next column. Each column is a line of the board, each digit a count of pebbles, each 0 an empty line.

Change base. To write 4000 seconds in base sixty, divide by 60: 66, remainder 40. Divide 66 by 60: 1, remainder 6. Read the last quotient, then the remainders backwards: 1,6,40, or 1

hour, 6 minutes and 40 seconds.

> **Safety.** Small pebbles are a choking hazard for young children. Choose stones too large to swallow, or keep the board out of their reach.

History and evolution

The oldest firmly dated use of place value is a scratch tablet from Ur, of 2043 BCE, that adds up weights in base sixty. By about 1800 BCE, Babylonian school tablets use it routinely. There was no zero and no mark separating whole numbers from fractions, so the reader judged the size of a number from context. From around 700 BCE some scribes put a sign in an empty middle place, never at the end. Greek astronomers kept base sixty for fractions, which is why hours and degrees still have sixty minutes.

The Maya reached place value and zero on their own. Long Count dates appear in southern Mexico from the first century BCE, and stelae at Uaxactun dated 357 CE write empty places with a zero sign.

Our digits come from India. In 628 Brahmagupta defined zero as a number minus itself and gave rules for calculating with it, though his claim that zero divided by zero is zero is wrong. The Bakhshali manuscript, found near Peshawar in 1881, writes zero as a dot; radiocarbon dates obtained in 2017 for three of its leaves range from the third to the tenth century, and the date of the text is disputed. The oldest undisputed dated zero in India is at Gwalior, in 876.

Across late-medieval Europe, accounts were often still cast on a ruled cloth with brass counters.

In ninth-century Baghdad, al-Khwarizmi wrote a book on Indian reckoning, now known only in Latin; his name gave the word algorithm. Fibonacci learned the digits in North Africa and taught them in his Liber abaci of 1202. In 1299 the Florentine money changers' guild barred them from its account books, and counting boards stayed in use in northern Europe into the sixteenth century.

Key figures

Base-sixty place value
First firmly dated at Ur in 2043 BCE; routine in Babylonian schools by about 1800 BCE

Zero treated as a number
Brahmagupta, Brāhmasphuṭasiddhānta, 628 CE

Oldest undisputed dated zero in India
Gwalior inscription, 876 CE, in the numbers 270 and 50

Maya zero
Zero signs on stelae of Uaxactun dated 357 CE

Liber abaci
Fibonacci, Pisa, 1202

Sources

1. Bases, positions and computations (Chemla, 2025) · Philosophical Transactions of the Royal Society B https://pmc.ncbi.nlm.nih.gov/articles/PMC12536272/
2. On the Alleged Counting with Sexagesimal Place Value Numbers in Mathematical Cuneiform Texts from the Third Millennium B.C. (Friberg, 2005) · Cuneiform Digital Library Journal https://cdli.earth/articles/cdlj/2005-2
3. A history of Zero · MacTutor History of Mathematics, University of St Andrews https://mathshistory.st-andrews.ac.uk/HistTopics/Zero/
4. Babylonian numerals · MacTutor History of Mathematics, University of St Andrews https://mathshistory.st-andrews.ac.uk/HistTopics/Babylonian_numerals/
5. Indian numerals · MacTutor History of Mathematics, University of St Andrews https://mathshistory.st-andrews.ac.uk/HistTopics/Indian_numerals/
6. Brahmagupta · MacTutor History of Mathematics, University of St Andrews https://mathshistory.st-andrews.ac.uk/Biographies/Brahmagupta/
7. Carbon dating finds Bakhshali manuscript contains oldest recorded origins of the symbol 'zero' · Gardens, Libraries and Museums, University of Oxford https://www.glam.ox.ac.uk/node/218481
8. The Bakhshālī Manuscript: A Response to the Bodleian Library's Radiocarbon Dating (Plofker, Keller, Hayashi, Montelle, Wujastyk, 2017) · History of Science in South Asia https://journals.library.ualberta.ca/hssa/index.php/hssa/article/view/22
9. The use of Zero as a placeholder by the Maya (J. G. Atkinson) · Mexicolore https://www.mexicolore.co.uk/maya/home/the-maya-and-zero/1000
10. The Calendar Inscriptions · Archaeology Magazine, Archaeological Institute of America https://archaeology.org/issues/november-december-2012/collection/calendar-inscriptions/
11. Arabic numerals · MacTutor History of Mathematics, University of St Andrews https://mathshistory.st-andrews.ac.uk/HistTopics/Arabic_numerals/
12. Fibonacci · MacTutor History of Mathematics, University of St Andrews https://mathshistory.st-andrews.ac.uk/Biographies/Fibonacci/
13. The mathematician Fibonacci, or how the number 7 came to Europe · Swiss National Museum https://blog.nationalmuseum.ch/en/2020/03/the-mathematician-fibonacci-or-how-the-number-7-came-to-europe/

Fact-checked on 2026-10-14

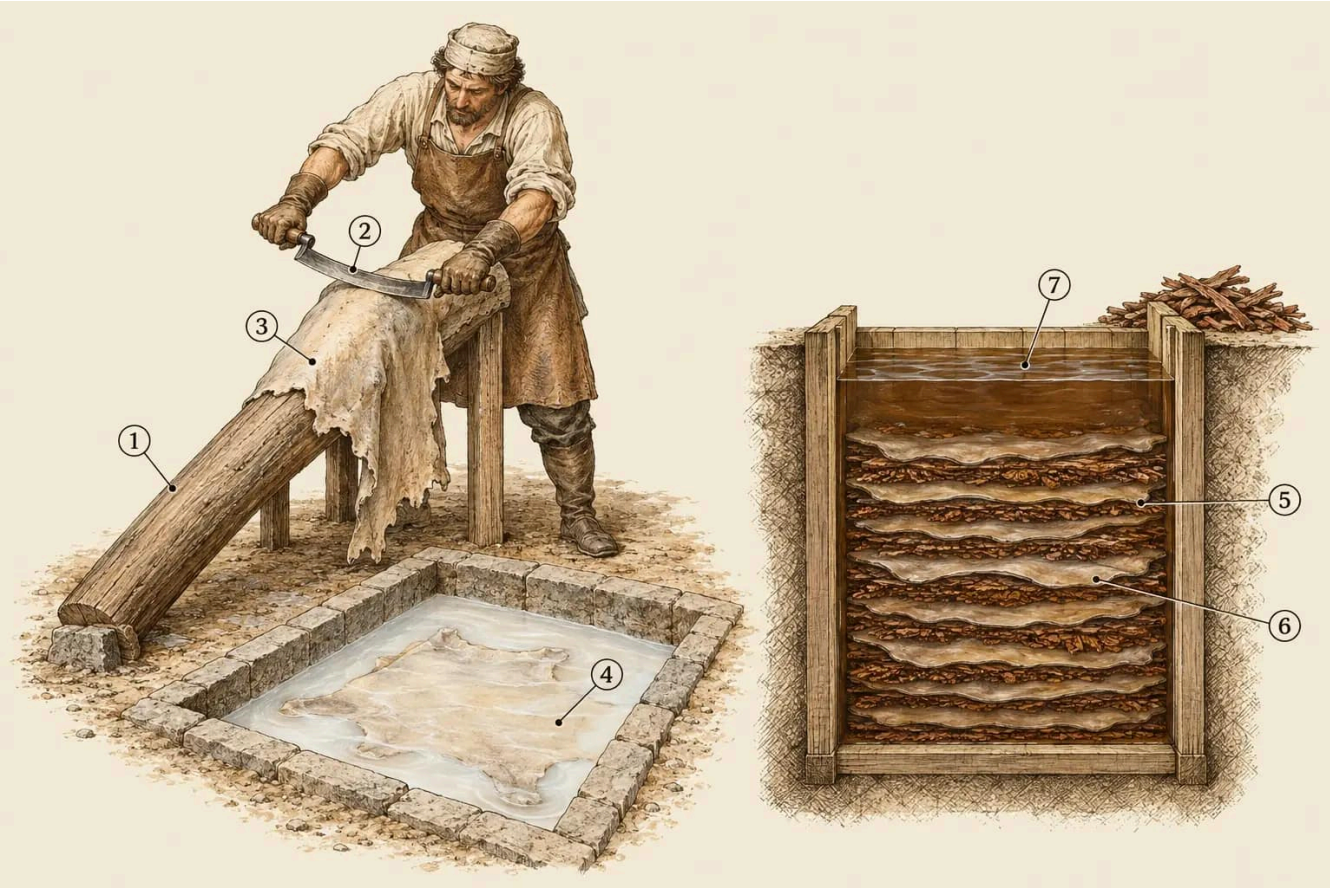
Leather Tanning

Raw hide, oak bark and months in pits

c. 1,500 BCE · Antiquity · Settlement

Requires: Stone Tools (p. 5), Control of Fire (p. 9)

Leads to: Horse Collar (p. 173), Piston Pump (p. 157)



1 Tanner's beam 2 Two-handled scraping knife 3 Hide being dehaired and fleshed 4 Lime pit 5 Layer of crushed oak bark 6 Hide laid in the tan pit 7 Tan liquor

Tanning turns a raw animal hide, which soon rots when wet and dries hard as wood, into leather that stays supple and resists decay far better. In the pit method the hide is cleared of hair and flesh, then left for months in water and crushed oak bark, whose tannins bind to the fibres of the skin.

What it is

A fresh hide is mostly water and collagen, a protein woven into a dense mat of fibres. In warm weather it starts to rot within days. If it dries first, it becomes rawhide, hard and horny, which softens in water and rots if it stays wet.

Leather is a hide whose fibres have been changed to resist both. It can get wet and dry again with far less risk of rotting or setting stiff, it can be cut, stitched and moulded, and kept dry it lasts for centuries. Shoes, harness, buckets and bellows were made from it. Hunters softened skins with fat and smoke, later craftsmen used alum, and most leather today is tanned with chromium salts. This plate follows the method that served Europe and the Mediterranean for some two thousand years: vegetable tanning with bark, in pits.

Leather in section, enlarged: the smooth grain on top, the tangle of collagen fibres below. Beside it, raw hide with the hair on.

How it works

Many plants store tannins, bitter compounds that protect them against insects and fungi. Oak bark is rich in them, and so are chestnut wood, sumac leaves, oak galls and acacia pods. Crushed bark steeped in water gives a brown liquid that tanners called ooze, or tan liquor.

In this liquid, tannin molecules work their way between the collagen fibres of a cleaned hide and attach to them at many points. Coated in this way, the fibres no longer glue together as they dry, and bacteria break them down far more slowly. The hide becomes firm, brown leather.

Tannin moves in from the surface, and a strong liquor at the start would seal the outer layers and leave a raw core. Hides therefore started in weak, used liquor and moved to stronger ones over weeks and months.

The hide must first be opened up. Lime water or a lye made from wood ash makes it swell, loosens the hair roots and removes part of the fat and soft proteins. The hair and the top layer of skin can then be scraped off and the flesh side cleaned, so the tannin enters from both faces.

How to build

This outlines the traditional bark method for one cow hide as tanneries practised it; it is not a tested recipe. Count on most of a year. You need a hide from a healthy animal of known origin, watertight tubs or barrels, slaked lime or wood ash, plenty of dried oak bark, a wooden beam and a blunt two-handled knife.

Soak and lime. Soak a salted hide in clean water for a day or two until it is limp, then put it in water mixed with slaked lime or wood-ash lye and stir it daily. The hide is ready when the hair slips out under a thumb.

Dehair and flesh. Lay the hide over the sloping beam, hair side up, and push the blunt knife away from you to strip the hair. Turn it and scrape the flesh side clean of fat and membrane. Wash out as much lime as you can in several changes of water, because lime left in the hide spoils the tanning; the weak, slightly sour used liquor of the next stage takes up what remains.

Prepare the bark. Peel bark from felled oaks in spring, dry it, crush it and steep it in water for several days.

Tan in the pits. Put the hide in weak liquor first and move it every day for a few weeks. Then lay it flat or folded in a tub between layers of crushed bark and cover it with stronger liquor. Tanneries stacked many hides this way in one pit. Renew bark and liquor every few months. At J & F J Baker in Devon, the last traditional oak-bark tannery in

Oak bark is peeled in spring, when the rising sap loosens it from the wood.

Britain, hides spend three months in liquor and nine more stacked with bark. Cut a sliver from the thickest part: the leather is done when the brown colour has gone right through, with no pale streak in the middle.

Dry and dress. Rinse, dry slowly in the shade, and work oil or tallow into the leather while it is still damp.

> **Safety.** Lime and wood-ash lye are caustic and can burn skin and eyes. Wear waterproof gloves, eye protection and boots, and use slaked lime rather than quicklime, which heats violently with water. Wash a splash off the skin at once with plenty of water; if lime gets in an eye, keep rinsing it with clean water and get medical help immediately. Raw hides can carry anthrax spores, which enter through cuts or are breathed in with dust and cause serious illness; you cannot tell by looking whether a hide is contaminated. Use only hides from inspected animals of known origin, never from an animal found dead, cover cuts, do not shake or beat dry hides, and wash hands and clothes after work. If you think you have been exposed, or a sore, fever or breathing trouble follows work with hides, see a doctor at once and say that you handle hides. Lime and tan liquors pollute: keep them in watertight tubs well away from wells, springs and streams, and never pour spent liquor on the ground, into drains or into water; take it to a proper disposal point.

History and evolution

People prepared skins long before they tanned them. Hunters in many regions worked brains or other fats into a scraped skin and then smoked it, so it could get wet without turning stiff. Ötzi, who died in the Alps around 3300 BCE, wore goat, sheep, deer and calf skins, and a shoe from the Areni-1 cave in Armenia, dated to 3627–3377 BCE, seems to be cowhide. How either was treated is uncertain.

Long before tan pits, skins were stretched, scraped, worked with fat and smoked.

Dating vegetable tanning is difficult: only chemical analysis can tell how an ancient leather was treated, and specialists read the results differently. Carol van Driel-Murray notes that Bronze Age leathers were mostly cured with fat, oil or smoke. Yet analysis of Egyptian leathers at the Metropolitan Museum, published in 2017, found plant tannins in objects of the Middle or New Kingdom, between about 2000 and 1100 BCE. The Greek botanist Theophrastus wrote about tanning plants around 300 BCE, and in north-west Europe tanned leather arrives with the Roman conquest. At Pompeii a tannery with fifteen cylindrical tanks was working when the eruption of 79 CE buried it.

Alum tawing, with a mineral salt instead of tannin, gave a pale, soft leather prized for gloves, but water washes the alum out and the skin can dry hard again. Pit tanning changed little until the end of the nineteenth century, when chromium salts cut the work from months to days. Chrome tanning is an industrial process with toxic waste, not a home craft. Bark-tanned leather is still made for saddles, belts and soles.

Key figures

Time in the pits

About 12 months at a surviving English oak-bark tannery; 11 to 18 months, sometimes 2 years, for heavy ox hides in 1810

Liming

A few days for ox and cow hides, two to three weeks for calfskins (practice described in 1810)

Oldest leather shoe found

Areni-1 cave, Armenia, 3627–3377 BCE; how its leather was treated is not known

Oldest plant tannins detected in leather

Egyptian objects of the Middle or New Kingdom, about 2000–1100 BCE (analysis published in 2017)

Tannery of Pompeii

15 cylindrical tanks, in use until the eruption of 79 CE

Sources

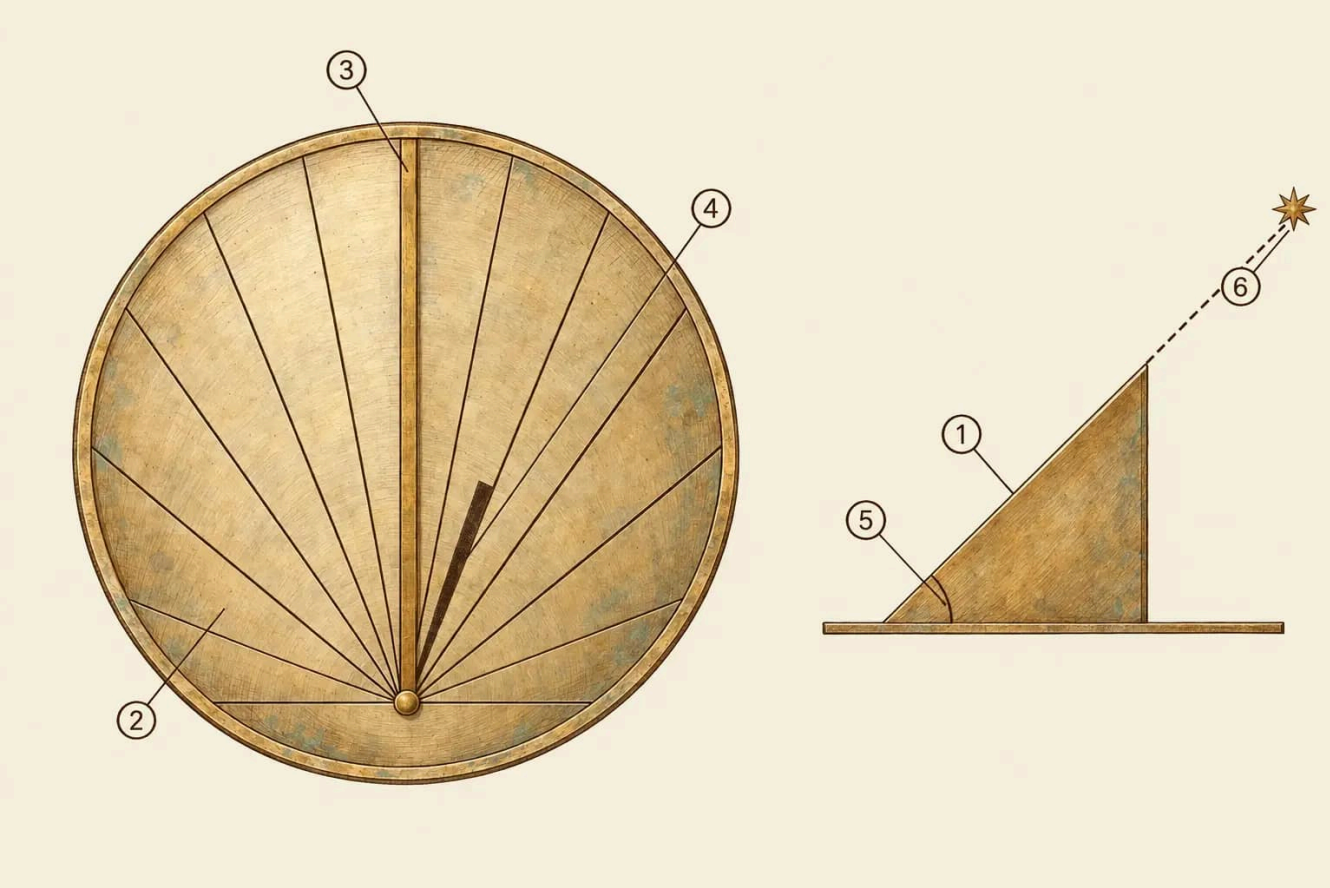
1. Tanning (Encyclopaedia Britannica, 4th edition, 1810) · Encyclopaedia Britannica, transcribed by Jim Clifford, University of Saskatchewan https://jimclifford.ca/early_encyclopedia_britannica/articles/1810/eb_4th_1810_020179.html
2. The Process · J & F J Baker & Co., oak bark tannery, Colyton https://www.jfjbaker.co.uk/the-process
3. Hide Products · Sean Manning, Book and Sword (after C. van Driel-Murray) https://www.bookandsword.com/?p=10459
4. First Direct Evidence of Chalcolithic Footwear from the Near Eastern Highlands (Pinhasi et al., 2010) · PLoS ONE https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0010984
5. Evidence of the use of vegetable tannins in leather tanning in the Middle Kingdom/New Kingdom of ancient Egypt (Elnaggar, 2017) · ICOM-CC Leather and Related Materials Working Group Newsletter https://www.icom-cc.org/dlfile.aspx?file=https://www.icom-cc.org/docs/content/ICOMCC-LRM-Newsletter-june-2017.pdf
6. The large tannery of Pompeii: from restoration to valorisation · Archaeological Park of Pompeii https://pompeiisites.org/en/comunicati/the-large-tannery-of-pompeii-from-restoration-to-valorisation-a-positive-example-of-public-and-private-sector-collaboration/
7. Skins & hides: introduction · Lowimpact.org https://www.lowimpact.org/categories/skins-hides
8. Leather terminology: tawing · Popov Leather https://popovleather.com/pages/leather-terminology-tawing
9. Anthrax: people at increased risk (animal products) · Centers for Disease Control and Prevention https://www.cdc.gov/anthrax/animal-products/products.html
10. Hydrated Lime, Safety Data Sheet CASDS06 · Cement Australia https://cementaustralia.com.au/sites/default/files/2025-02/CASDS06_Hydrated_Lime.pdf
11. Clothing of the Iceman · South Tyrol Museum of Archaeology https://www.iceman.it/en/clothing/

Fact-checked on 2026-10-13

Sundial

Telling time with a shadow

c. 1,500 BCE · Antiquity · Settlement



1 Style (the shadow-casting edge) 2 Dial plate 3 Noon line 4 Shadow 5 Angle equal to the latitude 6 Celestial pole

A sundial tells the time from the shadow that the Sun casts on a marked surface. The oldest surviving examples come from Egypt in the fifteenth century BCE, and until mechanical clocks spread in the late Middle Ages it was the main way to divide the day.

What it is

A sundial is an instrument that shows the time of day by the position of a shadow. A rod or blade, the gnomon, stands over a surface marked with lines, and its shadow sweeps across them as the Sun crosses the sky.

The plate shows a horizontal garden dial drawn for latitude 45°, seen from above, with its gnomon seen from the side. The sloping edge of the gnomon, the style, points at the celestial pole, which keeps the hours equal all year round.

How it works

The Earth turns once a day about an axis that points, in the northern hemisphere, close to the Pole Star. Seen from the ground, the Sun turns about that same axis at a steady 15° per hour. A style set parallel to the axis therefore sits at the centre of the Sun's daily circle, and the plane through the style and the Sun turns at that same steady rate

whatever the season. In practice the style is tilted toward the north (toward the south in the southern hemisphere) at an angle equal to the latitude: about 48.9° in Paris, 41.9° in Rome.

On a horizontal dial that turning plane meets a flat plate, so the shadow sweeps unevenly and the hour lines are not evenly spaced. The angle between the noon line and the line for each hour follows a simple rule: its tangent equals the sine of the latitude times the tangent of 15° per hour from noon. At 45°, the lines for one to six hours after noon lie at about 11°, 22°, 35°, 51°, 69° and 90°. They crowd together near noon and spread out toward six o'clock, which lies at right angles to the noon line.

An Egyptian shadow clock: the crossbar faced east in the morning and was turned round at noon.

A sundial shows local solar time, not the time on a watch. Clock time follows the central meridian of the time zone, so a dial reads 4 minutes slow for every degree of longitude west of it, and 4 minutes fast for every degree east. Because the Earth's orbit is an ellipse and its axis is tilted, the Sun also runs up to about 16 minutes fast or slow over the year: this is the equation of time, often engraved in a small table beside the dial. Summer time adds one more hour.

How to build it

A horizontal dial needs a flat plate of slate, stone, hardwood or metal about 30 cm across, a thin triangle of brass or aluminium for the gnomon, a protractor, a ruler, a spirit level and a calculator. These steps are for the northern hemisphere. South of the equator, put the dial centre near the northern edge and make the style rise toward the south.

Draw the hour lines. Read your latitude from a map to the nearest tenth of a degree. Mark the dial centre near the southern edge of the plate and draw the noon line from it to the far edge. For each hour from noon, compute the angle from the rule above and draw the line on both sides of the noon line: the morning hours lie to the west, the afternoon hours to the east. Draw the six o'clock lines straight across at 90°, where the rule breaks down; this simple dial covers the hours from six to six.

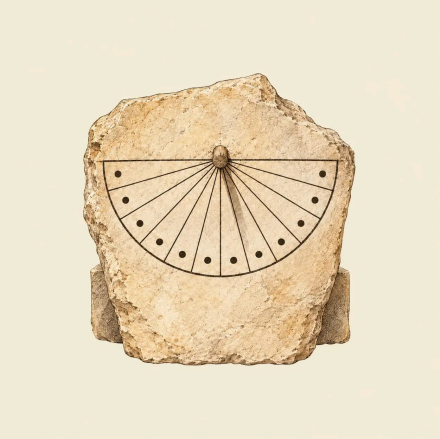
Cut the gnomon. Make a right triangle whose sharp angle equals your latitude. Fix it upright along the noon line with the sharp corner on the dial centre, so the sloping edge rises toward the north. If the blade is thicker than a couple of millimetres, open the dial along the noon line by that thickness: the morning lines start from one face and the afternoon lines from the other.

Find true north. A compass points to magnetic north, which can be several degrees off. On a sunny day, plant a vertical stick on level ground, mark the tip of its shadow in mid-morning and draw a circle through that mark around the foot of the stick. In the afternoon, mark the point where the shadow tip touches the circle again. The line between the two marks runs east and west, the morning mark lying to the west. Standing on the morning mark and facing the afternoon one, north is on your left. The result is approximate, because the Sun's path shifts a little during the day; it is best near the solstices.

Set it up. Place the dial on a level support, with the noon line on the north-south line and the gnomon rising toward the north.

> **Safety.** Never look at the Sun directly, even for a moment, and never through binoculars or a lens: it damages the eyes without pain. File the edges of a metal gnomon smooth, and set the dial where nobody can fall onto its blade.

History and evolution



A dial painted on a limestone flake, found in 2013 in the Valley of the Kings and dated to the thirteenth century BCE.

The oldest surviving sundials are Egyptian shadow clocks from the reign of Thutmose III (about 1479 to 1425 BCE). They are L-shaped bars of stone: the raised crossbar at one end faced east in the morning, its shadow fell on marks along the bar, and at noon the instrument was turned to face west. In 2013 a team from the University of Basel found another kind of dial on the floor of a workman's hut in the Valley of the Kings: a flat piece of limestone painted with a black half circle in twelve sectors, with a hole at the centre for a peg.

Greek tradition credits Anaximander of Miletus, around 560 BCE, with bringing the gnomon to Greece from Babylonian practice. Greek and Roman makers carved hemispherical dials, bowls of stone whose hour lines divided daylight into twelve parts. Those hours were unequal: a summer hour was longer than a winter one. Pliny the Elder reports two dates for the first public sundial in Rome, 293 BCE and 263 BCE. The second was taken from Catania in Sicily during the First Punic War. It had been laid out for Sicily, so it read slightly wrong in Rome, yet it served for 99 years, until a more accurate dial was set up beside it in 164 BCE.

In the eighth century the English monk Bede encouraged dials that marked the hours of prayer, and many medieval churches had a simple scratch dial cut into a stone of their south wall. A style parallel to the Earth's axis gives equal hours throughout the year. The astronomer Ibn al-Shatir built such a dial in 1371 for the Umayyad Mosque in Damascus, and European dials used the idea from at least 1446. Mechanical clocks spread across Europe from the fourteenth century, but for centuries they kept poor time and were checked and set against sundials.

A scratch dial: a peg in the central hole cast its shadow on the lines below.

Key figures

Oldest surviving sundials
Egypt, reign of Thutmose III (about 1479 to 1425 BCE)

Apparent motion of the Sun
15° per hour around the celestial pole

Tilt of the style
Equal to the latitude of the place (about 48.9° in Paris)

Equation of time
The Sun runs up to about 16 minutes fast or slow over the year

Sources

1. Ancient sundials · North American Sundial Society https://sundials.org/index.php/all-things-sundial/ancient-sundials?start=9
2. How sundials work · British Sundial Society https://sundialsoc.org.uk/all-about-sundials/how-sundials-work/
3. Pliny the Elder, Natural History, book 7 (7.212-215 on Rome's first sundials) · Attalus.org (translation) https://www.attalus.org/pliny/hn7c.html
4. Monumental Timekeepers (David Rooney) · Lapham's Quarterly https://www.laphamsquarterly.org/node/11636
5. Sundial · Wikipedia https://en.wikipedia.org/wiki/Sundial
6. History of sundials · Wikipedia https://en.wikipedia.org/wiki/History_of_sundials
7. General Solar Position Calculations · NOAA Global Monitoring Laboratory https://gml.noaa.gov/grad/solcalc/solareqns.PDF
8. The Sundial Primer: Horizontal Sundial (Carl Sabanski) · The Sundial Primer https://mysundial.ca/tsp/horizontal_sundial.html

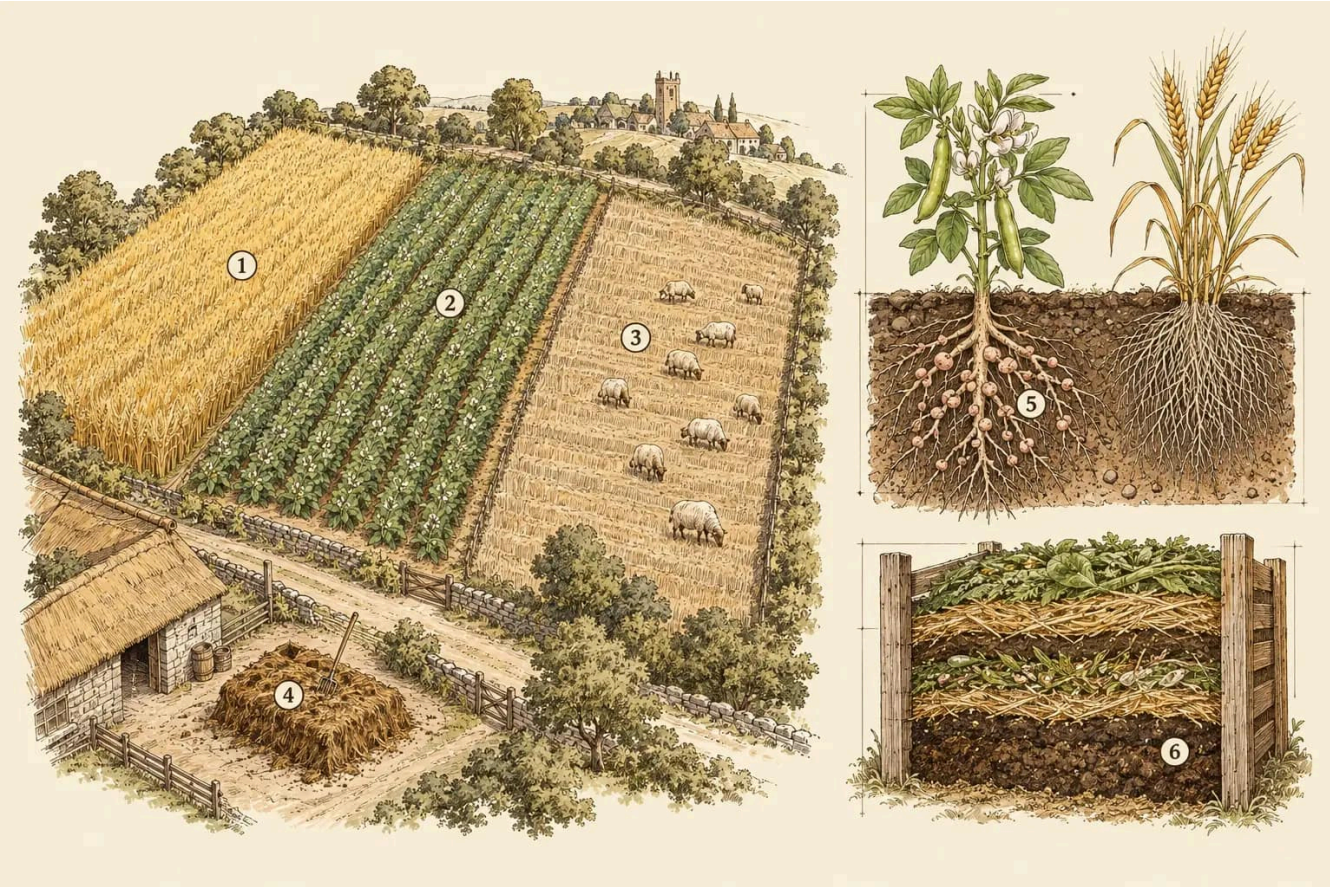
Fact-checked on 2026-10-12

Crop Rotation

Keeping fields fertile year after year

c. 700 BCE · Antiquity · Settlement

Requires: Plough (p. 58)



1 Winter wheat 2 Beans and peas 3 Fallow grazed by sheep 4 Manure heap 5 Root nodules on a bean 6 Layers of a compost heap

Crop rotation changes what grows on a field from one year to the next, and uses fallow, manure and legumes to give back what the harvests take away. It keeps the soil fertile and starves the pests of each crop; in Europe it led from a resting year every other year to rotations with no fallow at all.

What it is

Sown with the same crop year after year, a field tends to yield less unless its nutrients are put back. The plants draw the same nutrients from the same soil, and the pests of that crop find a host waiting for them each spring. Crop rotation changes what grows on each piece of land from year to year, in a planned cycle.

It goes with fallow, a season without a crop; with manure and compost, which return dung and plant waste to the soil; and with legumes such as beans, peas and clover, which add nitrogen from the air. The plate shows a three-field farm and its manure heap. On the right, a bean root is drawn beside a wheat root, above a compost heap cut open.

How it works

Besides water and air, plants need mineral nutrients from the soil, three of them in large amounts. Nitrogen builds proteins and leaves; a cereal short of it turns yellow. Phosphorus serves roots and seeds. Potassium keeps water in the cells and stems upright. Every sack of grain that leaves the farm takes some of each away.

Nitrogen runs short first, although the air is four-fifths nitrogen gas, because plants cannot use the gas. Legumes can, with help from soil bacteria called rhizobia. The bacteria settle in small swellings on the roots, the nodules, and turn nitrogen from the air into ammonia; the plant makes protein from it and feeds the bacteria with sugars in return. When the roots and stems rot, or the whole crop is ploughed in green, much of that nitrogen passes to the next crop. An established stand of red or white clover can fix roughly 85 to 225 kg of nitrogen per hectare in a year, a short or poor crop far less.

Nodules on a pea root. A working nodule is pink or red inside.

Phosphorus and potassium cannot come from the air; they return with manure, compost, urine and ashes.

Changing crops also slows pests and diseases that attack a single plant family: without their host for a few years, most of them decline. Some last far longer. The spores of clubroot, a disease of cabbages and turnips, can stay in the soil for up to 20 years, and onion white rot for at least 15, so infected ground is best kept free of their hosts. Fallow adds no nitrogen, but lets the farmer plough out weeds and gives grazing.

How to build

Tools: a spade or plough, a fork and planks for a bin.

Divide the ground. Mark out four plots of equal size and sort the crops into four groups, keeping related plants together: legumes (peas, beans); cabbages, kale, turnips and radishes; potatoes and tomatoes; onions and roots (leeks, carrots, beetroot, parsnips).

Move each group one plot on every year. A common order is legumes, cabbages, potatoes, then onions and roots. Cabbages follow legumes to use the nitrogen left behind.

Sow green manure on bare ground. After an early harvest, sow a green manure and dig it in while still soft, a few weeks before the next crop. Clover, vetch and field beans are legumes: sow them where cabbages come next, not where peas and beans are due.

Build the compost heap. On bare soil in half shade, set up a bin about one metre each way. Alternate layers about 15 cm thick of soft green material (grass, vegetable waste, fresh manure from grazing animals) and dry brown material (straw, dead leaves, cardboard), with at least as much brown as green. Add a little soil now and then; keep the heap as damp as a wrung-out sponge.

Turn it and check the heat. Push a long thermometer into the centre. A heap that holds 55 °C or more for several days kills many germs and weed seeds, but only the core gets that hot, so each time it cools, fork the outside into the middle and let it heat again. The compost is ready when dark, crumbly and earthy, after a few months to a year or more.

A heap that works well steams on a cold morning.

Use manure with care. Spread manure from cattle, horses, sheep, goats or poultry in autumn and dig it in, never onto growing plants.

> **Safety.** Fresh manure carries germs such as *E. coli* and *Salmonella*. Manure that looks well rotted, and garden compost made with it, may still hold them, because a home heap never heats evenly: treat both as raw manure. Spread them at least 120 days before harvesting crops whose edible part touches the soil or can be splashed with soil by rain or watering, such as lettuce, carrots or strawberries, and at least 90 days before other crops. Never put dog, cat, pig or human waste on vegetable beds or in their compost. Wash your hands with soap after handling manure or compost and before touching food, and wash produce in drinking water. Pregnant women, young children, older people and anyone with a weak immune system should not eat raw vegetables from manured ground.

History and evolution

Nitrogen isotopes in charred grain from 13 Neolithic sites, from Greece to Britain, show that farmers manured their crops from about 6000 BCE.

Hesiod's advice on fallow, around 700 BCE, is one of the earliest written accounts to survive and gives this plate its date. Varro, in 37 BCE, describes lupins or beans ploughed in on thin soil as they begin to pod, in place of dung. Columella, a century later, rated lupins ploughed in as good as the best manure, but doubted that beans grown for seed enriched the land.

In China, the Qimin Yaoshu, a farming manual finished around 544 CE by Jia Sixie, says millet fields must change crop each year and names mung and adzuki beans as the best crops to precede millet.

Between the Loire and the Rhine, many Frankish estates moved in the late eighth and ninth centuries from two courses, half the land resting each year, to three: winter grain, then oats, barley, peas and beans sown in spring, then fallow. Spring sowing needs summer rain, so the system stayed north of the Alps.

Fodder crops later replaced fallow. The eighteenth-century Norfolk four-course rotation, associated with Charles Townshend, grew wheat, turnips, barley and clover in turn. The economic historian Robert Allen credits nitrogen-fixing plants with about half the rise in English grain yields from the Middle Ages to the Industrial Revolution.

In 1838 Jean-Baptiste Boussingault found that clover and peas gained nitrogen in a soil without organic matter, while wheat and oats did not. In 1886 Hermann Hellriegel and Hermann Wilfarth traced the gain to the root nodules and their microbes, and in 1888 Martinus Beijerinck isolated the bacterium.

Sheep penned on turnips eat the crop where it grows and manure the ground for the barley that follows.

Key figures

Early evidence of manuring

Neolithic Europe, from about 6000 BCE (nitrogen isotopes in grain)

Three-course rotation

Frankish lands, late 8th–9th century; fallow cut from half to a third of the land

Nodule bacteria shown to fix nitrogen

Hellriegel and Wilfarth, 1886; published 1888

Early written advice on fallow

Hesiod, Greece, about 700 BCE

Nitrogen fixed by established clover

Roughly 85–225 kg per hectare per year

Sources

1. Hesiod, Works and Days, lines 458–464 (trans. H. G. Evelyn-White) · Theoi Classical Texts Library https://www.theoi.com/Text/HesiodWorksDays.html
2. Varro, On Agriculture, Book I (trans. W. D. Hooper and H. B. Ash) · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Varro/de_Re_Rustica/1*.html
3. Columella, On Agriculture, Book II (trans. H. B. Ash) · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Columella/de_Re_Rustica/2*.html
4. Manure used by Europe's first farmers 8,000 years ago (Bogaard et al., PNAS 2013) · University of Oxford via ScienceDaily https://www.sciencedaily.com/releases/2013/07/130716134740.htm
5. Millet: Original Chinese Staple (on the Qimin Yaoshu) · Science and Technology Daily https://www.stdaily.com/web/English/2026-05/25/content_522073.html
6. Agricultural technique, in A. Verhulst, The Carolingian Economy · Cambridge University Press https://www.cambridge.org/core/books/carolingian-economy/agricultural-technique/BA332C43E77E49855C580F1276F12809
7. Lynn White Jr., Technology in the Middle Ages (Technology in Western Civilization, vol. 1, 1967, excerpt) · Manchester University (course reading) https://users.manchester.edu/FacStaff/SSNaragon/Kant/LP/Readings/White,%20Plow.html
8. Norfolk four-course system · Wikipedia https://en.wikipedia.org/wiki/Norfolk_four-course_system
9. The Nitrogen Hypothesis and the English Agricultural Revolution: A Biological Analysis (R. C. Allen, 2008) · Journal of Economic History, Cambridge University Press https://www.cambridge.org/core/journals/journal-of-economic-history/article/nitrogen-hypothesis-and-the-english-agricultural-revolution-a-biological-analysis/7B2406F0F800AA11E4843EDB58D558C6
10. Utilisation biologique de l'azote de l'air : repères chronologiques · Encyclopædia Universalis https://www.universalis.fr/encyclopedie/utilisation-biologique-de-l-azote-de-l-air-reperes-chronologiques/
11. Prof. Dr. Hermann Hellriegel · Anhalt University of Applied Sciences https://www.hs-anhalt.de/en/life/bernburg/campus/history/prof-dr-herrmann-hellriegel.html
12. Is Nitrogen Fixation Oversold with Legume Cover Crops? · University of Nebraska–Lincoln, CropWatch https://cropwatch.unl.edu/2016/nitrogen-fixation-oversold-legume-cover-crops
13. Crop rotation · Royal Horticultural Society https://www.rhs.org.uk/vegetables/crop-rotation
14. Club root · Royal Horticultural Society https://www.rhs.org.uk/disease/club-root
15. Onion white rot · Royal Horticultural Society https://www.rhs.org.uk/disease/onion-white-rot
16. Aged manure is not composted manure · University of Minnesota Extension https://blog-crop-news.extension.umn.edu/2022/02/aged-manure-is-not-composted-manure.html
17. Composting · Royal Horticultural Society https://www.rhs.org.uk/soil-composts-mulches/composting
18. Composting Manure and Other Organic Materials (NebGuide G1315) · University of Nebraska–Lincoln Extension https://extensionpubs.unl.edu/publication/g1315/na/pdf/view
19. Guidelines for Using Manure on Vegetable Gardens (Bulletin 2510) · University of Maine Cooperative Extension https://extension.umaine.edu/publications/2510e/

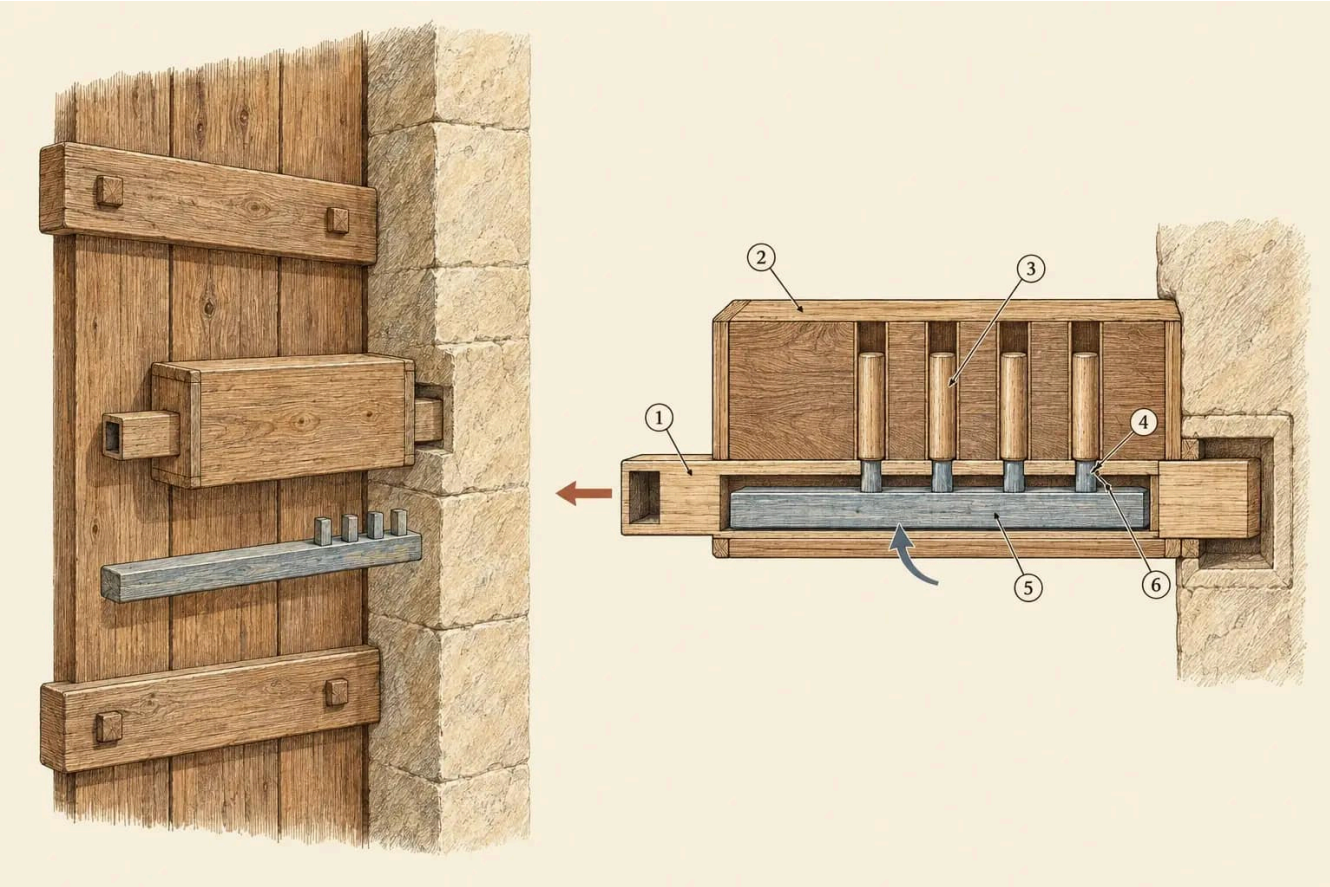
Fact-checked on 2026-10-14

Lock & Key

A bolt that only its key frees

c. 700 BCE · Antiquity · Settlement

Requires: Stone Tools (p. 5)



1 Bolt 2 Lock case 3 Pins 4 Holes in the bolt 5 Key 6 Pegs of the key

A lock holds a bolt in place until a key of the right shape releases it. Wooden pin locks were in use in the ancient Near East, and the same principle, refined in the nineteenth century, works in most door cylinders today.

What it is

A lock keeps a door, a lid or a chain closed, and a key-operated lock is meant to open only with the matching key. Every key-operated lock has the same three parts: a bolt that does the holding, something that blocks the bolt, and a key whose shape removes the block.

The plate shows the wooden pin lock often called the Egyptian lock. It needs no metal and no spring, yet it already works like a modern pin-tumbler cylinder.

How it works

The lock case is a block of wood fixed to the inside of the door. A square bolt slides through a tunnel in its lower part, and its end enters a socket in the doorpost. The bolt is hollow, and the top wall of the bolt has a row of holes.

Above them, loose wooden pins hang in vertical holes in the case. When the bolt is pushed home, the pins drop by their own weight into the holes and lock it.

The key is a long flat bar carrying pegs that match the holes. The owner slides it into the hollow of the bolt and lifts it. The pegs push the pins up until their lower ends are flush with the top of the bolt, and the bolt, with the key still inside it, can be drawn back. A key with a peg out of place leaves a pin in its hole.

Later locks used other blocking parts. A warded lock has fixed obstacles, the wards, around the path of the turning key, and only a key with cuts in the right places can turn far enough to throw the bolt. A lever lock has a stack of pivoting levers that must each be lifted to exactly the right height before the bolt can pass.

The modern pin-tumbler cylinder keeps the idea of pins that the key must lift to a set height. A brass plug turns inside a fixed housing. Five or six pairs of pins, pushed down by small springs, cross the boundary between them and stop the plug from turning. The notches on the key lift each pair so that the gap between the lower pin and the upper pin lies exactly on that boundary, the shear line, and the plug turns.

In a warded lock, the slots cut in the key's bit let it turn past the fixed wards and throw the bolt.

How to build it

A wooden pin lock makes a good weekend project for a box or a cabinet. Anyone can open it with a little patience, so treat it as a demonstration piece.

Make the bolt. Take a hardwood bar 40 mm wide, 45 mm high and 40 cm long. Plough a channel 20 mm wide and 30 mm deep into its underside, starting from the inner end and running well past the middle, then glue a thin strip under it to close the channel into a tunnel. The 15 mm of wood left above the channel is the top wall. Drill three or four holes, 10 mm across, through that wall at uneven spacings.

Make the case. Build a block around a square tunnel that the bolt can slide through, either by drilling and chiselling it out or by gluing the block up from four boards around the bolt. With the bolt in its locked position, drill down through the top of the block into the bolt's holes so that every hole lines up. Cut a 10 mm dowel pin for each hole and glue a short collar of thicker dowel near its top, so that it can fall through the top wall of the bolt and no further: its lower end must stop flush with the roof of the channel, or the key will not go in. Widen the top of each hole in the case to take the collar, then glue a cap over the block so the pins stay inside.

Make the key. Plane a flat bar about 10 mm thick that slides freely in the channel. Glue dowel pegs into it at the same spacings as the holes, each standing 15 mm tall, exactly the thickness of the top wall; bar and pegs together leave 5 mm of clearance under the roof as the key slides in. When the key bar is lifted against the roof, the pegs fill the holes and push the pins up until they are just clear of the bolt. Leave room above the collars so the pins can rise that far.

Fit and test. The pins work by gravity, so mount the case on an upright surface, such as the inside of a cabinet door, with the pins hanging straight down, and cut the socket for the bolt in the frame. Either work the lock from the inside or cut a hand opening beside it. Sand the pins until they drop freely and wax the bolt.

> **Safety.** Clamp the work before sawing or drilling, keep both hands behind the cutting edge of chisels, and wear eye protection when using a drill or a router. Never fit a homemade lock to a door that people may need to open in a hurry, such as a fire exit or a bathroom.

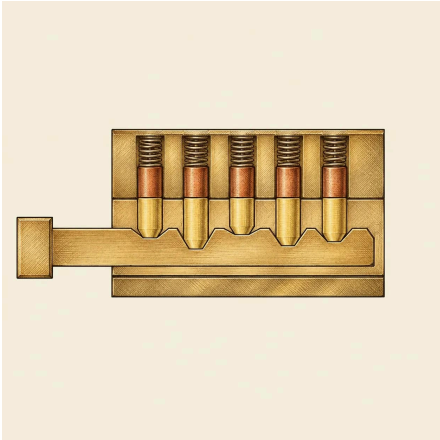
History and evolution

Locks are hard to date because wood rarely survives. The French excavator Paul-Émile Botta found, in the Assyrian palace of Sargon II at Khorsabad, a gate closed by a large wooden lock of the pin type, and Austen Henry Layard recovered a bronze key of the same shape at Nineveh. Popular histories call the Khorsabad lock 4,000 years old, but the palace dates from the eighth century BCE, and the archaeologist D. T. Potts traced that figure to a misread catalogue. He also argued that older Mesopotamian omen texts already name the bolt, the pins and the lock, which would make the design older than any surviving example. The name “Egyptian lock” comes from its long use in Egypt, where it was still in daily use in the nineteenth century.

Roman key rings opened small caskets; the slots in the bit let it pass the wards inside the lock.

Greek writers knew keys with several teeth, and Roman smiths made the lock in iron and the key in bronze, added wards and built padlocks. Small Roman keys were often made as finger rings, probably to open caskets and jewel boxes rather than doors; Roman clothes had no pockets, so a key worn on the hand was both safe and at hand. Such rings turn up in numbers on Roman sites in Britain, notably in London and Colchester, where a wooden box was buried in a grave with its key ring still in the lock. Medieval locks were mostly warded, often richly decorated, and easy to pass with a thin tool.

In England, Robert Barron patented the double-acting lever lock in 1778. Joseph Bramah patented a cylindrical lock with sliding plates in 1784 and later offered a reward to anyone who could pick the one in his London shop window; accounts date the challenge to 1790, while the challenge board kept at the Science Museum is dated 1801. The American locksmith Alfred Hobbs finally opened it during the Great Exhibition of 1851, after about 51 hours of work over 16 days. In 1818 Jeremiah Chubb added a detector to the lever lock: a lever lifted too high jammed the mechanism and showed that someone had tried to pick it. Abraham Stansbury patented a pin-tumbler lock in England in 1805, and Linus Yale Sr. patented his own versions in the United States in the 1840s. His son, Linus Yale Jr., patented a pin-tumbler lock with a round key in 1861, then in 1865 a lock opened by a thin, flat steel key cut along its edge. The cylinder locks on most doors today descend from that design.



In a pin-tumbler cylinder, the key brings every gap between lower and upper pin onto the shear line.

Key figures

Oldest lock of this kind found in place
Palace of Sargon II at Khorsabad, Assyria, 8th century BCE

Bramah's challenge lock
Patented in 1784, offered with a reward from 1790 or 1801 (sources differ), picked in 1851 after about 51 hours of work

Chubb's detector lock
1818

Flat pin-tumbler key
Patented by Linus Yale Jr. in 1865

Sources

1. Lock and key in ancient Mesopotamia (D. T. Potts, Mesopotamia 25, 1990) · Università di Torino, Mesopotamia https://www.yeshiva.org.il/midrash/pdf/wiki/potts_1990_-_lock_and_key_in_ancient_mes.pdf
2. Lock and key · Encyclopedia.com (Gale) https://www.encyclopedia.com/science-and-technology/technology/technology-terms-and-concepts/lock-and-key
3. Ring (Roman bronze key ring, 547-1871) · Victoria and Albert Museum https://collections.vam.ac.uk/item/O377794/ring/
4. Challenge board for Bramah padlock, 1801 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co50474/challenge-board-for-bramah-padlock
5. Improvement in locks, US patent 48,475 (Linus Yale Jr., 1865) · Google Patents https://patents.google.com/patent/US48475A/en
6. Lock and key · Wikipedia https://en.wikipedia.org/wiki/Lock_and_key
7. An Account of the Manners and Customs of the Modern Egyptians (E. W. Lane, 1836), ch. 1 · Project Gutenberg https://www.gutenberg.org/ebooks/70796
8. Lock (Encyclopædia Britannica, 11th edition, 1911) · Wikisource https://en.wikisource.org/wiki/1911_Encyclop%C3%A6dia_Britannica/Lock
9. Working model of Egyptian pin lock (1966-364) · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co50403/working-model-of-egyptian-pin-lock

Fact-checked on 2026-10-12

III

Crafts & cities

Potter's Wheel

Shaping clay by rotation

c. 4,000 BCE · Prehistory · Crafts & cities

Requires: Pottery (p. 22)

1 Wheel head 2 Clay vessel 3 Vertical shaft 4 Collar bearing 5 Flywheel 6 Pivot bearing

A potter's wheel is a heavy disc that spins on a vertical axis, so that clay set at its centre can be shaped evenly all round by the potter's hands. It began in the Near East as a slow turntable more than six thousand years ago; the fast wheel, which stores enough momentum to throw a pot from a lump of clay, followed.

What it is

A potter’s wheel is a round, flat head mounted on a vertical shaft that turns freely. The potter sets a lump of wet clay at its centre, spins it, and presses the clay with wet hands or a tool. Because every point of the clay passes under the hands in turn, a single steady pressure shapes the whole circumference at once.

There are two kinds. A slow wheel, or tournette, is turned by hand in short pushes. It helps a potter to even out a pot built from coils of clay and to finish its rim. A fast wheel keeps turning on its own because it is heavy, and it is fast enough to throw a pot: to raise it in a few minutes from a solid lump, using only the spin and the potter’s hands.

The two kinds overlap, and archaeologists now distinguish the machine from the forming technique used on it. The plate shows a kick wheel, a fast wheel driven by the foot, of a type used in European workshops before electric motors.

How it works

The kick wheel has one vertical shaft, usually of iron. At the top it carries the wheel head, at waist height for a seated potter. Near the floor it carries the flywheel, a thick, heavy disc of wood, stone or concrete. The shaft runs in two bearings: a collar just below the head that keeps it upright, and a pivot at the bottom, where its pointed or rounded end turns in a cup and carries the weight.

The potter sits on a bench behind the wheel and pushes the flywheel round with one foot. A heavy wheel takes several kicks to get going, but once it spins it stores energy and keeps turning while the hands work. The heavier the flywheel, and the more of its weight lies near the rim, the longer it keeps its speed. Most potters spin the wheel anticlockwise; in Japan the tradition is clockwise.

Throwing follows a fixed order. First the clay is centred: pressed with both hands until it runs true and no longer wobbles. The potter then opens it by pushing the thumbs down into the middle, leaving a floor, and draws the clay out into a thick ring. Pulling up with one hand inside and one outside raises the wall, thinner and taller each pass. Finally the shape is swelled or narrowed, the rim is smoothed, and the pot is cut from the head with a wire. Hands and clay are kept wet throughout, and a wooden rib held against the turning wall smooths it and removes the excess water.

The stages of throwing: centring, opening, raising a cylinder and shaping the pot.

Tools of the thrower: a wooden rib to smooth the wall, a wire to cut the pot off, a sponge, a pointed stick and a trimming loop.

Clay keeps a record of how a pot was made. The ridges and marks left by fingers and tools on the inner and outer wall, and the way the clay is layered inside it, let archaeologists tell a pot thrown from a lump on a fast wheel from one built of coils and only shaped on a turning wheel. Many early wheel-made pots turn out to be of the second kind, which is how the slow growth of throwing can be traced. Tools leave traces as well: a rib leaves a smooth band, and a wire drawn under a pot that is still turning leaves a curved, shell-like pattern on its base.

How to build it

A kick wheel can be built in a workshop from timber, a steel shaft, two bearings and a home-cast flywheel. The Mother Earth News plan listed in the sources uses a frame about 75 cm (30 inches) on each side, which also carries the seat. The finished flywheel weighs roughly 60 to 75 kg, so choose bearings, hub and fixings rated for that load, or follow a complete published plan.

Build the frame. Bolt a cube-shaped frame of 10 × 10 cm posts and 5 × 10 cm rails, with a cross-rail just below the top for the upper bearing and a sturdy rail at the bottom for the lower one. Fix a plank seat at the back and a footrest at about knee height on the kicking side.

Fit the shaft and bearings. Use a straight steel shaft about 25 mm in diameter. Bolt a flange bearing flat onto the bottom rail to carry the weight, and a second flange bearing flat under a support on the top rail to keep the shaft upright; lock both to the shaft with their set screws. Self-aligning, sealed bearings are easiest. Check with a plumb line that the shaft is exactly vertical and that it turns without touching any timber.

Cast the flywheel. Cut a plywood disc about 60 cm across with a hole at its exact centre, pass the shaft through it and bolt a steel hub or collar, fixed to the shaft, to the plywood. Wrap a strip of roofing felt or sheet metal round the disc to form a mould 15 to 18 cm deep, fix bolts through the plywood so that they stand up into the mould, and fill with concrete 10 to 12 cm thick, so that it sets round the hub. Leave it at least two days before moving it, keep it damp while it cures, and do not spin it until the concrete has reached the strength its maker gives for loading.

Mount the head. Fit the shaft with its flywheel into the bearings and fix a wheel head of wood or metal, 25 to 30 cm across, to the top. Spin the wheel by hand and correct any wobble before you put clay on it.

> **Safety.** The flywheel is heavy and keeps turning for a long time: keep fingers, feet and loose clothing out of the gap between wheel and frame, and never stop it by grabbing the rim. Never step or stand on the flywheel, which can damage its mounting. Wear eye protection and gloves when mixing concrete, which is caustic. Clay dust contains silica: clean the wheel and floor wet, never by dry sweeping.

History and evolution

People made pots by hand for many thousands of years before the wheel. Some of the earliest well-studied rotary devices for pottery come from the southern Levant, in the second half of the fifth millennium BCE; claims for earlier wheels elsewhere are debated. Research by Valentine Roux and colleagues shows that potters there coiled their vessels and then shaped them on the wheel, and that only a few specialists did this work, for fine bowls with a special status. On this view the early wheel spread for prestige more than for speed.

A stone turntable in two parts: the upper disc turns on its pivot, seated in the socket of the lower stone.

By the Uruk period in Mesopotamia, around 3400 BCE, the fast wheel was in use, and a potter's wheel from Ur has been dated to about 3100 BCE. The technique reached the Aegean during the third millennium BCE, although whether it came by way of Crete is debated, and Britain only in the first century BCE. In the Americas, potters made fine ware without any wheel until European contact. Egyptian myth has the god Khnum shaping the first humans on a potter's wheel.

When the kick wheel, with its long shaft and foot-driven flywheel, first appeared is uncertain; some ancient wheels were turned by hand or with a stick. Later wheels used a treadle and crank to turn the up-and-down motion of the leg into rotation, and electric motors now drive many wheels.

Key figures

Early wheel-shaped pottery
Southern Levant, second half of the 5th millennium BCE

Fast wheel in Mesopotamia
In use by the Uruk period, c. 3400 BCE

Potter's wheel from Ur
Dated to about 3100 BCE

Reached Britain
1st century BCE

Sources

1. Unveiling the sign value of early potter's wheels based on a 3-D morphometric analysis of Late Chalcolithic vessels from the southern Levant (Roux and Harush, 2022) · Bar-Ilan University research portal (Journal of Archaeological Science: Reports) https://cris.biu.ac.il/en/publications/unveiling-the-sign-value-of-early-potters-wheels-based-on-a-3-d-m/
2. Potter's wheel · Buckinghamshire Council Heritage Portal https://heritageportal.buckinghamshire.gov.uk/theme/tbc463
3. Pottery kick wheel plans · Mother Earth News https://www.motherearthnews.com/diy/pottery-kick-wheel-plans-zmaz70ndzgoe/
4. Potter's wheel · Wikipedia https://en.wikipedia.org/wiki/Potter%27s_wheel
5. A preliminary study of rotation velocity regulation in pottery wheel-throwing: fieldwork with Indian potters using the low-inertia kick-wheel (Gandon et al., 2021) · HAL open archive (Journal of Archaeological Science: Reports) https://amu.hal.science/hal-03475151
6. The Ancient Greek potter’s wheel: experimental archaeology and web applications for velocity analysis (Neth and Hasaki, 2021) · Interdisciplinaria Archaeologica https://iansa.eu/papers/IANSA-2021-02-neth.pdf
7. Ceramics Unit 8: Wheel Throwing · Colorado State University Extension (4-H) https://co4h.colostate.edu/wp-content/uploads/sites/27/2026/03/Ceramics-Unit-8-Wheel-Throwing.pdf
8. Weights of clay needed for ware sizes · Lakeside Pottery https://www.lakesidepottery.com/HTML%20Text/Tips/weights-of-clay-needed-for-ware-size.pdf
9. Water of plasticity · Digitalfire Reference Library https://digitalfire.com/test/wopl

Fact-checked on 2026-10-12

Bronze

Copper and tin, harder together

c. 3,300 BCE · Prehistory · Crafts & cities

Requires: Pottery (p. 22), Control of Fire (p. 9), Charcoal (p. 62)

Leads to: Battery (p. 234), Gears (p. 149), Iron Smelting (p. 133), Piston Pump (p. 157)

1 Crucible of molten bronze 2 Pot bellows 3 Clay nozzle (tuyère) 4 Outer clay mould 5 Clay core 6 Pouring cup and channel

Bronze is copper alloyed with a little tin, usually about a tenth. It is harder than copper, melts at a lower temperature and fills a mould well, and from the fourth millennium BCE it gave its name to an age of tools, weapons, vessels and statues.

What it is

Bronze is an alloy, a metal made of two or more elements, here mostly copper with a smaller share of tin; the classic recipe is about nine parts copper to one of tin by weight. Surviving ancient objects range from about two thirds to 95% copper, and other metals such as arsenic, lead or zinc were sometimes present.

Tin makes copper harder, so that a blade keeps its edge better. Bronze melts over a range around 950 °C, depending on the tin content, while pure copper melts at 1,085 °C; the lower temperature is easier to reach with a charcoal fire and bellows. Molten bronze also runs freely into a mould.

How it works

Pure copper is made of crystals whose layers of atoms slip easily over one another, which is why it bends and dents. Tin atoms are larger. Scattered through the copper, they jam those layers, so the metal resists bending and denting. Hammering the cold metal hardens it further, so a bronze blade could be cast, then beaten along the edge to harden it.

The tin content decides how the metal can be used. Bronze with about 10% tin was the standard for casting tools and weapons; softer bronze with about 6% was hammered into sheet. Bell metal has more than 20% tin: it is hard and rings well but breaks if dropped. Too much tin makes any bronze brittle.

Raw materials of the Bronze Age trade: a four-handled copper "oxhide" ingot and pieces of tin.

Copper and tin ores rarely occur in the same place. Copper was mined in many regions, Cyprus among the richest; tin came from far fewer places, such as Cornwall, the Taurus Mountains and Afghanistan or its neighbours. Bronze therefore depended on long trade routes, and a disruption in the tin supply could stop production far away.

A two-piece stone mould: closed, the two halves form the axe, and the metal is poured in at the narrow end.

Simple shapes such as flat axes were cast in open moulds or in two-piece moulds of stone or clay. Hollow or detailed objects could be made by the lost-wax method. The founder modelled the object in wax around a clay core, added wax rods that would become the pouring channel, and covered everything in fine clay. Baking the mould melted the wax out. Molten bronze poured into the hot mould filled the space the wax had left, and the mould was broken away once the metal had cooled. Modern art foundries still work this way: they pour bronze at well over 1,000 °C into a mould heated beforehand to several hundred degrees, so that it does not crack.

How to build it

Casting bronze means working with metal at more than 1,000 °C. Learn it in a foundry course or a school workshop with an experienced caster before trying it anywhere else. The steps below describe a small lost-wax casting.

Make the model. Shape a small object in casting wax, solid and no thicker than a finger at any point. Attach a wax rod and a wax cup at the thickest part: they will form the pouring channel.

Invest it. Fix the wax cup on a rubber sprue base, set a steel flask over it and fill the flask with an investment sold for bronze casting, a mix of plaster and silica; when the base is removed, the cup forms the pouring opening. Follow the maker's instructions for mixing, setting and drying exactly: each system has its own.

Burn out the wax. Heat the mould upside down in a kiln on the burnout schedule given for the investment, so that the wax runs out and the mould is fully dry. Pour while it is still hot: a cold or damp mould can crack or blow out metal.

Melt the metal. Use ready-made casting bronze (copper with about 10% tin) or weigh out clean copper and tin in a 9 to 1 ratio. Melt it in a clay-graphite crucible in a furnace with forced air, add the tin last if you alloy it yourself,

and skim the dross.

Pour and finish. Lift the crucible with proper tongs and pour in one steady stream until the cup is full. Leave it to cool, break off the mould, cut away the channel and file, chase and polish the surface.

> **Safety.** Molten metal causes severe burns and fires. Wear protective clothing made for molten-metal splash, a face shield over safety glasses, foundry gloves and boots, with trousers over the boots so that metal cannot run inside, and keep onlookers away. Every tool, mould and ingot must be bone dry: a drop of water under molten metal turns to steam and throws metal out. Pour over dry sand, never over concrete, and work outdoors or under strong extraction. Never melt scrap of unknown composition: brass gives off zinc fumes, and some old alloys contain lead or other toxic metals. Investment and broken moulds release silica dust: mix and break them out wet or under dust extraction, and wear a certified, properly fitted respirator for fine silica dust.

History and evolution

Copper alloyed with arsenic was made on the Iranian plateau, at sites such as Tal-i Iblis, around 3800 to 3400 BCE. Arsenical copper is hard, but its fumes are poisonous. The oldest tin bronze known so far is a foil from Pločnik in Serbia, which its excavators date to about 4650 BCE, although the context of the find has been challenged; it was probably smelted from an ore that already contained both metals. In the Near East the Bronze Age is dated from the middle of the fourth millennium BCE, at first mostly with arsenical copper; tin bronze became the usual alloy there during the third millennium. In China the Bronze Age began in the early second millennium BCE.

The Uluburun wreck, which sank off southern Turkey around 1300 BCE, shows the scale of the trade. Its hold carried about 10 tonnes of Cypriot copper, including some 350 oxhide ingots, and about a tonne of tin, roughly the ten-to-one proportion of bronze. In China, the Shang and Zhou courts had ritual vessels cast for offerings and burials, using a piece-mould method with no parallel elsewhere.

A Shang ritual cauldron of the ding type. Chinese founders cast such vessels in moulds assembled from many clay pieces.

Around 1200 BCE, wars and migrations around the eastern Mediterranean broke many trade routes; one explanation is that tin became scarce, although the evidence varies from region to region. Iron, whose ore is found almost everywhere, slowly replaced bronze for tools and weapons as smiths learned to work it. Bronze stayed in use for bells, statues, mirrors, coins and ship fittings, and today for bearings, springs and marine parts that must resist seawater.

Key figures

Classic alloy
About 9 parts copper to 1 part tin

Melting
Over a range around 950 °C, depending on the tin (pure copper: 1,085 °C)

Oldest tin bronze found
A foil from Pločnik, Serbia, dated c. 4650 BCE (disputed)

Uluburun cargo, c. 1300 BCE
About 10 t of copper and 1 t of tin

Sources

1. Tainted ores and the rise of tin bronzes in Eurasia, c. 6500 years ago (Radivojević et al., Antiquity, 2013) · Cambridge University Press https://www.cambridge.org/core/journals/antiquity/article/tainted-ores-and-the-rise-of-tin-bronzes-in-eurasia-c-6500-years-ago/496710374082FC211C512670F0A98004
2. Uluburun Shipwreck · World History Encyclopedia https://www.worldhistory.org/Uluburun_Shipwreck/
3. Metalworking techniques · Victoria and Albert Museum https://www.vam.ac.uk/articles/metalworking-techniques
4. Rodin's lost-wax casting process · North Carolina Museum of Art https://learn.ncartmuseum.org/resources/rodins-lost-wax-casting-process/
5. Jue (ritual wine vessel), Late Shang dynasty · University of Arkansas Museum https://scholarworks.uark.edu/uamumaa/2
6. Bronze · Wikipedia https://en.wikipedia.org/wiki/Bronze
7. Cu-Sn system: calculated phase diagram and invariant reactions (after Shim, Oh, Lee and Lee, 1996) · National Institute of Standards and Technology https://www.metallurgy.nist.gov/phase/solder/cusn.html
8. C90700 tin bronze: data sheet · Wieland Concast, with physical data from the Copper Development Association https://www.concast.com/files/C90700.pdf
9. C91100 tin bronze: data sheet · Wieland Concast, with physical data from the Copper Development Association https://www.concast.com/files/C91100.pdf
10. C91300 bell metal: data sheet · Wieland Concast, with physical data from the Copper Development Association https://www.concast.com/files/C91300.pdf
11. Experimental design of the Cu-As-Sn ternary colour diagram (Radivojević et al., 2018) · Journal of Archaeological Science 90 https://doi.org/10.1016/j.jas.2017.12.001
12. Arsenic bronze: dirty copper or chosen alloy? A view from the Americas (Lechtman, 1996) · Journal of Field Archaeology 23 https://doi.org/10.1179/009346996791973774
13. From the object to the mould: is there a connection between microstructure of a cast bronze object and its mould material used? (Jochum Zimmermann, Künzler Wagner and Osimitz, 2012) · EXARC Journal https://exarc.net/ark:/88735/10076
14. Castability control in metal casting via fluidity measures (Dewhirst, PhD thesis, 2008) · Worcester Polytechnic Institute https://web.wpi.edu/Images/CMS/A_2.pdf
15. Effect of composition and pouring temperature of Cu-Sn on fluidity and mechanical properties of investment casting (Slamet et al., 2024) · Archives of Foundry Engineering 24(3) https://doi.org/10.24425/afe.2024.151290

Fact-checked on 2026-10-12

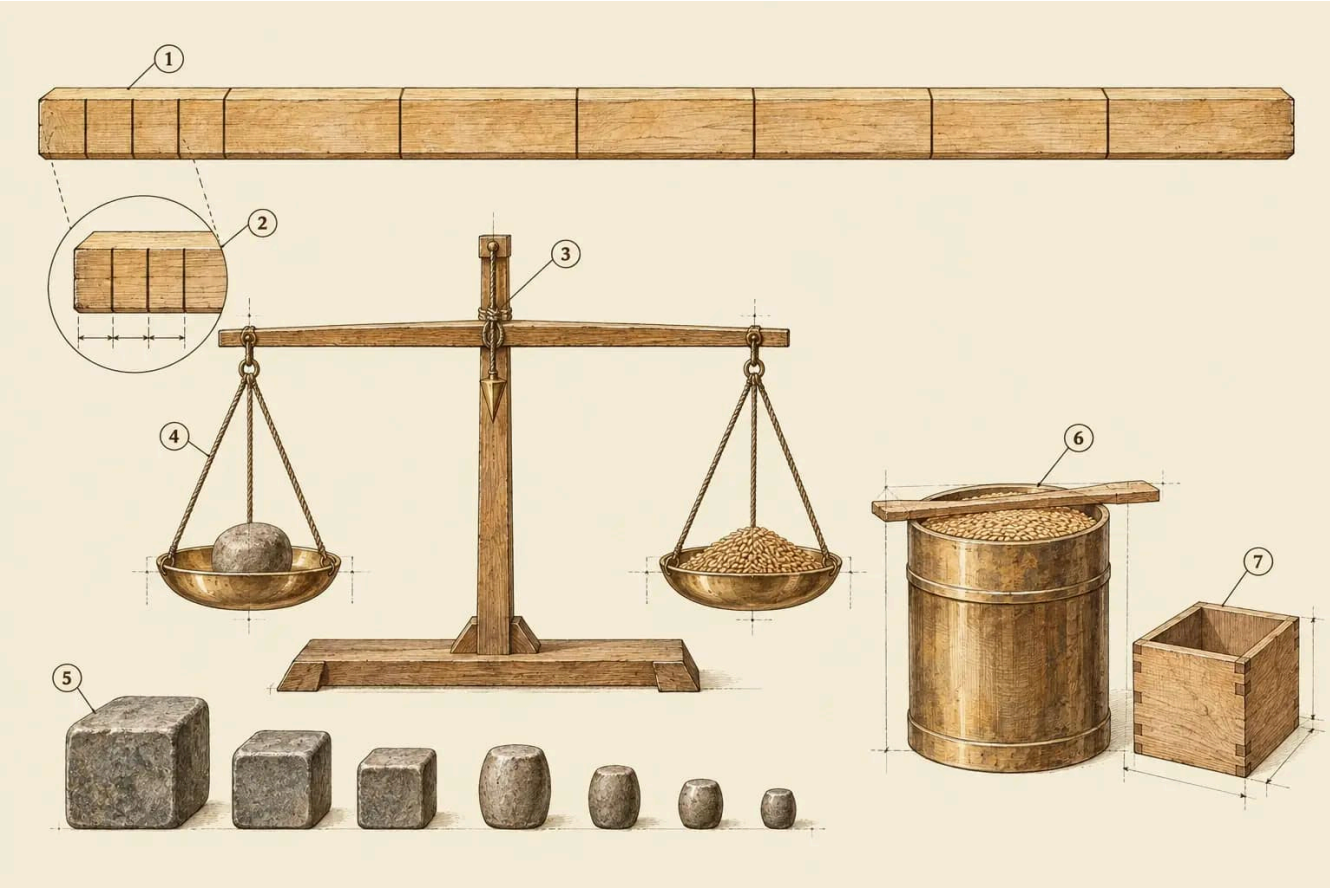
Measures and standards

The cubit, the balance and the metre

c. 3,000 BCE · Antiquity · Crafts & cities

Requires: Stone Tools (p. 5), Rope & Cordage (p. 13), Pottery (p. 22)

Leads to: Aqueduct (p. 141), Celestial Navigation (p. 205), Oral rehydration (p. 360), Portland Cement (p. 250), Thermometer and barometer (p. 217)



1 Cubit rod, the master of length 2 First palm divided into four fingers 3 Beam hung at its exact centre, with pointer
4 Pan hung on cords 5 Set of stone weights 6 Grain measure with its strike-stick 7 Cube made from the rod's unit

A measure is a length, weight or volume agreed in advance, and a standard is the object that holds it: a rod, a set of stones or a vessel, kept safe and copied. Egypt measured in cubits, palms and fingers, balance weights spread from Mesopotamia from about 3000 BCE, and the same work of keeping and copying references led to the metre and the kilogram.

What it is

A measure lets people compare things that are not side by side: beams ordered from a distant forest, grain sold by volume, copper sold by weight. The units are arbitrary. What matters is that every copy agrees with every other.

A standard is the object that fixes a unit, such as a rod, a weight or a vessel. An authority keeps it, and working copies are checked against it. The plate shows the basic tools as a rebuilder could make them: a cubit rod, an equal-arm balance with stone weights, a grain measure and a box that turns a length into a volume.

How it works

Length. The oldest units come from the body: forearm, palm, finger, foot. Since bodies differ, a rod fixes the chosen length. The Egyptian royal cubit had 7 palms of 4 fingers, 28 fingers in all, and surviving rods measure about 52 to 53 cm. Kha, an overseer of works buried at Deir el-Medina, received a gilded cubit rod from the king but probably worked with a folding one found in the same tomb. Two rods are compared without numbers, side by side with ends flush.

Weight. An equal-arm balance compares two loads. The beam hangs from its centre and the pans hang at equal distances on either side, so the beam is level only when both pans hold the same weight. Weights are pieces of hard stone or metal ground until they balance a reference, often flattened underneath so they do not roll.

In the Indus cities of the third millennium BCE, weights were mostly chert cubes. A 1938 study of those from Mohenjo-daro found a unit of about 0.86 g and weights of 1, 2, 4, 8, 16, 32 and 64 units, then larger steps such as 160, 200, 320 and 640. The commonest were 16 and 32 units, about 13.7 and 27.4 g. In several common sizes, individual weights strayed from their mean by only one to two per cent on average.

Indus weights were cubes of banded chert; in the smaller sizes, each was about half the one before it.

Volume. Grain, oil and wine were sold with vessels of agreed size, and dry goods were levelled with a straight stick, the strike. A volume can also come from a length: the Roman amphora used as a unit was a cubic foot, and the first kilogram was the mass of a cubic decimetre of water.

How to build

You need a straight, seasoned hardwood bar about 60 cm long, a second bar for the beam, strong cord, two identical bowls, hard fine-grained stones, files, a flat grinding stone, a marking knife, dividers and thin boards.

Choose and copy the master. Any length can be the unit: a forearm, or a metre rule. Cut two fine lines across the rod at its ends; lines last longer than end faces, which wear. Keep this master dry and use it only to check copies. To copy it, lay a blank rod against it, transfer each mark with the knife, then turn the copy end for end, line up its first mark with the master's and compare the others: a mark that no longer matches shows an error.

Divide without arithmetic. For 7 palms, open the dividers to a guess and step them seven times along the rod. If the last step misses the end line, adjust and start again until it lands on it. Divide a palm into 4 fingers the same way.

Make the balance. Hang the beam by a cord or pin at the middle of its top edge, so that most of its mass lies below the pivot and it returns to level. Hang the pans from notches at equal distances from the centre, fix a pointer and scrape the heavier end until the empty beam hangs level.

Check it by swapping the loads. Balance a stone against sand, then swap the stone and the sand. If the beam stays level, the arms are equal. If not, move one notch slightly, level the empty beam again and repeat the test. Then add small objects to one pan and note the smallest that moves the pointer: weights checked on this balance are no truer than that.

Make weights from a reference. Even an imperfect balance copies a weight by substitution: balance the reference with sand, take it out, and grind a new stone until it balances the same sand. For a series in which each weight is

twice the one before, grind a stone to match two units together, then one to match that stone plus the two units, and so on. Check large weights against the sum of the small ones, as errors add up.

Get a volume from the rod. Build an open box whose inside length, width and depth are each one palm. Its water content can mark a level on a vessel, or be weighed to tie a weight to your length; the first kilogram also fixed the water's temperature. For grain, pour loosely, do not shake, and level with the strike.

> **Safety.** Grinding stone makes fine dust that can contain silica: grind wet, wear eye protection and a P2 or P3 dust mask, and clean up with water, not a broom. Clamp the work when cutting with a knife. Do not make weights of lead. Home-made measures are not legal for trade: in most countries, selling by weight or volume requires verified instruments.

History and evolution

Balance weights appear in Mesopotamia and Egypt around the start of the third millennium BCE. Mesopotamian texts define the shekel, about 8.4 g, as 180 grains of barley, and many weights are polished stones, some carved as ducks or lions. A University of Göttingen team compared 2,274 weights from 127 sites dated about 3000–1000 BCE. Similar units spread from Mesopotamia to Europe, while the Indus had its own system. Around the mean of each unit, the weights scatter with a coefficient of variation (standard deviation divided by the mean) of about 5 to 6 per cent. When the team made 100 copies on replica balances, each from a randomly chosen model, the copies scattered by about as much, 5.4 per cent, and the authors argue that merchants kept the units in step by checking their weights against each other, without a central authority.

A public measuring table: a buyer filled a cavity, then drained it through the hole below.

Towns still kept official references. At Pompeii a stone table in the forum held cavities sized to the local Oscan measures; after Augustus unified Roman measures, the council had them enlarged and four more cut. Henry VII of England had a bronze standard yard made in 1495–1497 and sent copies to the boroughs; it proved inaccurate and was replaced around 1588.

In 1791 the Paris Academy of Sciences proposed a metre of one ten-millionth of the distance from the pole to the equator, and surveyors measured the meridian from Dunkirk to Barcelona. In 1799 a platinum metre, defined by its end faces, and a kilogram equal to a cubic decimetre of water were deposited in the French Archives. The bar soon became the unit in its own right.

In 1875 seventeen countries signed the Metre Convention, which created the International Bureau of Weights and Measures near Paris. From 1889 the metre was the distance between two lines on an X-shaped platinum-iridium bar at 0 °C, and the kilogram the mass of a platinum-iridium cylinder, with copies sent to member states. Later checks showed the copies slowly drifting from the original, by a median of about 25 micrograms in 1989–1991. The metre was redefined by krypton light in 1960 and by the speed of light in 1983. Since 20 May 2019 the kilogram has rested on the Planck constant.

The international kilogram was kept under glass bells; the metre of 1889 was a bar with an X-shaped section.

Key figures

Egyptian royal cubit

7 palms of 4 fingers, 28 in all; surviving rods measure about 52 to 53 cm

Bronze Age weights compared

2,274 weights from 127 sites, c. 3000–1000 BCE

Kilogram

A platinum-iridium cylinder from 1889; defined by the Planck constant since 20 May 2019

Indus weights (Mohenjo-daro)

Unit about 0.86 g; the commonest weights were 16 and 32 units, about 13.7 and 27.4 g

First metre and kilogram

Platinum standards deposited in the French Archives in 1799

Sources

1. Royal cubit rod inscribed with the name of pharaoh Amenhotep II (Suppl. 8647) · Museo Egizio, Turin https://collezioni.museoegizio.it/en-GB/material/S_8647
2. Cubit rod (Liverpool M13825) · Global Egyptian Museum / World Museum Liverpool https://globalegyptianmuseum.org/detail.aspx?id=4424
3. System of weights (A. S. Hemmy), in E. J. H. Mackay, Further Excavations at Mohenjo-daro (1938) · Archaeological Survey of India https://richardsproat.com/indus_weights/Hemmy-1938-weights-Mohenjodaro-Mackay.pdf
4. Hanging in the Balance: Precision Weighing in Antiquity (William B. Hafford, Expedition 47.2, 2005) · Penn Museum https://www.penn.museum/sites/expedition?p=9719
5. Bronze Age: how the market began (press release, 29 June 2021) · University of Göttingen https://www.uni-goettingen.de/en/73613.html?id=6309
6. Bronze Age weight systems as a measure of market integration in Western Eurasia (Ialongo, Hermann and Rahmstorf, PNAS 118, 2021) · Proceedings of the National Academy of Sciences https://pmc.ncbi.nlm.nih.gov/articles/PMC8271817/
7. Bronze Age Merchants Developed Measurement System · Archaeology Magazine https://archaeology.org/news/2021/06/30/210701-bronze-age-weights/
8. Roman Weights and Measures · University of Kent https://blogs.kent.ac.uk/lucius-romans/2017/12/13/roman-weights-and-measures/
9. VII.7.31 Pompeii, Mensa Ponderaria · Pompeii in Pictures https://pompeiiinpictures.com/pompeiiinpictures/R7/7%2007%2031.htm
10. Cooking the volumes (Amelia Carolina Sparavigna, 2012) · arXiv, Politecnico di Torino https://arxiv.org/abs/1201.3774
11. Exchequer standard yard of King Henry VII, 1495-1497 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co57527/exchequer-standard-yard-of-king-henry-vii-1495-1497-rules-measuring-devices-linear-standards
12. Time Line for the Definition of the Meter (William B. Penzes) · National Institute of Standards and Technology https://www.nist.gov/document/museum-timelinepdf
13. Defining the International System of Units (SI) · NIST Museum https://www.nist.gov/nist-museum/defining-international-system-units-si
14. Historical perspective: Unit of mass, kilogram · Bureau International des Poids et Mesures https://www.bipm.org/en/history-si/kilogram
15. Historical perspective: Unit of length, metre · Bureau International des Poids et Mesures https://www.bipm.org/en/history-si/metre
16. The evolution of the metre · Physics World https://physicsworld.com/a/the-evolution-of-the-metre-how-a-product-of-the-french-revolution-became-a-mainstay-of-worldwide-scientific-collaboration/
17. SM052 Analytical balance, circa 1962 · University of Malta Science Museum https://staff.um.edu.mt/rlib1/sm/balance.htm
18. Site 1149, table T17: physical properties by lithology (ODP Leg 185 Initial Reports) · Ocean Drilling Program, Texas A&M University https://www.iodp.tamu.edu/publications/185_IR/chap_04/c4_t17.htm

Fact-checked on 2026-10-13

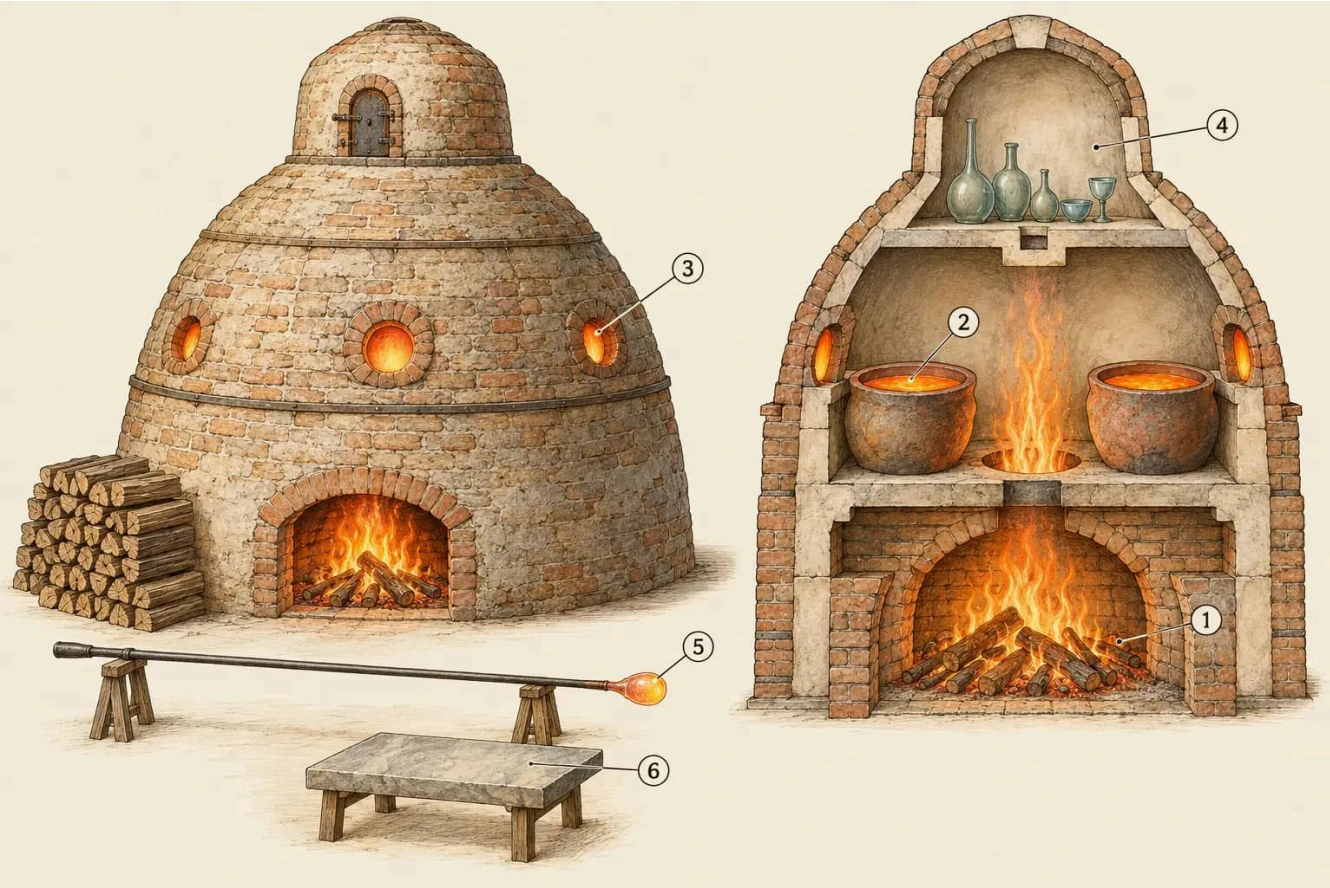
Glass

Melted sand you can see through

c. 2,500 BCE · Antiquity · Crafts & cities

Requires: Pottery (p. 22)

Leads to: Anaesthesia (p. 286), Canning & Pasteurisation (p. 242), Eyeglasses (p. 192), Incandescent Light Bulb (p. 310), Penicillin (p. 342), Photography (p. 254), Solar cell (p. 355), Thermometer and barometer (p. 217), Vaccination (p. 229)



1 Fire chamber 2 Crucible of molten glass 3 Working opening (glory hole) 4 Annealing chamber
5 Blowpipe with a gather of glass 6 Marver

Glass is sand melted with a flux such as soda and a little lime, then cooled before it can crystallise, so that it sets into a hard solid that lets light through when it is pure. Made first as beads in Mesopotamia, it became an everyday material once glassblowers in the eastern Mediterranean learned to inflate it on a pipe in the first century BCE.

What it is

Glass is a solid without crystals. When sand is melted with the right additions and the liquid cools fast enough, its atoms have no time to line up into a regular lattice. They freeze in place in a disordered network, which is why glass is hard and brittle, and why it softens gradually when heated instead of melting at one temperature. Clear glass lets light through because its ingredients absorb little visible light and a good melt holds no bubbles or crystals to scatter it.

Ordinary glass, ancient and modern, is soda-lime glass. Silica sand forms the network. Soda, from the mineral natron or from the ashes of salt-marsh plants, lowers the melting temperature to a level a wood fire can reach. Lime, often present in the sand as crushed shell, makes the glass stable so that water does not attack it.

The plate shows a round glass furnace of the kind described by Georgius Agricola in 1556, with the blowpipe and marver of the glassblower.

How it works

The furnace has three levels. Wood burns in the lowest chamber. Its flames rise through a round hole into the middle chamber, where clay pots hold the melt; Agricola describes big-bellied pots about two feet high placed through openings in the wall. Heat then passes through a smaller opening into the top chamber, which is cooler and serves for annealing.

A glassblower dips the end of an iron blowpipe into a pot and turns it to wind up a gather of molten glass, like honey on a spoon. Rolling it on the marver, a smooth slab of stone or iron, centres it and cools its skin. A puff of breath makes a bubble. The worker then reheats the piece at the working opening, blows and swings it to stretch it, and shapes it with jacks, paddles and wooden blocks. To finish the rim, the vessel is attached by its base to a solid iron rod, the pontil, and cracked off the blowpipe.

The glassblower's tools: blowpipe, iron rod, jacks, shears, paddle and wooden block.

Glass shrinks as it cools, and its outer skin hardens before the inside. A piece cooled in open air keeps stresses locked inside it and can burst hours later. Annealing prevents this: the finished vessels go into a hot chamber and cool slowly over many hours. Agricola noted that vessels not cooled slowly "would burst asunder".

Colour comes from impurities and additions. Iron in the sand tints glass green or brown; manganese, which Roman-era glassmakers added as a decolouriser, counteracts it, and cobalt gives a deep blue.

How to build it

Glass is gathered from a furnace at well over 1,000 °C and shaped while it is still glowing hot. Learn glassblowing in a hot shop or a glass course with an instructor; studios rent furnace time once you know the basics.

Start from cullet. Beginners work from ready-made glass, bought as cullet made for remelting and melted in the studio furnace. Making glass from a raw batch of sand, soda and lime takes higher temperatures and long melts, and the raw powders are hazardous.

Gather and marver. Preheat the end of the blowpipe, dip it into the pot and turn it steadily to collect a small gather. Roll it on the marver to make it round and even.

Blow and shape. Blow a short puff, cap the mouthpiece with your thumb and let the air warm and expand. Reheat often at the glory hole and keep the pipe turning so the glass does not sag. Shape with wet wooden blocks, paddles and jacks, and use the jacks to form a narrow neck, the jack line, between the piece and the pipe.

Transfer and finish. A helper brings a pontil with a dab of hot glass to the base; chill the jack line with a drop of water from the jacks and tap the pipe to release the piece onto the pontil. Reheat, open the rim with the jacks,

then, as the instructor directs, release the piece from the pontil onto a heat-proof support and place it gently in the annealer.

Anneal. The annealing oven holds the piece at a set temperature, then cools it slowly on a schedule matched to the glass and its thickness; for small pieces the cycle usually runs overnight. Handle it only once the instructor's cycle is complete.

> **Safety.** Furnaces, glory holes and hot glass cause severe burns and fires: wear natural-fibre clothes and closed shoes, tie back hair, and treat every piece of glass as hot until proven cold. Use eye protection made for glasswork against glare and infrared. Silica sand and batch powders must not be breathed in, so leave raw glassmaking to equipped workshops. Anneal every finished piece, and never expose hot glass to water or a sudden draught: it can shatter. Melt only glass the studio has approved, of known composition, in a ventilated furnace: old lead crystal and unknown coloured glass can give off harmful fumes.

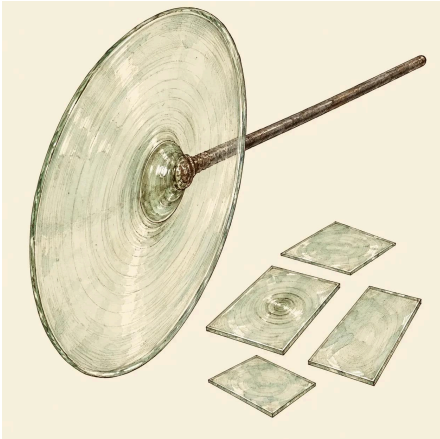
History and evolution

A core-formed flask: before glassblowing, small vessels were built up around a removable core.

Glass first appears as small beads in Mesopotamia in the second half of the third millennium BCE, probably as an offshoot of glazes and faience. The first vessels, from the late sixteenth century BCE, were made in northern Mesopotamia and soon in Egypt by core-forming: hot glass was wound around a core of clay and sand on a metal rod, decorated with coloured trails, and the core was scraped out once the glass had cooled.

Glassmaking later split into two trades. Large furnaces near the coasts of the Levant and Egypt turned sand and natron into raw glass, cast as slabs that could weigh around 10 tonnes; the slabs were broken, and the chunks travelled across the Mediterranean to workshops that remelted and shaped them. This division of work was in place by the middle of the first millennium BCE. In the second half of the first century BCE, craftsmen in this region learned to inflate glass on a blowpipe. The earliest closely dated evidence, glass tubes blown into bulbs, comes from a workshop in Jerusalem. Blowing made glass cheap, and in the Roman empire it became tableware, storage bottles and window panes.

In northern Europe from around 1000 CE, glassmakers used potash from wood ash instead of soda. In 1291 Venice ordered its glassmakers to move their furnaces to the island of Murano. George Ravenscroft, who patented a new clear glass in 1674, is traditionally credited with English lead crystal. For centuries window panes were cut from crown glass, a bubble spun open into a flat disc, or from blown cylinders split and flattened, and both methods limited the size of a pane. In the 1950s Alastair Pilkington and Kenneth Bickerstaff developed the float process at St Helens, in which molten glass spreads on a bath of molten tin into a flat ribbon. It went into profitable production around 1960 and is now the standard way to make window glass.



Crown glass: a bubble opened on the pontil and spun into a disc. The thick centre where the rod was attached is the bull's-eye.

Key figures

Oldest glass objects
Beads, Mesopotamia, second half of the 3rd millennium BCE

First glass vessels
Core-formed, late 16th century BCE

Glassblowing
Second half of the 1st century BCE, eastern Mediterranean

Float glass
Glass floated on molten tin, developed in the 1950s

Sources

1. The history of ancient glass · Republic of Türkiye, Ministry of Culture and Tourism https://www.ktb.gov.tr/EN-120370/the-history-of-ancient-glass.html
2. Composition of Late Hellenistic to Early Roman glass vessels from the Souk excavations, Beirut (Freestone, Brems and Degryse, Rendiconti Lincei, 2025) · UCL Institute of Archaeology https://discovery.ucl.ac.uk/id/eprint/10215996/1/Freestone_s12210-025-01311-x.pdf
3. Georgius Agricola, De re metallica (1556), trans. H. C. and L. H. Hoover, Book XII · Project Gutenberg https://www.gutenberg.org/cache/epub/38015/pg38015.txt
4. History of glass · Wikipedia https://en.wikipedia.org/wiki/History_of_glass
5. Float glass · Wikipedia https://en.wikipedia.org/wiki/Float_glass
6. Standard Glass DGG X, Soda-Lime-Silica Glass: viscosity-temperature behaviour measured by the PTB · Deutsche Glastechnische Gesellschaft https://hvg-dgg.de/fileadmin/Standard_Glass_DGG_X.pdf
7. Physical properties of glass · EAG Laboratories https://www.eag.com/app-note/physical-properties-of-glass/
8. Intraoral pressure in ethnic wind instruments (Goss, 2013), citing intraoral pressures up to 200 mbar in glassblowing · arXiv https://arxiv.org/abs/1308.5214
9. Draper point · Wikipedia https://en.wikipedia.org/wiki/Draper_point

Fact-checked on 2026-10-12

Iron Smelting

Wider adoption around 1200 BCE; ore, charcoal and a bloomery

c. 1,200 BCE · Antiquity · Crafts & cities

Requires: Bronze (p. 120), Charcoal (p. 62)

Leads to: Bicycle (p. 246), Canning & Pasteurisation (p. 242), Internal Combustion Engine (p. 303), Magnetic Compass (p. 189), Electric Motor (p. 270), Electric Generator (p. 266), Mechanical Clock (p. 196), Printing Press (p. 200), Sewing Machine (p. 262), Steam Engine (p. 221), Steel (p. 137), Transformer (p. 318)

1 Bellows 2 Tuyère (clay air nozzle) 3 Charge of charcoal and ore 4 Clay furnace wall 5 Iron bloom 6 Tapped slag

Iron smelting extracts metal from ore heated with charcoal in a small clay furnace supplied with air by bellows. This bloomery normally produces a solid, low-carbon lump called a bloom, which the smith consolidates and forges into wrought iron.

What it is

Iron is one of the most common elements in the Earth's crust, yet it is almost never found as metal. It sits in ores as oxides: red haematite, black magnetite, brown bog ore dug out of marshes. Smelting pulls the oxygen out of these ores and keeps the metal.

For close to three thousand years the tool for this was the bloomery, a clay furnace about a metre tall in which charcoal burns in a blast of air from bellows. It is named after its product, the bloom, a spongy lump of iron mixed with slag. Hammered while hot, the bloom becomes wrought iron, tough and easy to forge. Ploughshares, nails and swords were made of it until the blast furnace took over in Europe at the end of the Middle Ages.

Inside, a raw bloom is a sponge of iron and slag. Hours of forging turn it into a bar.

How it works

Burning in front of the air nozzle, the charcoal heats the furnace. Higher up the shaft, where oxygen is scarce, it forms carbon monoxide, and this gas takes oxygen away from the iron oxide as it rises through the charge. The ore gives up its oxygen in stages, and the reaction becomes fast above about 900 °C.

The bloom is first consolidated with light blows while hot; it can be reheated between rounds of hammering.

The furnace runs at around 1,100 to 1,200 °C and normally produces a solid, low-carbon bloom. Pure iron melts at 1,538 °C, but carbon-rich iron can melt at bloomery temperatures. Silica and other minerals in the ore combine with part of the iron oxide to form iron-rich slag, which can flow at about 1,180 °C depending on its composition. The slag trickles down past the tuyère, the clay air nozzle, while metal grains gather just below it into the bloom. The smelter drains the slag through an arch at the base, or the slag collects in a pit underneath.

The bloom leaves the furnace as a glowing, porous mass full of slag and charcoal. A fragile bloom may need gentle first blows, sometimes with a wooden mallet. It can also be cooled and reheated before consolidation; immediate hammering at white heat is not essential. Repeated heating and forging compact the metal and expel much of the slag. Weight loss varies with the bloom and the forging method. Carbon content is usually low and uneven, so soft iron and patches of steel may occur in the same bloom.

How to build

What follows is the outline of a small smelt, not a measured drawing. You need clay mixed with sand and straw, ore, a lot of charcoal, bellows or a blower, and a team for a full day.

Prepare the ore. Roast it in an open fire to drive off water and make it brittle, then break it to pieces of about a centimetre. Break the charcoal to about two centimetres and sieve out the dust so the gas can flow through the charge.

Build the shaft. On dry ground, raise a clay cylinder about a metre high and 25 to 30 cm across inside, with walls several fingers thick. Leave a hole near the bottom for the tuyère and an arch that can be opened and sealed again with clay. Let it dry slowly for several days, then finish with a small fire inside.

Preheat and charge. Fill the shaft with charcoal and supply air until it glows throughout. In WIRG experiments, charges of about 1 kg each of ore and charcoal are added at intervals of 10–15 minutes, with 15–20 kg of each reported per run. That is 15–20 paired charges, representing roughly 2.5–5 hours of charging at that cadence, rather than five continuous hours. The reported run takes about five hours including the final burn-down, with preheating separate. Allow extra charcoal for preheating and the final charcoal-only charge; the paired-charge total is not the full fuel requirement.

Control the blast. Monitor temperature and charge descent, and adjust the air supply to keep reduction and slag flow going. Carbon uptake depends on the charcoal-to-ore ratio, furnace atmosphere, residence time and slag chemistry. More air alone does not predict cast iron: some experiments produced lower-carbon iron at higher airflow. Tap accumulated slag as needed; WIRG reports a first tapping after about three hours.

Extract and consolidate. After the last charge burns down, open the front and remove the bloom with tongs. Begin gently if it is fragile, for example with a wooden mallet, then use stronger blows as it holds together. Cooling and reheating before consolidation are also possible. Reheat in a forge between passes until the metal forms a coherent bar.

> **Safety.** A bloomery runs above 1,100 °C. Liquid slag causes deep burns and starts fires. Work outdoors on bare, dry ground, away from dry grass, with dry sand ready. Keep tools and the slag-tapping ground dry. Never let water touch hot or molten slag or enter the hot furnace: sudden steam formation can cause an explosion. Wear leather boots, gloves, an apron and eye protection, and never stand in front of the tapping arch. Carbon monoxide leaves the top: keep your face away from the stack and never smelt indoors. Damp clay or ore can burst when heated.

History and evolution

People worked iron before they could smelt it. Some of the oldest iron objects were hammered from meteorites, which contain nickel. Evidence points to early smelting in Anatolia, in present-day Turkey, though the place and date of its invention remain uncertain. Fragments from Kaman-Kalehöyük dated to about 1800 BCE include some carbon steel, and their uneven carbon suggests smiths who were still experimenting. Around 1250 BCE the Hittite king Hattusili III wrote a letter about making “good iron”.

Around 1200 BCE marks a phase of wider iron adoption in the Near East, with different regions adopting it at different times. Smelting itself was already known earlier. By about 1100 BCE it was common in Cyprus and the Levant, most of Europe used it from around 800 BCE, and by 500 BCE bloomeries were known from the Mediterranean to Scandinavia. Unlike the copper and tin for bronze, iron ore could be dug almost anywhere.

Africa had its own traditions, with furnaces in Nubia by the seventh century BCE and in West Africa by the sixth at the latest. China probably learned bloomery smelting from the west around the eighth century BCE, then moved early to furnaces hot enough to make liquid cast iron.

Pot bellows: pumping the leather covers in turn keeps the air flowing without a break.

European blooms weighed about two kilograms for centuries, small enough to forge by hand. Roman furnaces, up to two metres tall, gave blooms of 10 to 15 kg, and around 1500 water-driven hammers could work blooms of 100 kg or more. The blast furnace at Lapphyttan in Sweden was already operating from the mid-twelfth century. Blast furnaces spread more widely in later medieval centuries and were producing cast iron in quantity by around 1500; bloomeries gradually

declined. Catalan forges in Spain and southern France were still working in the middle of the nineteenth century.

Key figures

Furnace temperature
About 1,100–1,200 °C (pure iron melts at 1,538 °C)

Charge
In WIRG trials, about 1 kg each of ore and charcoal per charge, at intervals of 10–15 minutes

Length of a smelt
About 5 hours for charging and burn-down in WIRG experiments; preheating is separate

Bloom size
About 2 kg in the early Iron Age, 10–15 kg in Roman furnaces

Wider adoption
Around 1200 BCE in the Near East; smelting began earlier

Sources

1. Bloomery · Wikipedia https://en.wikipedia.org/wiki/Bloomery
2. Iron and Steel in Early Europe · H. Föll, Kiel University https://www.tf.uni-kiel.de/matwis/amat/iss/kap_a/backbone/ra_3_1.html
3. Experimental Bloomery 4: The smelt · Wealden Iron Research Group https://www.wealdeniron.org.uk/?p=930
4. Questioning Diversity (of Iron) in the Workplace: Bloomery Iron, Cast Iron, China and the West (Liu & Wood, 2025) · Internet Archaeology 69 https://www.intarch.ac.uk/journal/issue69/14/full-text.html
5. Kaman-Kalehöyük · Wikipedia https://en.wikipedia.org/wiki/Kaman-Kaleh%C3%B6y%C3%BCk
6. The explosion of No. 5 Blast Furnace, Corus UK Ltd, Port Talbot · Health and Safety Executive https://www.hse.gov.uk/pubns/web34.pdf
7. Lee Sauder and Skip Williams Smelt Iron · H. Föll, Kiel University https://www.tf.uni-kiel.de/matwis/amat/iss/kap_a/advanced/aa_2_5.html
8. Experimental Bloomery Ironmaking: The Bloom · Wealden Iron Research Group https://www.wealdeniron.org.uk/Expt/bloom.htm
9. Experimental Bloomery Ironmaking: The Smelt · Wealden Iron Research Group https://www.wealdeniron.org.uk/Expt/smelt.htm
10. Medieval Iron in Society (Rapport H 34) · Jernkontoret https://www.jernkontoret.se/en/publications/history-of-mining-and-metallurgy1/Publications/rapport-h-34/
11. The Innovation and Adoption of Iron in the Ancient Near East (Erb-Satullo, 2019) · Journal of Archaeological Research, Springer Nature https://link.springer.com/article/10.1007/s10814-019-09129-6
12. Flow Rates · Darrell Markewitz, Wareham Forge https://www.warehamforge.ca/ironsmelting/flowrates.html
13. Experimental Iron Smelting: Norse Bellows Air · Darrell Markewitz, Wareham Forge https://warehamforge.ca/ironsmelting/norse-air.html
14. The St Fagans Experimental Bloomery: the First Six Years (Young, 2005) · Historical Metallurgy Society News 59 https://historicalmetallurgy.org/media/pjwd2b5o/hmsnews59.pdf

Fact-checked on 2026-10-12

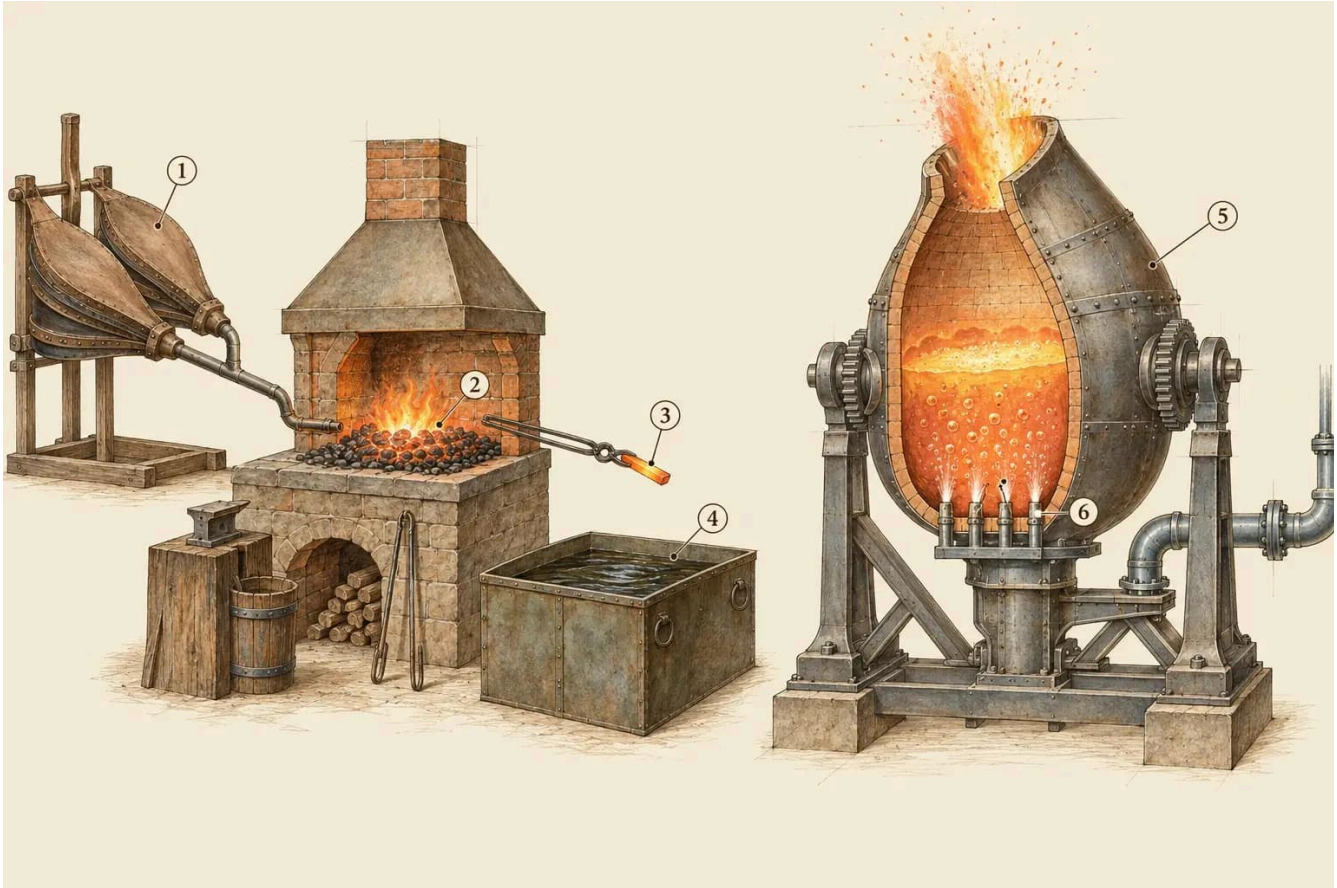
Steel

Iron with just enough carbon

c. 1,000 BCE · Antiquity · Crafts & cities

Requires: Iron Smelting (p. 133), Charcoal (p. 62)

Leads to: Internal Combustion Engine (p. 303), Magnetic Compass (p. 189), Printing Press (p. 200), Reinforced Concrete (p. 299), Sewing Machine (p. 262), Steam Turbine (p. 314), Water Turbine (p. 258), Wind Turbine (p. 326)



1 Bellows 2 Forge hearth 3 Hot steel held in tongs 4 Quench tank 5 Bessemer converter 6 Air tuyères in the converter bottom

Steel is iron with a small, controlled share of carbon, usually between about 0.1 and 1.5%. It is forged hot; with enough carbon it can be hardened by heating and quenching, then tempered to make it tougher at some cost in hardness.

What it is

Pure iron is soft: a knife made of it bends and soon goes blunt. Add a little carbon, a few tenths of a percent up to about one and a half, and the metal still forges hot. With enough carbon, heated and plunged into water or oil, it becomes hard enough to cut iron. That alloy is steel.

By its carbon it sits between two other materials. Wrought iron has almost no carbon: it is tough and welds easily but will not harden. Cast iron holds 2 to 4% carbon: it pours into moulds but is brittle and cannot be forged. By heating and cooling it, the smith can move steel between hard and tough. It is now by far the most used metal.

How it works

Carbon atoms are small and sit in the gaps between iron atoms. Cold iron holds very little carbon, so the excess forms hard iron carbide. In slowly cooled steel it lies in thin layers between soft iron, a mixture that is strong but can still be filed.

Above about 727 °C the iron crystal starts to rearrange into a form that dissolves carbon, and once the change is through the steel no longer attracts a magnet. How much hotter, and for how long, it must be held for enough carbide to dissolve depends on the steel. Cooled slowly, the carbon comes back out as carbide. Quenched, it has no time: it stays trapped in a strained crystal called martensite, very hard and as brittle as glass.

So the smith tempers it: reheats it to between about 200 and 350 °C, which eases the strain and makes it much tougher at the cost of a little hardness. On polished steel a thin oxide film forms whose colour follows the heat, from pale straw near 210 °C through brown and purple to dark blue near 290 °C. These colours, which also depend on time and on the surface, were the smith's rough guide: straw for a razor or a wood chisel, purple to blue for a spring. Annealing, heating and then cooling very slowly, gives the softest state, easy to cut and file.

Below about 0.3% carbon, steel hardens little; more carbon makes it harder and less forgiving. Iron packed in charcoal and held at red heat for hours takes up carbon at its surface. Quenched afterwards, it gets a hard skin over a tough core: this is case hardening.

As the shank is heated, the colours run towards the edge; the smith cools the tool when the right one reaches it.

How to build

Heat treatment is the part of steelmaking a small workshop can do. Start from a known plain high-carbon tool steel and keep its data sheet, which gives exact temperatures, soak times and quenching medium. Old files are the traditional source, but their steel is unknown and some cheap ones are only surface-hardened.

Soften and shape. Anneal the bar as its data sheet says. The traditional way, bringing it to a dull red and letting it cool overnight in wood ash, is only approximate. Grind the softened bar into a small punch or cold chisel, keeping it cool.

Harden. Heat the working end evenly in a charcoal fire or with a gas torch. The old sign is that a magnet no longer sticks, then a little more heat, to cherry red seen in shade, but the temperature and soak time of the data sheet are more reliable. Plunge the piece straight and fully into the quenching medium it names, usually oil for a small tool, in a bath of several litres kept well below its flash point. Move the piece up and down until cool.

Test. A new file drawn across the hardened end should skid without biting. If it bites, the surface may only have lost carbon in the fire, or the hardening may have failed: grind a small spot bright and test again before heating once more.

Temper at once. The data sheet gives the tempering temperature and time, best kept in an oven: a common cycle is an hour at temperature, a cooling to room temperature, then a second hour. The traditional method is quicker and only approximate. Polish the end bright with abrasive paper, heat the shank slowly and watch the colours travel towards the tip. Cool the tool when brown to purple, about 260 to 270 °C, reaches the edge of a cold chisel, or straw, about 220 °C, the edge of a wood chisel.

> **Safety.** Forge heat causes deep burns, and steel below red heat looks cold when it is not: treat every piece as hot. Wear safety glasses, with a face shield over them when quenching, leather gloves for handling hot work but never at the grinder, leather shoes, and cotton or wool clothes. Work outdoors or with strong ventilation, because forges give off carbon monoxide and hot oil gives off smoke. Use a metal oil container with a metal lid at hand, and plunge the work fully and quickly, which limits flare-ups. If it catches fire, close the lid; never throw water on burning oil or let water into hot oil. Keep a dry powder extinguisher nearby. Never hammer, bend, drop or try to snap hardened, untempered steel: it can shatter and throw sharp fragments.

History and evolution

Fragments from Kaman-Kalehöyük in Anatolia, around 1800 BCE, contain steel, probably by accident. A quenched and lightly tempered pick from Mount Adir in Galilee was long dated to the twelfth century BCE, but that date is now questioned. No single find fixes the start of deliberate steelmaking. This plate uses around 1000 BCE as a convention, the time when iron came into common use in the Levant, between about 1100 and 900 BCE.

A crucible broken open after firing, and the steel cake it held.

In southern India, iron sealed in clay crucibles with carbon-rich matter was melted into even cakes of 1 to 1.5% carbon; crucibles at Kodumanal date from around the second century BCE. This crucible steel, which Europeans later called wootz, is the kind used for the patterned blades known as Damascus steel. In Sri Lanka, hillside furnaces blown by the monsoon made steel from the seventh to the eleventh century CE, perhaps for trade across the Indian Ocean.

In China, a grave of the state of Yan from the early third century BCE holds quench-hardened steel, though Chinese iron was then mostly cast iron. Held hot in air for days, or stirred in a fining hearth under a blast, cast iron lost carbon and became steel or wrought iron; excavated fineries date from the first century BCE.

Early modern Europe used cementation, first developed in Germany. At Derwentcote in England, from around 1730, Swedish iron bars packed in charcoal were held above 1,100 °C for six to ten days; the blister steel was then bundled and forge-welded into shear steel. Around 1740 the clockmaker Benjamin Huntsman melted blister steel in crucibles and cast it into uniform steel.

In the cementation chest, iron bars spend a week or more in charcoal and come out blistered.

In 1856 Henry Bessemer blew air through molten pig iron; the carbon and silicon burned, and their heat kept the metal liquid. Open-hearth furnaces followed in the 1860s. In 1952 at Linz, in Austria, converters blown with pure oxygen began work; they still make most steel, while electric furnaces, fed mostly with scrap, make about 29%.

Key figures

Carbon
About 0.1–1.5%; wrought iron has less, cast iron 2–4%

Hardening heat
The change starts near 727 °C; each grade has its own quenching temperature and hold

Tempering colours
Straw at about 220 °C, purple about 270 °C, dark blue about 290 °C

Bessemer blow
About 15 tonnes of iron turned to steel in 10–20 minutes

World output, 2024
About 1.9 billion tonnes, 29% of it from electric furnaces

Sources

1. Iron and Steel in Early Europe · H. Föll, Kiel University https://www.tf.uni-kiel.de/matwis/amat/iss/kap_a/backbone/ra_3_1.html
2. A Brief History of Martensites · Sethna group, Cornell University https://sethna.lassp.cornell.edu/Tweed/Martensite_History.html
3. The Transition from Bronze to Iron in Canaan: Chronology, Technology, and Context (Yahalom-Mack & Eliyahu-Behar, 2015) · Radiocarbon, Cambridge University Press https://doi.org/10.2458/azu_rc.57.18563
4. Early iron in China, Korea, and Japan (Wagner) · Donald B. Wagner https://donwagner.dk/KoreanFe/KoreanFe.html
5. Crucible steel in South India: preliminary investigations on crucibles from some newly identified sites (Srinivasan & Griffiths) · MRS Online Proceedings Library, Cambridge University Press https://www.cambridge.org/core/journals/mrs-online-proceedings-library-archive/article/abs/crucible-steel-in-south-indiapreliminary-investigations-on-crucibles-from-some-newly-identified-sites/0C7F9DB996F0DD5758502D8F62201947
6. Wootz Crucible Steel: A Newly Discovered Production Site in South India (Srinivasan, 1994) · Papers from the Institute of Archaeology, UCL https://student-journals.ucl.ac.uk/pia/article/id/164
7. Wind-Powered Furnaces · Archaeology, Archaeological Institute of America https://archive.archaeology.org/9609/newsbriefs/srilanka.html
8. History of Derwentcote Steel Furnace · English Heritage https://www.english-heritage.org.uk/visit/places/derwentcote-steel-furnace/history/
9. A Crucible of Steel History · West Yorkshire Steel https://westyorkssteel.com/blog/a-crucible-of-steel-history
10. Bessemer Process · Grace's Guide to British Industrial History https://www.gracesguide.co.uk/Bessemer_Process
11. Bessemer Converter · Sheffield Museums https://www.sheffieldmuseums.org.uk/whats-on/bessemer-converter/
12. The history of LD steelmaking: back to the roots · Primetals Technologies https://www.primetals.com/en/metals-magazine/the-history-of-ld-steelmaking-back-to-the-roots/
13. 60 years of the Linz-Donawitz (LD) process · voestalpine https://www.voestalpine.com/stahl/en/Stories/60-years-of-the-Linz-Donawitz-LD-process
14. The share of EAF in global steel production in 2024 increased to 29.1% (worldsteel data) · GMK Center https://gmk.center/en/news/the-share-of-eaf-in-global-steel-production-in-2024-increased-to-29-1/
15. Austenitizing, Magnetism, and Heat Treating · Larrin Thomas, Knife Steel Nerds https://knifesteelnerds.com/2019/03/18/magnet-heat-treating/
16. Steel Tempering Temperatures: Colour Chart · West Yorkshire Steel https://westyorkssteel.com/technical-information/steel-heat-treatment/tempering-temperatures

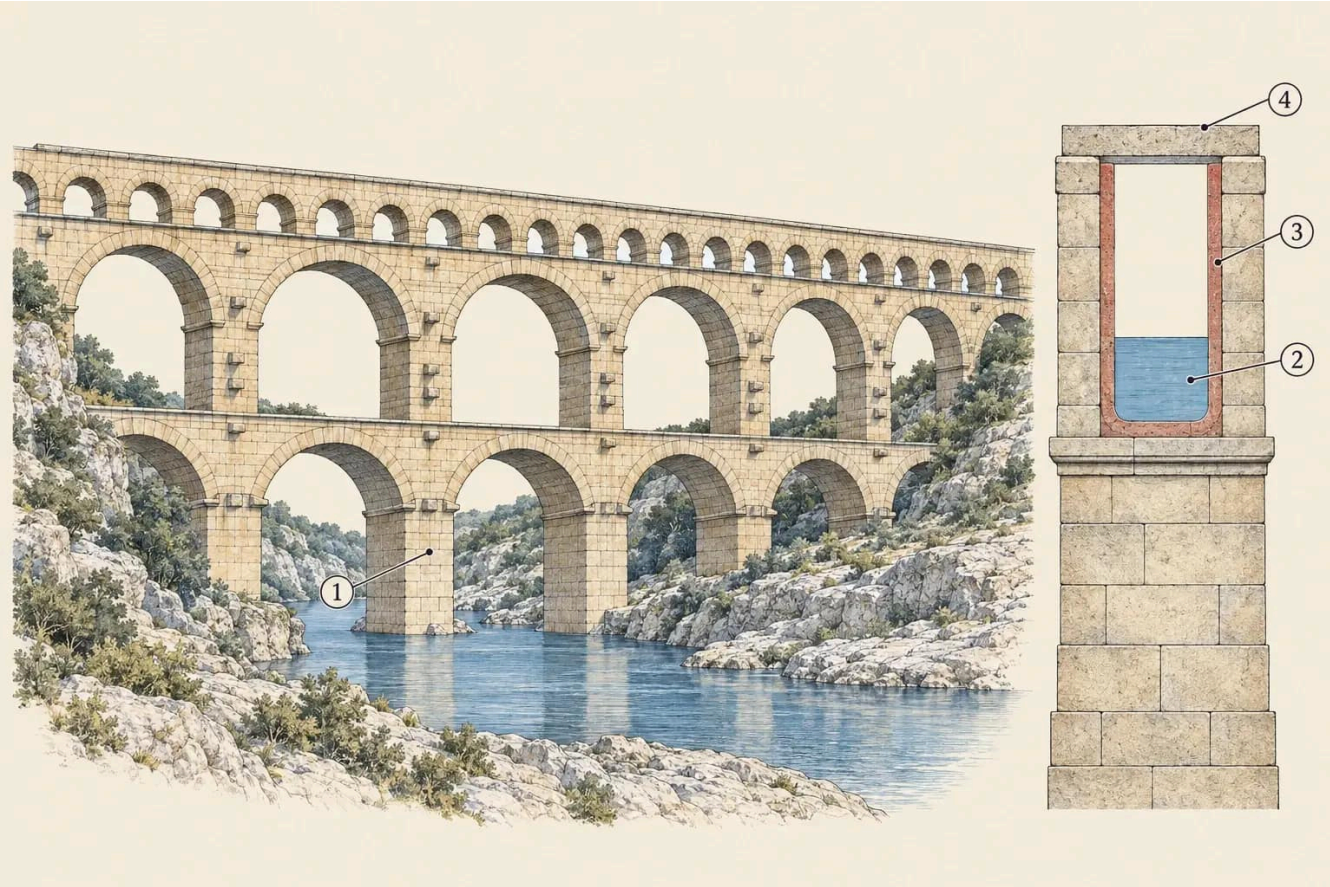
Fact-checked on 2026-10-14

Aqueduct

Water carried by gravity alone

c. 690 BCE · Antiquity · Crafts & cities

Requires: Bricks (p. 39), Measures and standards (p. 124), Lime and lime mortar (p. 30), Irrigation (p. 51), Arch and Vault (p. 70)



1 Arcades (piers and arches) 2 Water channel (specus) 3 Waterproof lining (opus signinum) 4 Cover slabs

An aqueduct brings water from a distant spring to a town in a channel that falls very slightly along its length, so that gravity alone keeps the water moving. The Romans built hundreds of them, in tunnels, in covered trenches and on arcades such as the Pont du Gard, and some carried tens of thousands of cubic metres a day.

What it is

An aqueduct is a man-made watercourse that carries water from a source to the place where people use it. Most of its length is hidden: a stone or concrete channel, roofed over, running in a trench or a tunnel along the side of the hills. The tall arcades that people picture are only the places where the channel had to cross a valley without losing height.

The plate shows such a crossing, of the kind built over the Gardon river near Nîmes in the first century CE. The channel runs along the top of the highest tier.

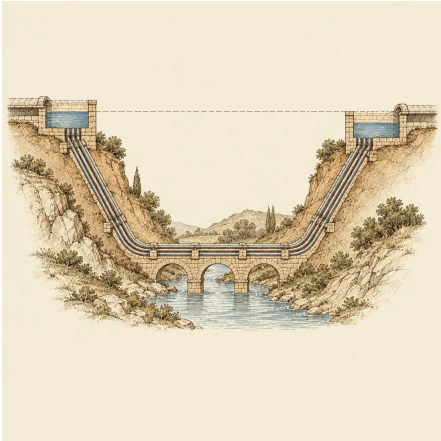
How it works

Where the water runs in an open channel, as it does over most of an aqueduct, the channel must fall steadily from the spring to the town, never rising and never dropping too fast. Too little slope and the water slows and drops its silt; too much and it scours the lining. The aqueduct of Nîmes, about 50 km long, loses only 12 to 13 m between source and town (measurements differ slightly), an average of about 25 cm per kilometre, and much less on some stretches. On the Pont du Gard itself the fall is a few centimetres.

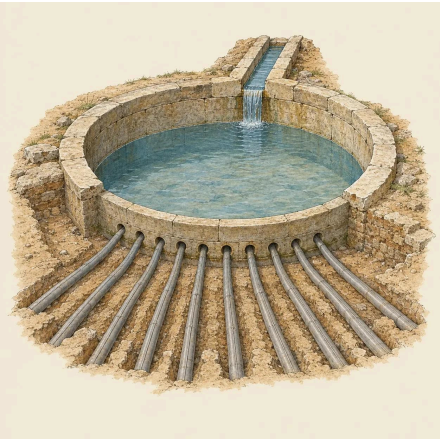
The channel, called the specus, was usually about as wide as a man and a little taller, so that workers could walk inside to clean it. Its floor and walls were coated with opus signinum, a lime mortar full of crushed tile and pottery that sets hard and holds water. Rounded fillets at the foot of the walls closed the corners where leaks begin. Stone slabs or a vault covered the top, kept out dirt and sunlight, and stopped the water from warming up.

Laying out such a slope over tens of kilometres was the surveyors' work. Vitruvius, writing in the late first century BCE, describes the chorobates, a long wooden table whose plumb lines, or a groove filled with water on windy days, show when it is level. With it and with sighting rods, a team could carry a level line across a whole landscape and mark the fall on stakes.

Deep valleys could also be crossed by an inverted siphon. The water entered a tank on the near slope, ran down through sealed lead pipes, crossed the valley bottom on a low bridge and climbed the far slope to a second tank set a little lower. Vitruvius already describes this arrangement and calls the long, nearly level stretch across the valley floor the venter, the belly. Siphons saved masonry, but the lead was costly and the joints had to withstand high pressure. Vitruvius's text, as usually translated, also calls for vents to let trapped air escape, although the exact meaning of his term is debated. For ordinary supply pipes he preferred fired clay, because he believed that water carried in lead was bad for health.



An inverted siphon: the water rises again on the far side, but never quite to its starting level.



The round distribution basin at Nîmes, where ten lead pipes took the water to the districts of the town.

At the town the water reached a distribution tank, the castellum. Vitruvius describes one divided into three, with separate outlets for the public fountains, the baths and private houses, arranged so that the fountains would be the last to run short. The one that survives at Nîmes is a round basin about 5.5 m across, from which ten lead pipes ran to the districts. Water flowed day and night; what was not used ran on to wash the drains. Vitruvius adds that the rents paid by private households were meant to pay for the upkeep of the aqueduct. Estimates of the flow at Nîmes range from about 20,000 to 40,000 m^3 a day, and the water took about a day to arrive from the spring.

How to build it

Large Roman aqueducts took public money, skilled surveyors and big building crews. On a garden scale the same principles bring water from a spring or a roof tank to a pond or a field, without a pump.

Find the levels. Mark the source and the point of arrival, then measure the height between them. A clear plastic tube filled with water works as a modern chorobates: the water stands at the same height at both ends. Peg the

route every few metres and note the height at each peg.

Choose the slope. A smooth channel carrying clean water typically needs a fall of a few millimetres per metre; size it for the flow you expect, and avoid steep stretches where the water would run fast. Spread the fall along the route as evenly as the ground allows, and plan a gentle detour along the contour rather than a hump that would stop the flow.

The chorobates: a levelling table about 20 Roman feet long, checked with plumb lines or with water in a groove.

Dig and lay the channel. Dig a trench to the pegged depths, firm its floor and lay the channel: half-pipes of fired clay, a masonry channel lined with hydraulic lime or cement mortar and left to cure before water is let in, or plain pipe. Check the fall with the tube at every joint. Seal the joints and round off the inner corners if you build in masonry.

Add a settling basin. Just after the source, build a small tank where the water slows down and drops its sand before it enters the channel. Fit a grid against leaves, and an overflow so that a flood does not burst the work.

Cover it. Close the channel with slabs or tiles. Covered water stays cleaner and cooler, and fewer algae grow in it.

> **Safety.** Trench sides can collapse, especially in loose or wet ground: shore them or slope them back before you work in a deep trench, and never work alone in one. Do not use lead pipes or lead solder for water that people or animals will drink, and treat the system as non-potable: do not drink its water. Lime mortar is caustic: wear gloves and eye protection, and a dust mask when mixing dry lime. Any open tank or pond is a drowning risk for small children: fence it or cover it. Building arches or walls above head height means work at height and heavy stones: use proper scaffolding and get advice from a builder.

History and evolution

Channels for water are much older than Rome. The Assyrian king Sennacherib, between about 703 and 690 BCE, had a canal built to bring water to Nineveh, and at Jerwan it crossed a valley on a limestone bridge more than 280 m long. It is often called the oldest known aqueduct bridge.

Rome's first aqueduct, the Aqua Appia, was begun in 312 BCE under the censor Appius Claudius Caecus, who also built the Via Appia. It ran about 16.5 km, almost entirely underground. Others followed: the Anio Vetus in 272 BCE, the Aqua Marcia in 144 BCE, more than 90 km long, and the Aqua Claudia and Anio Novus, finished in 52 CE. At the end of the first century CE the emperor Nerva named Frontinus water commissioner, and his treatise lists nine aqueducts serving the city, with their lengths and the illegal tapping he uncovered.

The Pont du Gard was probably built between about 40 and 60 CE, although some studies extend the range to 80. Its three tiers have 6, 11 and 35 arches; 12 more of the top tier have been lost. The large limestone blocks of its arches, some of them weighing up to 6 tonnes, are laid without mortar. The Nîmes aqueduct fell out of use as deposits and roots blocked it, probably by the sixth century. The bridge survived partly because people used it to cross the river; in 1743–1747 Henri Pitot built a road bridge against its lower tier, and it became a World Heritage Site in 1985.

Medieval towns and monasteries built smaller aqueducts, and modern supply systems combine gravity channels and tunnels with pressure pipes, pumps and reservoirs. A constant gentle fall still governs canals, sewers and other channels that flow by gravity.

Key figures

Rome's first aqueduct

Aqua Appia, 312 BCE, about 16.5 km, almost all underground

Pont du Gard

About 48 m high, three tiers of arches, built c. 40–60 CE

Nîmes aqueduct

About 50 km long for a fall of 12 to 13 m (about 25 cm per km)

Estimated flow at Nîmes

About 20,000 to 40,000 m^3 a day (estimates vary)

Sources

1. Jerwan Aqueduct · Columbia University, Media Center for Art History https://mcid.mcah.columbia.edu/mapping-mesopotamian-monuments/jerwan-aqueduct
2. Frontinus, De aquis urbis Romae, Book I (trans. R. H. Rodgers) · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Frontinus/De_Aquis/Rodgers/1**.html
3. Vitruvius, The Ten Books on Architecture, Book VIII · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/8*.html
4. Pont du Gard · Structurae https://structurae.net/fr/ouvrages/pont-du-gard
5. Nîmes: the castellum · Archaeology Magazine (Archaeological Institute of America) https://archive.archaeology.org/onsite/provence/nimes2.html
6. Pont du Gard · Wikipedia https://en.wikipedia.org/wiki/Pont_du_Gard
7. Roman hydraulic engineering: the Pont du Gard aqueduct and Nemausus (Nîmes) castellum (Water, 2021) · MDPI https://www.mdpi.com/2073-4441/13/1/54
8. Hydraulics of Roman aqueducts: myths, fables, realities · University of Queensland (H. Chanson) https://staff.civil.uq.edu.au/h.chanson/rom_aq.html
9. Pont du Gard · Wikipédia https://fr.wikipedia.org/wiki/Pont_du_Gard
10. Manning's n table (after Chow, Open-channel hydraulics, 1959) · San Diego State University (V. M. Ponce) https://ponce.sdsu.edu/open_channel_hydraulics_05_manningsntable.html

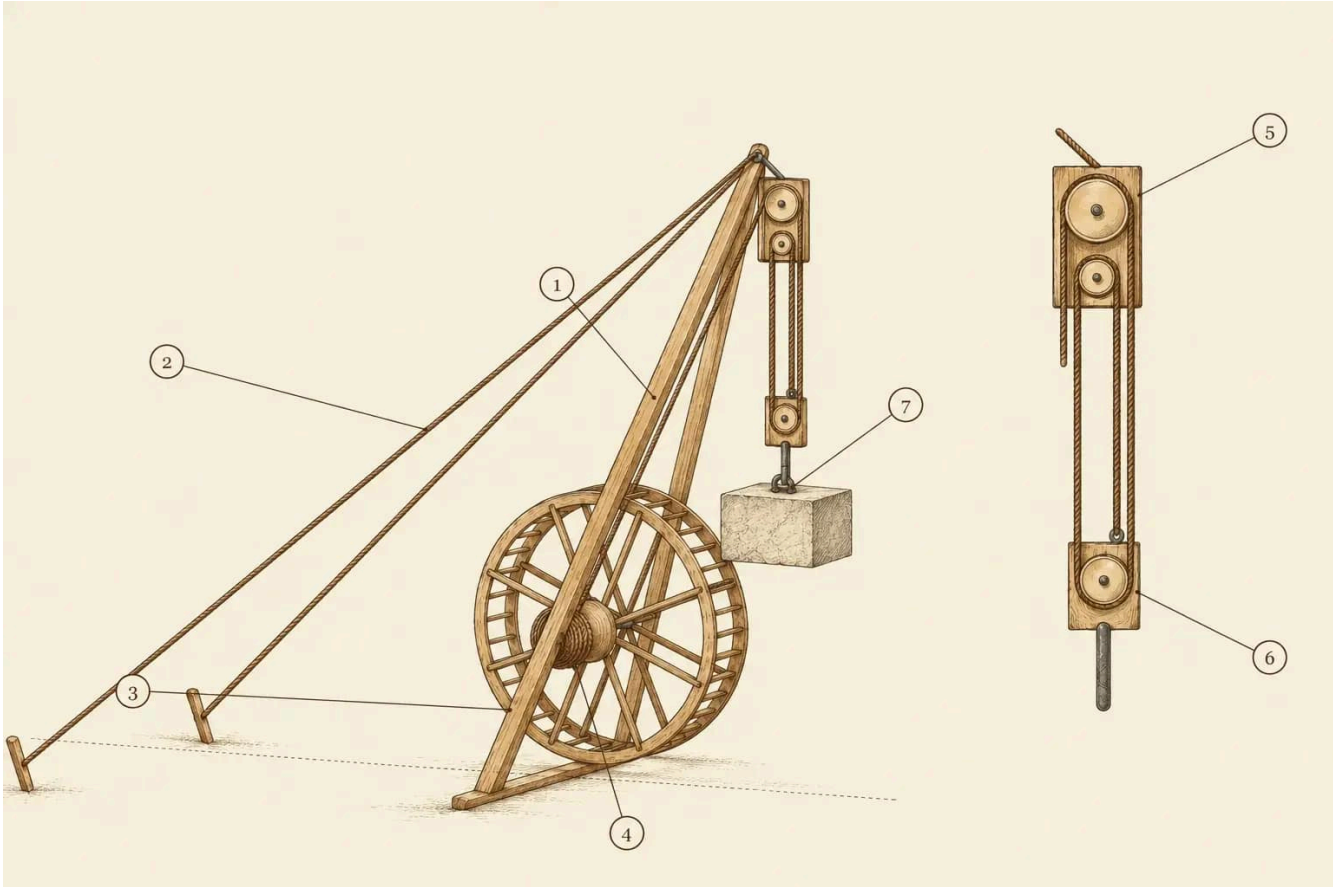
Fact-checked on 2026-10-12

Crane & Pulley

Lifting more than you weigh

c. 515 BCE · Antiquity · Crafts & cities

Requires: Rope & Cordage (p. 13), Wheel & Axle (p. 78)



1 Leg of the timber frame 2 Stay rope 3 Treadwheel 4 Winding drum 5 Upper block with two pulleys
6 Lower block with one pulley 7 Lewis set in the stone

A crane lifts a load by trading distance for force: a rope runs through several pulleys and onto a drum turned by a winch or a treadwheel, so that a few people can raise a stone many times their own weight. Greek builders used cranes from the late sixth century BCE, and Roman and medieval builders used them to raise temples and cathedrals and to load ships.

What it is

A crane is a frame that holds a load in the air while people or engines raise it. The ancient crane had three parts: a timber frame or mast held by stay ropes, a set of pulleys at its head, and a winch at its foot. The winch was a horizontal axle turned with levers, or a large wheel that men walked inside, the treadwheel.

Each of its parts, the lever, the wheel and the rope, is older than the crane. The crane combines them so that the small force of a few people, applied over a long distance, becomes a large force over a short one.

How it works

A single fixed pulley only changes the direction of a pull. The gain comes when the load hangs from a movable pulley. The rope then holds it on two strands, and each strand carries half the weight. To lift the stone by one metre you must pull two metres of rope, but with half the effort.

The simplest tackle: two strands hold the lower pulley, so the pull needed is about half the weight.

Add more pulleys to both blocks and the load is shared by more strands. Vitruvius, writing in the late first century BCE, names the blocks by their number of pulleys: three for the trispastos, five for the pentaspastos, and many for the polyspastos. With five strands, a pull equal to the weight of 20 kg holds about 100 kg, before friction. Friction in the axles of the pulleys takes back part of the gain, more with every pulley added.

The winch multiplies the force a second time. A rope wound on a thin axle and turned by long levers acts like a wheel and axle: if the levers are ten times longer than the axle's radius, the force on the rope is ten times the force on the levers. A treadwheel works the same way, with the weight of the men walking inside it as the effort. For very heavy loads, Vitruvius describes a drum wide enough for men to walk inside it, which gives more power than a capstan.

Greek lifting tongs: pulling on the ring squeezes the tips into notches cut in the block.

The load also has to be held. Greek builders cut holes or U-shaped channels in their blocks for ropes, used iron tongs whose tips fitted into holes in the sides, or set a lewis, a dovetailed iron wedge, into a hole in the top. These cuttings, still visible on temple stones, are the main evidence for the use of cranes. Vitruvius describes iron shears hung under the lower block, their teeth fitted into holes in the stone. Building cranes of this kind had little reach to the side, so a block was lowered close to its final place and pushed into position with levers.

How to build it

A tabletop model shows how pulleys and a winch multiply force. Keep it small: it is a demonstration, not a lifting device.

Make the frame. Lash two wooden dowels or broom handles about 1 m long together near their tops, spread their feet about 50 cm apart on a baseboard and screw them down. Clamp the baseboard to a sturdy table so the model cannot tip, and tie two stay cords from the top to screw eyes at the back of the board, so that the frame leans slightly forward but the hanging load stays above the board.

Rig the tackle. Hang a small pulley block with two sheaves from the top and a block with one sheave below it. Tie a strong cord to the top of the lower block, take it over one upper sheave, under the lower sheave and over the second upper sheave. Three strands now hold the lower block.

Add a winch. Drill a hole through each leg near the bottom and pass a short dowel through both so that it turns freely; glue a crank handle to one end; the free end of the cord will be tied to its middle after the first test below.

Drill a hole in one leg for a removable peg: with the peg in, the crank rests against it and holds the load. Keep hold of the crank whenever you pull the peg out to wind further.

Measure the gain. Make this first test before the cord is tied to the axle. Weigh the lower block, then hang a bag of sand of no more than 500 g from it. Pull the free end slowly and steadily with a spring balance, lifting the bag only a few tens of centimetres: you should read a little more than a third of the bag and block together; the rest is friction. Lower the bag, tie the cord to the middle of the axle and compare how far the crank handle travels with how far the bag rises.

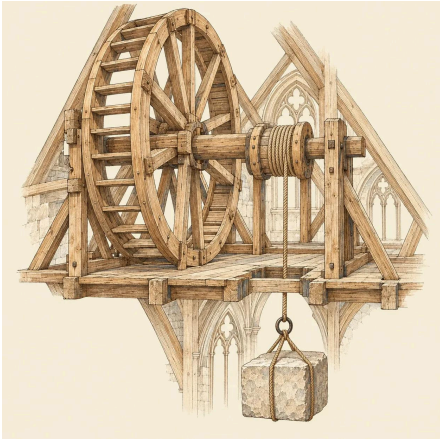
> **Safety.** Keep a hand on the crank whenever the load is raised: a plain axle runs back as soon as it is let go. Set the model where a falling bag cannot land on hands or feet, and keep fingers clear of the pulleys and the winding axle. Do not scale the model up to lift heavy objects: real lifting needs equipment rated and approved for lifting and lowering suspended loads, used by people trained in rigging.

History and evolution

The pulley appears on an Assyrian relief of the ninth century BCE. Greek builders of the seventh century BCE cut rope channels in blocks of 200 to 400 kg at Isthmia and Corinth, and some researchers think lifting frames were being tried by then. Cranes became normal on Greek building sites from about 515 BCE, when cuttings for lifting tongs and lewis irons appear on temples such as that of Apollo at Delphi. The first clear written description of the compound pulley is in the Mechanical Problems, a Greek text of the early third century BCE.

Roman builders used both the winch and the treadwheel. A relief from the tomb of the Haterii family in Rome, carved around 100 CE, shows a treadwheel crane at work. Modern estimates, which assume a tackle of three rows of five pulleys, suggest that the largest compound crane, the polyspastos, could lift about 3 tonnes with four men at the winch, and about 6 tonnes with a treadwheel. The heaviest Roman blocks, such as the architraves of Baalbek, needed several cranes or other means.

Treadwheel cranes return in French building records around 1225, and harbour cranes are documented at Utrecht in 1244, Antwerp in 1263 and Bruges in 1288. Gothic builders often worked their hoists from the roof timbers, above the vaults they were building, and several medieval treadwheels still stand in English church towers. The great harbour crane of Gdańsk, built in 1442–1444, burned in 1945, and its timberwork has been rebuilt. In 1586 Domenico Fontana raised the Vatican obelisk, estimated at 330 to 360 tonnes, with a timber lifting tower. From 1801 two steam engines worked the cranes that built the London Dock, and in the 1840s William Armstrong built water-powered hydraulic cranes; electric motors and steel jibs came later, but cranes still lift with pulley blocks and a drum.



A medieval treadwheel hoist set above the vaults: the rope from the drum drops through an opening in the floor.

Key figures

Earliest firm evidence
Lifting cuttings on Greek temple blocks, c. 515 BCE

Gdańsk harbour crane
Built 1442–1444, timberwork rebuilt after 1945

Roman polyspastos (modern estimate)
About 3 t with four men at a winch, about 6 t with a treadwheel

Vatican obelisk, 1586
About 330 to 360 t (estimates vary), raised by Domenico Fontana

Sources

1. J. J. Coulton, Lifting in early Greek architecture (Journal of Hellenic Studies 94, 1974) · Society for the Promotion of Hellenic Studies (copy hosted by the University of Athens) https://eclass-b.uoa.gr/modules/document/file.php/BAAG112/630416_Lifting%20in%20Early%20Greek%20Architecture_Coulton_Journal%20of%20Hellenic%20Studies1974.pdf
2. Vitruvius, The Ten Books on Architecture, Book X (hoisting machines) · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/10*.html
3. Greek temple ruins suggest lifting machines in use 1.5 centuries earlier than previously believed · University of Notre Dame, via Newswise https://www.newswise.com/articles/greek-temple-ruins-suggest-lifting-machines-in-use-1-5-centuries-earlier-than-previously-believed
4. Rochester Bridge Trust magazine: John Rennie and the London Dock (steam engines working the construction cranes, 1801) · Rochester Bridge Trust https://rbt.org.uk/wp-content/uploads/2021/11/RBT-40pp-A4-Magazine-Single-Pages-Updated.pdf
5. Crane (machine) · Wikipedia https://en.wikipedia.org/wiki/Crane_(machine)
6. Treadwheel crane · Wikipedia https://en.wikipedia.org/wiki/Treadwheel_crane
7. Treadwheel crane, Harwich (built 1667): wheels of 16 ft on an axle of 13½ in · The Harwich Society https://www.harwich-society.co.uk/maritime-heritage-trail/treadwheel-crane/
8. Block and tackle (friction: the sheave friction factor of API RP 9B) · Wikipedia https://en.wikipedia.org/wiki/Block_and_tackle
9. Human power (sustained output of a labourer, after Marks' Standard Handbook for Mechanical Engineers) · Wikipedia https://en.wikipedia.org/wiki/Human_power

Fact-checked on 2026-10-12

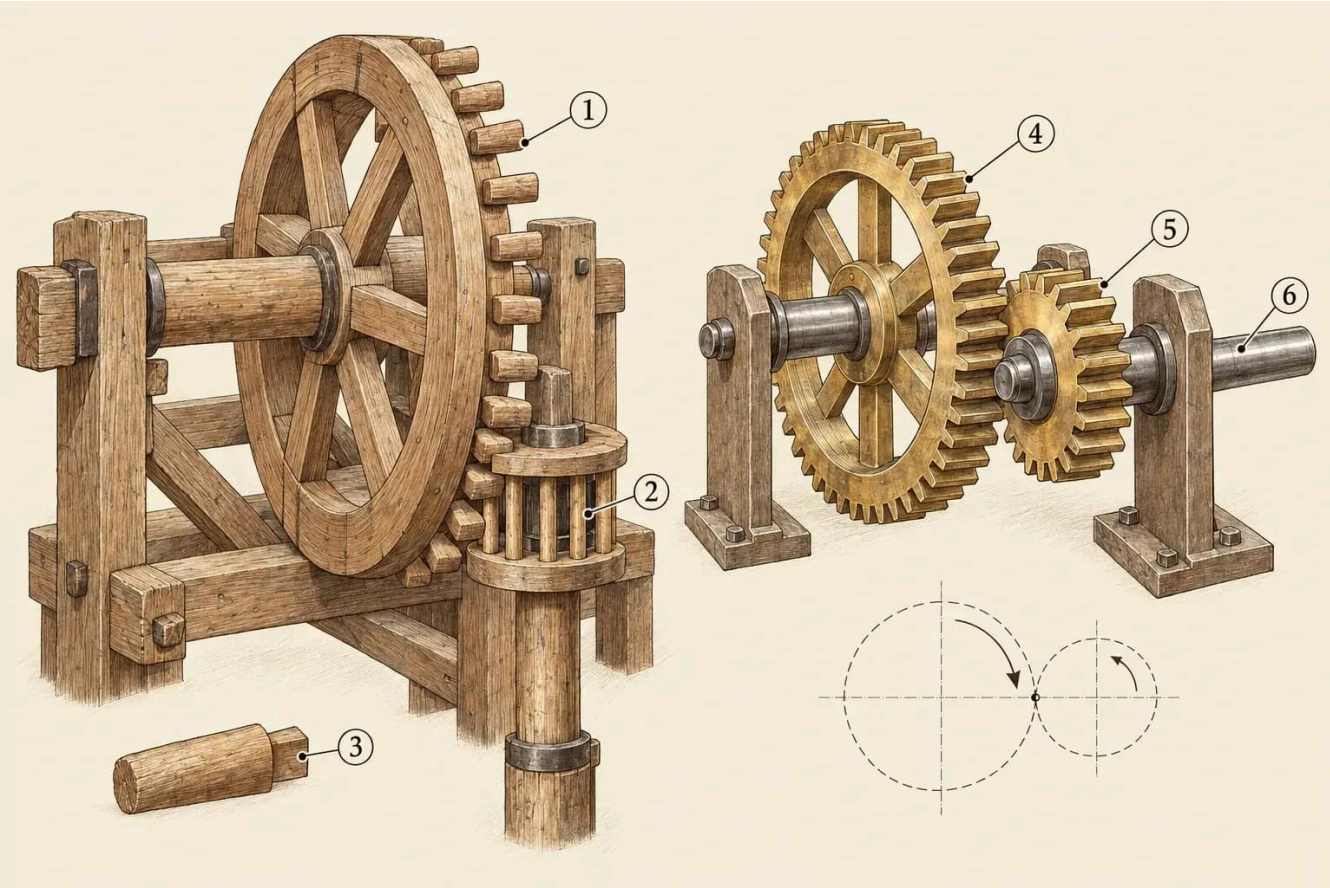
Gears

Teeth that trade speed for force

c. 300 BCE · Antiquity · Crafts & cities

Requires: Bronze (p. 120)

Leads to: Mechanical Clock (p. 196), Sewing Machine (p. 262), Steam Engine (p. 221), Water Wheel (p. 153), Windmill (p. 181)



1 Face wheel with wooden cogs 2 Lantern pinion 3 Loose wooden cog 4 Spur gear 5 Pinion 6 Shaft

A gear is a wheel with teeth that mesh with the teeth of another wheel, so one shaft can drive another without slipping. By choosing the number of teeth, a builder trades speed for force, changes the direction of motion or holds an exact ratio.

What it is

A gear is a wheel with teeth around its edge. When those teeth mesh with the teeth of a second gear, turning one wheel forces the other to turn without slipping. Gears drive mills, clocks, bicycles and car gearboxes.

A small gear driving a large one turns it more slowly but with more turning force, or torque. Two meshing spur gears turn in opposite directions, and a face wheel or a bevel gear turns the motion through a right angle. Because teeth cannot slip, a gear train also holds its ratio for years, which is what a clock depends on.

How it works

Take two meshing gears with 60 and 15 teeth. Every time a tooth of the large gear passes the point of contact, one tooth of the small gear passes too, so one turn of the large gear makes four turns of the small one. The speed ratio is the ratio of the tooth counts. The power that goes in comes out again, less friction, so torque changes the other way: the small gear turns four times faster with a quarter of the torque.

The plate shows two families. On the left is the wooden gearing of a mill: a face wheel, with pegs called cogs set into one side of its rim, drives a lantern pinion made of round staves held between two discs. A worn cog can be knocked out and replaced on its own. On the right are metal spur gears with shaped teeth on parallel shafts.

With plain pegs, the driven wheel speeds up and slows down slightly as each tooth comes into contact and leaves it, which brings noise, shaking and wear. For a steady ratio, the tooth flanks must follow curves chosen so that the push between two teeth always passes through the same point on the line between the shafts. The cycloid, long used in clocks, does this. So does the involute, the curve traced by the end of a taut string unwound from a circle. Involute gears keep their ratio even when the shafts sit slightly too far apart, and they are easier to cut, so nearly all modern gears use them.

Each turn of the worm moves the wheel on by a single tooth.

A worm is a screw that meshes with a toothed wheel. It can have one or several thread starts. The worm shown here has a single start and advances the wheel by one tooth per turn, giving a 30 to 1 reduction with a 30-tooth wheel. Whether the wheel can drive the worm backwards depends on geometry and friction. Self-locking can fail under vibration, so hoists and lifting winches need an independent load-holding brake. A rack, a straight toothed bar, turns rotation into straight-line motion.

How to build

Accurate metal gears need a lathe with a dividing plate or a gear-cutting machine. A wooden face wheel and lantern pinion, outlined here, can be made with hand tools.

Choose the ratio. Pick tooth counts for the output speed you need, for example 45 cogs and 8 staves, about 5.6 to 1. Counts with no common factor spread the wear, because every cog meets every stave in turn.

Lay out the pitch. Cogs and staves must be spaced at exactly the same distance, the pitch, measured along their pitch circles. Scribe the circle and step it out with dividers; a millimetre of error per step adds up all the way round.

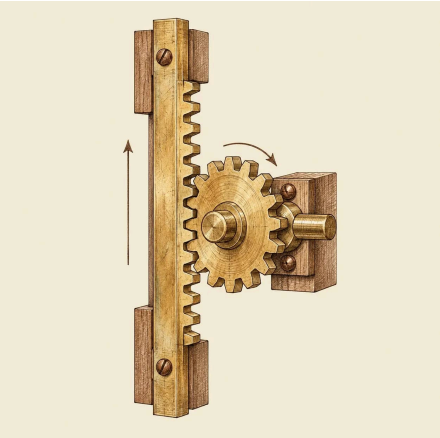
Make the wheel. Build the rim from seasoned hardwood such as oak, in overlapping segments so the grain follows the curve, and fix it to arms mortised through the axle. Cut a hole at each mark and drive in cogs of a dense, tough wood, with a tenon passing through the rim and wedged behind. Round off the working ends.

Make the lantern. Fix two discs on the shaft, drill them on the same pitch circle and drive round staves between them.

Set the mesh. Mount both shafts in solid bearings so that the cogs reach about halfway into the gaps between the staves, with a little play. Turn the gears slowly by hand, mark tight spots with chalk and pare them down. Grease the teeth with tallow.

> **Safety.** Meshing gears pull in fingers, hair and loose clothing at the point where the teeth come together. Fit a guard, tie back hair and sleeves, and never reach into gearing while it can turn: stop and lock the drive first.

History and evolution



A rack and pinion turns rotation into straight-line motion.

The *Mechanical Problems*, written in Aristotle's school around 280 BCE, describes wheels in contact turning in opposite directions, but says nothing of teeth; they may have been plain wheels relying on friction. The oldest gears that survive are small metal gears from China's Warring States period, in the fourth century BCE, kept at the museum in Luoyang.

In Alexandria in the third century BCE, Ctesibius built a water clock in which a rising float moved a rod and drums with equal teeth, as Vitruvius later described it. Archimedes is credited with the worm around 250 BCE.

The largest fragment of the Antikythera mechanism, with its four-spoked main wheel.

In 1901 divers found the most complex ancient gearing known in a wreck off the Greek island of Antikythera. The mechanism, made in the second or first century BCE, survives in 82 fragments holding 30 bronze gearwheels, about a third of the original machine. Turned by hand, it showed the positions of the Sun, the Moon and the planets and predicted eclipses.

Around 25 BCE Vitruvius described a water mill in which a toothed drum on the wheel's axle drove a larger horizontal wheel that turned the millstone. Face wheels and lantern pinions of this kind drove mills for the next fifteen centuries. Mechanical clocks spread in Europe from about 1300. Giovanni de' Dondi's astronomical clock is traditionally dated to 1348–1364, though the construction dates are disputed: Milan's science and technology museum gives 1365–1380. In the 1490s Leonardo da Vinci drew tooth shapes in the notebooks now called the Madrid Codices.

Philippe de La Hire analysed tooth curves in about 1694, and around 1754 Leonhard Euler set out the rule that teeth must follow for a steady ratio. In the nineteenth century cast-iron and then machine-cut steel gears drove the factories, and the involute replaced the cycloid in most machines.

Key figures

Speed ratio
Set by the tooth counts: 60 teeth driving 15 make the small gear turn 4 times faster

Oldest surviving gears
China, Warring States period (4th century BCE)

Antikythera mechanism
30 surviving bronze gearwheels, 2nd or 1st century BCE

Tooth theory
La Hire (c. 1694) and Euler (c. 1754) worked out the curves for a steady ratio

Sources

1. Gear · Wikipedia https://en.wikipedia.org/wiki/Gear
2. A Model of the Cosmos in the ancient Greek Antikythera Mechanism (Freeth et al., 2021) · Scientific Reports https://pmc.ncbi.nlm.nih.gov/articles/PMC7955085/
3. Geared power transmission technology (J. J. Coy, 1983) · NASA Technical Reports Server https://ntrs.nasa.gov/citations/19830011851
4. Vitruvius, De architectura, Book IX, chap. 8 (Ctesibius's water clock) · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/9*.html
5. Vitruvius, De architectura, Book X, chap. 5 (water wheels and mills) · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/10*.html
6. Self-locking of worm gear reducers · Tsubakimoto Chain https://tt-net.tsubakimoto.co.jp/tecs/engd/gen/engd_gen_ggm_gis_sfl.asp?lang=en
7. KWG Ground Worms and Worm Wheels: specifications · KHK Gears https://khkgears.net/pdf/kwg.pdf
8. L'Astrario di Giovanni Dondi · Museo Nazionale della Scienza e della Tecnologia Leonardo da Vinci https://artsandculture.google.com/story/l%E2%80%99astrario-di-giovanni-dondi-museo-nazionale-della-scienza-e-della-tecnologia-leonardo-da-vinci/0gURs225ZTyrJA?hl=it
9. Engrenage · Office québécois de la langue française https://vitrinelinguistique.oqlf.gouv.qc.ca/fiche-gdt/fiche/2091942/engrenage
10. Machinists' and Draftsmen's Handbook (Lobben, 1910), p. 325: a derrick crab worked out · Project Runeberg https://runeberg.org/lobben/0345.html
11. Effect of geometry and operating conditions on spur gear system power loss (Anderson and Loewenthal, NASA TM-81426, 1980) · NASA Technical Reports Server https://ntrs.nasa.gov/citations/19800010132
12. Human power: comfortable one-hand cranking (Jansen and Slob, ICED 03, 2003) · The Design Society https://www.designsociety.org/download-publication/23972/human_power_comfortable_one-hand_cranking

Fact-checked on 2026-10-12

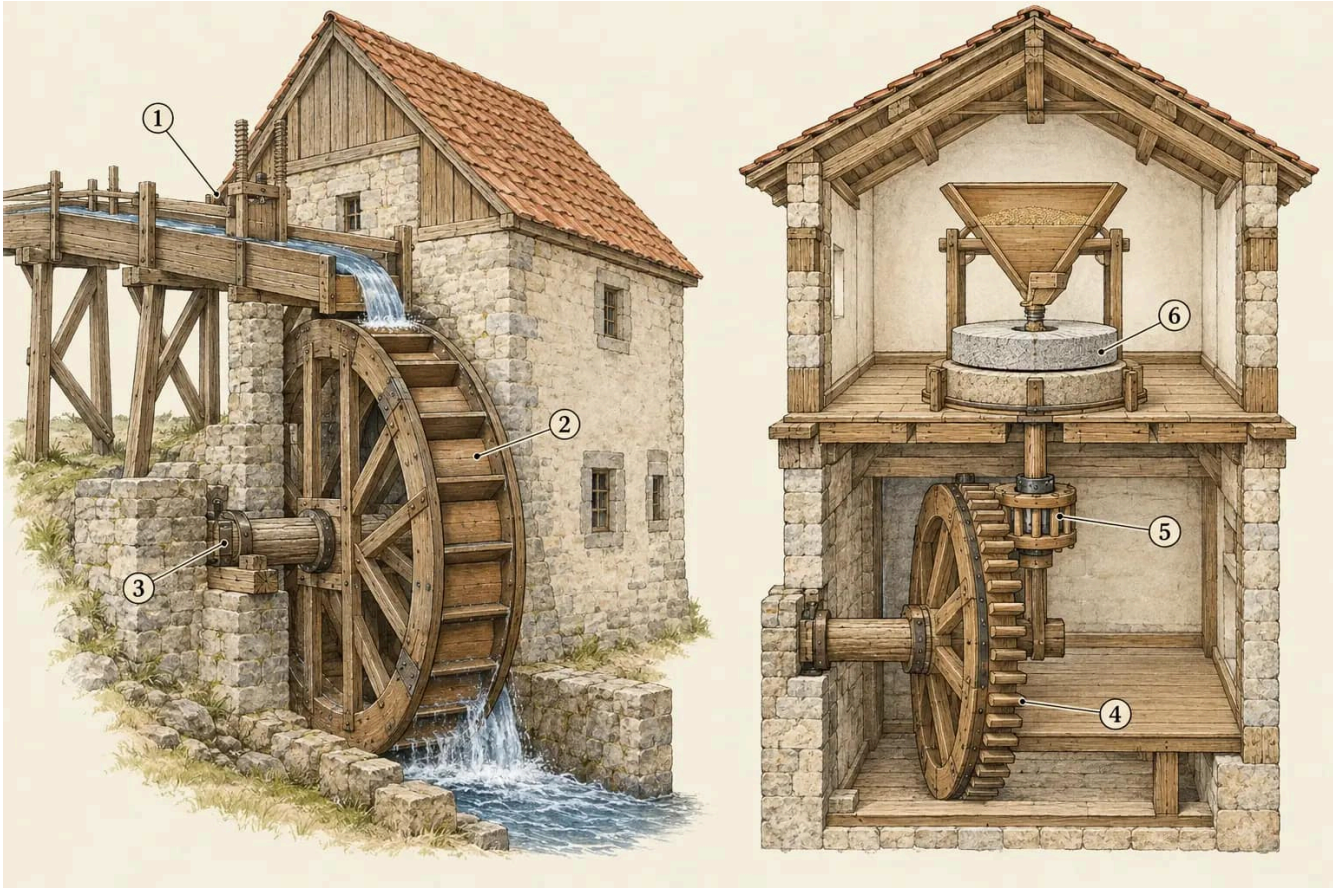
Water Wheel

A river turned into work

c. 300 BCE · Antiquity · Crafts & cities

Requires: Wheel & Axle (p. 78), Gears (p. 149)

Leads to: Water Turbine (p. 258), Windmill (p. 181)



1 Flume and sluice gate 2 Buckets 3 Axle 4 Pit wheel 5 Wallower 6 Millstones

A water wheel turns the flow or fall of water into rotation, which gears then pass to millstones, hammers, bellows or pumps. From the third century BCE until the nineteenth century it was the main source of mechanical power after people and animals.

What it is

A water wheel is a wheel fitted with paddles or buckets that moving water pushes round, and its axle drives machines. For two thousand years it ground grain. From the Middle Ages it also fulled cloth, sawed timber, worked the bellows and hammers of forges and pumped water out of mines.

An undershot wheel dips its paddles into a stream and the current pushes them. A simple traditional design needs no dam and converts only a small share of the available water energy into work. An overshot wheel, the kind on this plate, receives water at the top from a channel and turns under the weight of water in its buckets. It needs a fall at least as high as the wheel. A natural drop with an intake and channel can provide this fall; a dam and pond

are optional. A breastshot wheel receives water at axle height. Efficiency depends on the design and water supply; improved undershot wheels can also be efficient.

An undershot wheel: the current pushes the lowest paddles.

How it works

Water held in a millpond stores energy because of its height. In the overshot mill the flume (1), a wooden trough, carries it out over the top of the wheel, and a sluice gate lets the miller start the wheel, stop it and control its speed. The water drops into the buckets (2) on the descending side. That side is heavy and the other is empty, so the wheel turns slowly, a few revolutions a minute. The buckets hold their water as long as possible and empty near the bottom into the tailrace.

The available hydraulic power is $P = \rho g Q H$: water density ρ multiplied by gravitational acceleration g, volumetric flow Q and fall height H. With water at about 1,000 kg/m^3, g = 9.81 m/s^2, a flow of 100 litres per second (0.1 m^3/s) and a fall of four metres give about 3.92 kW before losses. A well-made overshot wheel converts most of this into work on its axle.

In the horizontal mill there is no gearing: the wheel's shaft is the millstone's spindle.

Inside the mill, the axle (3) carries the pit wheel (4), a large toothed wheel whose cogs drive the small wallower (5) on a vertical shaft. As in a windmill, the drive turns from horizontal to vertical and speeds up, because the wheel is slow and the upper millstone must turn much faster. That runner stone (6) grinds the grain, fed from a hopper, against the fixed bed stone beneath it.

Some mills have no gears at all. In the horizontal mill, long used in Ireland, Scandinavia and around the Mediterranean, a small wheel lies flat under the floor in a jet of water from a steep chute, and its vertical shaft turns the runner stone directly. Simple traditional designs are inexpensive and convert a relatively small share of the available water energy into work. Improved horizontal wheels can reach high efficiencies.

How to build

This outline is for a small overshot wheel driving a pump or a light machine. Taking water from a stream usually needs permission.

Find the fall. Look for a stream with a drop of two metres or more. Dig a channel, the leat, that leaves the stream upstream on a very gentle slope, so that at the wheel it runs well above the stream bed.

Size the wheel. Make the wheel a little smaller than the fall, so the water drops a short way into the top bucket. Its width depends on the flow. Buckets that are only partly filled spill less early.

Build the axle and arms. Use an oak axle, squared where the arms are fixed, with iron pins at the ends turning in bearings of hardwood or bronze on stone or concrete piers.

Make the shrouds and buckets. Fit the buckets at an angle between two rings of boards, the shrouds, and close the inner side with boards. Soak the wheel before use so the wood swells and the joints seal.

Fit the flume and sluice. Carry the water to the top of the wheel in a wooden trough on trestles, with a sliding gate and a spillway that sends the water past the wheel when it is stopped. Check that the wheel is balanced, then open the sluice gradually.

> **Safety.** A loaded wheel is heavy and does not stop at once: never climb on it or reach into it while it turns. Before maintenance, shut off the water supply, lock the sluice against reopening and divert any leakage away from the wheel. Verify that the wheel has stopped completely. From a safe position, drain retained water and secure the wheel and driven machinery with restraints rated for the remaining loads so stored energy cannot move them. Have a competent person establish and check this isolation. Fast water in a channel can knock over and drown an adult, so fence the tailrace and never work near it alone. Fit guards over all accessible gearing to prevent hands and clothing from reaching it.

History and evolution

The first wheels lifted water. In the third century BCE Philo of Byzantium described a wheel with compartments used for irrigation in Egypt. The historian M. J. T. Lewis argues that grain mills driven by water appeared in the same century, first with a vertical axle, then with a horizontal one. The earliest clear description of a geared water mill comes from Vitruvius around 25 BCE: an undershot wheel drives the millstone through a toothed drum and a larger horizontal wheel.

At Barbegal, near Arles in southern France, the Romans built sixteen overshot wheels in two rows of eight down a hillside, fed by an aqueduct. The complex was built in the second century CE. In China, Du Shi used water power to work the bellows of iron foundries in 31 CE.

In North Africa and the Near East, the noria, a large wheel turned by the current with pots on its rim, raised water into irrigation channels and supplied towns. In the tenth century the physician al-Razi described one in Iraq lifting about 153,000 litres an hour.

A noria: the current turns the wheel, and the wheel lifts part of the river.

Water mills multiplied in medieval Europe. The Domesday survey of 1086 counted about six thousand in England, and wheels came to drive fulling stocks, saws, forge bellows and trip hammers.

In the 1750s the English engineer John Smeaton tested model wheels. At comparable available hydraulic energy, his overshot designs did at least twice the work of his undershot designs. He published the results in 1759. This comparison applies to the tested designs; it is not a fixed ratio for all water wheels. The Laxey Wheel on the Isle of Man, finished in 1854 to pump water out of the Laxey mines, is 22.1 metres across. From 1827 Benoît Fourneyron's turbine began to replace the wheel, and the turbines of modern hydroelectric plants descend from it.

Key figures

First description
Philo of Byzantium, 3rd century BCE (a water-lifting wheel)

England, 1086
About 6,000 mills in the Domesday survey

Overshot or undershot
Overshot at least twice as efficient in Smeaton's tests at comparable available hydraulic energy (1759)

Largest working wheel
Laxey, Isle of Man: 22.1 m across, built 1854

Sources

1. Water wheel · Wikipedia https://en.wikipedia.org/wiki/Water_wheel
2. Vitruvius, De architectura, Book X, chap. 5 (water wheels and mills) · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/10*.html
3. The Scientists, the Engineers, and the Water Wheel · JSTOR Daily https://daily.jstor.org/the-scientists-the-engineers-and-the-water-wheel
4. Great Laxey Wheel · Manx National Heritage https://manxnationalheritage.im/?p=18117
5. John Smeaton · Wikipedia https://en.wikipedia.org/wiki/John_Smeaton
6. Providing and using work equipment safely: A brief guide · Health and Safety Executive https://www.hse.gov.uk/pubns/indg291.pdf
7. The second century CE Roman watermills of Barbegal: Unraveling the enigma of one of the oldest industrial complexes · Science Advances, American Association for the Advancement of Science https://pmc.ncbi.nlm.nih.gov/articles/PMC6124920/
8. Waterwheel · Energy Education, University of Calgary https://www.energyeducation.ca/encyclopedia/Waterwheel
9. Gravity water wheels as a micro hydropower energy source: A review based on historic data, design methods, efficiencies and modern optimizations · Politecnico di Torino, institutional repository https://iris.polito.it/handle/11583/2712517
10. High hydraulic performance in horizontal waterwheels · Universitat de Girona, Research Portal https://recerca.udg.edu/en/publications/high-hydraulic-performance-in-horizontal-waterwheels/

Fact-checked on 2026-10-12

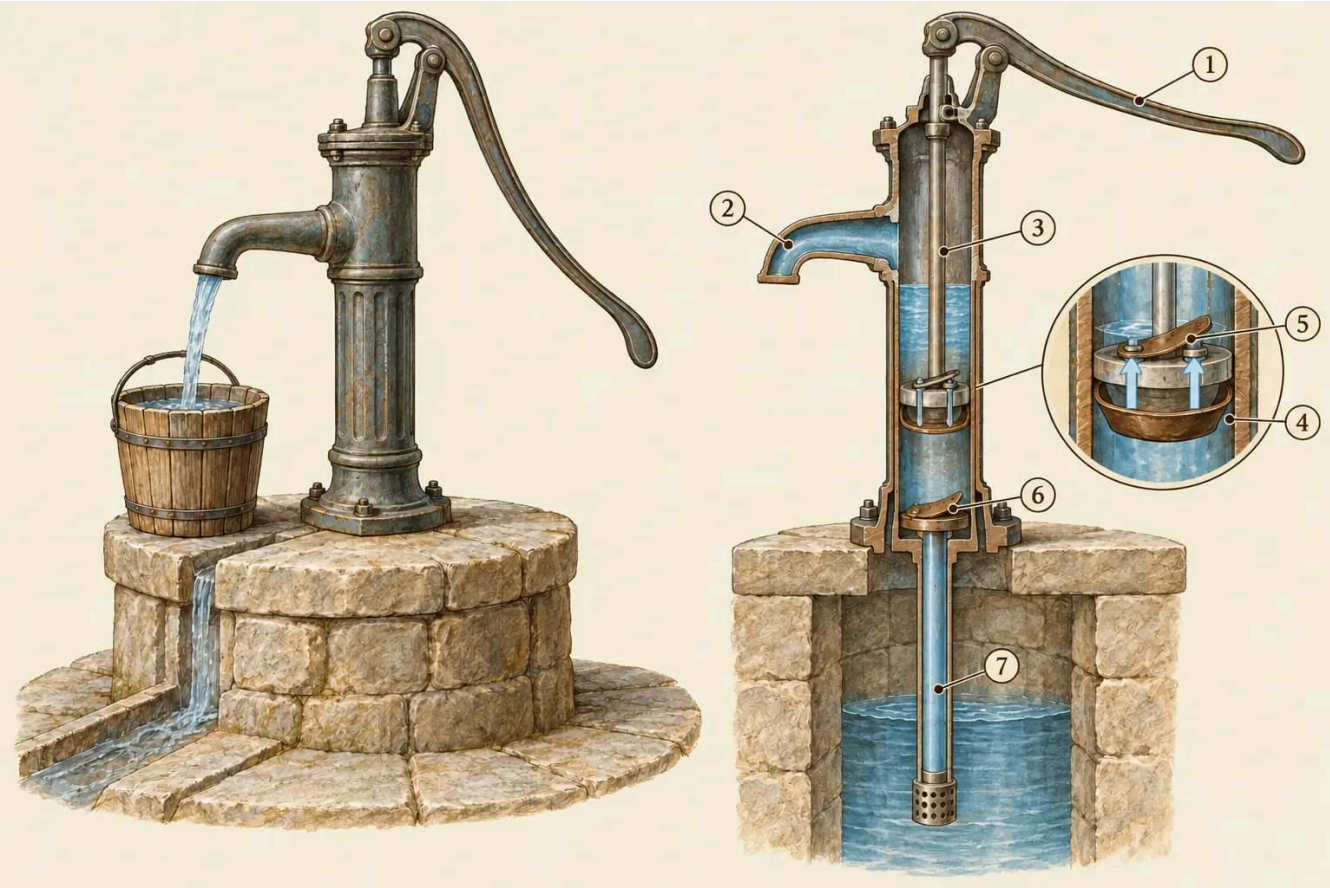
Piston Pump

Water raised by valve and piston

c. 270 BCE · Antiquity · Crafts & cities

Requires: Bronze (p. 120), Leather Tanning (p. 98)

Leads to: Refrigeration (p. 274), Steam Engine (p. 221)



1 Handle 2 Spout 3 Pump rod 4 Leather cup seal 5 Piston valve 6 Foot valve 7 Suction pipe

A piston pump moves water with a plug that slides up and down in a cylinder, between two valves that let the water pass one way only. Ctesibius of Alexandria is credited with the force pump, in the third century BCE; the suction pump, which draws water up from below, came into wide use in late medieval Europe and ended up on village wells all over the world.

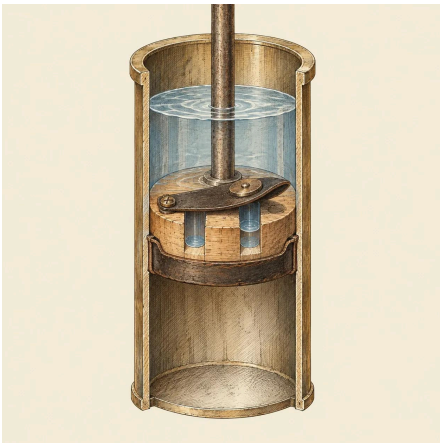
What it is

A piston pump moves water with a plug that slides up and down in a tube, between two valves that open one way only. Such pumps have drained mines, fed fountains, fought fires and drawn water from wells for over two thousand years.

A suction pump, or lift pump, stands above the water and draws it up a pipe. A force pump sits in the water, or below its outlet, and pushes the water out under pressure. The plate shows a nineteenth-century suction pump on a covered village well.

How it works

At the bottom of the cylinder sits the foot valve, a flap of leather or rubber that lifts to let water in and drops back onto its seat. The piston carries a second flap over holes bored through it, and a leather cup round its edge. The cup opens upwards, so the water above presses it against the wall.



On the upstroke the water above holds the flap shut; on the downstroke it lifts and the water passes through.

When the handle pulls the piston up, its valve stays shut and the water resting on it rises to the spout. Below the piston the pressure falls, and the air pressing on the well surface pushes water up the suction pipe and through the foot valve. On the downstroke the foot valve closes, the piston valve opens and the piston slips down through the water.

On the suction side the atmosphere does the work, and its push has a limit. At sea level the weight of the air balances a column of water about 10.3 metres high, or 76 centimetres of mercury. Leaks, friction and water boiling at low pressure keep a hand suction pump to about 7 metres, less in the mountains.

A force pump drives water out through a delivery valve, as high as the force applied and the pipes allow. Deep-well hand pumps put the cylinder below the water and work the piston with a long rod, so suction no longer sets the limit. Two cylinders worked in turn, or a double-acting piston that delivers on both strokes, even out the flow, and an air vessel on the outlet, where trapped air is squeezed and expands again, turns the pulses into a steady jet.

How to build

A small suction pump for a shallow well or rain tank can be made from plastic pipe, with the water less than about 6 metres below the cylinder, ideally 3 or 4.

Cylinder. Use 60 to 80 cm of smooth PVC pipe about 50 mm across, mounted upright, with a tee near the top as the spout. A narrower pipe runs from its base into the water. Every joint below the piston must be airtight.

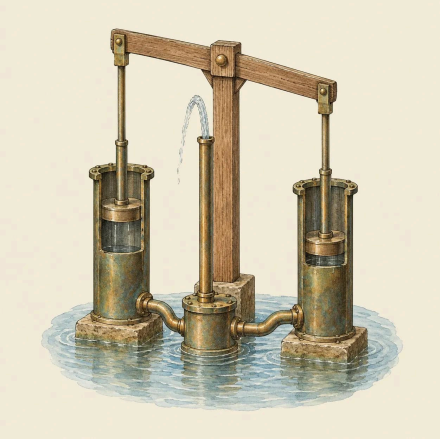
Foot valve. Close the bottom of the cylinder with a plug drilled with a hole about 2 cm across. Lay a disc of leather or inner-tube rubber over it, screwed down along one edge as a hinge and weighted with a washer.

Piston. Cut a plug of hardwood or plastic slightly smaller than the bore, drill holes through it and cover them with a similar flap. Clamp a cup of thick leather or rubber below it, rim turned upwards and centre cut away so the holes stay open. Soak a leather cup before fitting it. A rod joins the piston to a lever about a metre long, pivoted on a post.

Prime and maintain. Pour a cup of clean water into the cylinder to wet the cup and seal the valves, then pump. If it loses its water overnight, check the foot valve.

> **Safety.** Never leave a well open: cover it with a slab or a lid an adult can stand on, and keep children away. Never climb down a well, where the air may lack oxygen. Keep fingers clear of the pivot. Seal the pipe through the cover, slope the ground away and keep latrines and animals far off. Prime only with water safe to drink, since it runs into the well. Leather, inner tube and ordinary plastic are not made for drinking water: keep this pump for garden or washing water unless every wetted part is certified for drinking water. Do not drink from a well until a test has shown it safe; boiling kills germs but does not remove chemicals.

History and evolution



The pump of Ctesibius as Vitruvius describes it: two bronze cylinders working in turn and feeding one upright pipe.

Ctesibius, an engineer in Alexandria around 270 BCE, is credited with the force pump. Vitruvius described its bronze cylinders and valves about 25 BCE. A 2007 census by Richard Stein counted thirteen Roman metal pumps, mostly bronze, and eighteen wooden ones cut from oak blocks, most of them found in wells; one, from Silchester, is in Reading Museum.

Around 1206 al-Jazari described a pump driven by a water wheel, with two opposed pistons and true suction pipes. Suction pumps reached European mines in the late Middle Ages. In 1556 Georgius Agricola described sets of three pumps one above another, each with about seven metres of pipe, lifting into a tank for the next.

In 1638 Galileo reported that no suction pump could raise water more than eighteen braccia, about 10.5 metres, and thought the column broke under its own weight. His pupil Torricelli found the cause in 1644 (some accounts say 1643): mercury in a glass tube stands at about 76 cm, held up by the weight of the air. In 1648 Pascal had his brother-in-law carry the tube up the Puy de Dôme, where the mercury stood about 8.5 cm lower.

In London, Richard Newsham patented a fire engine in 1721 whose two pumps fed an air vessel for a continuous jet. For mines, Thomas Newcomen had built his first steam engine near Dudley in 1712 to work their pumps. In India, a UNICEF review in 1974 found that three quarters of the wells drilled over the previous seven years were not supplying water. UNICEF, the government and the firm Richardson and Cruddas then developed the India Mark II, with its cylinder down the borehole, able to lift water from 50 metres. Millions are in use, and it has been exported to more than 40 countries.

A fire engine of Newsham's type: two pumps worked by long handles, and an air vessel that keeps the jet steady.

Key figures

Suction limit in theory
About 10.3 m of water at sea level, the height the weight of the air can hold up

Suction limit in practice
About 7 m from the water surface up to a hand pump

Ctesibius's force pump
Alexandria, about 270 BCE; known through Vitruvius, about 25 BCE

Roman pumps found
13 in metal, mostly bronze, and 18 in wood (2007 census)

India Mark II hand pump
Lifts of 10–50 m, cylinder 63.5 mm across, millions installed since the late 1970s

Sources

1. Vitruvius, On Architecture, Book X, chapter 7 (Gwilt translation, 1826) · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/10*.html
2. Roman Wooden Force Pumps (R. J. B. Stein), in Énergie hydraulique et machines élévatrices d'eau dans l'Antiquité, 2007 · Publications du Centre Jean Bérard, OpenEdition Books https://books.openedition.org/pcjb/405
3. Horror vacui? The syphon experiment · Museo Galileo, Florence https://www.imss.fi.it/vuoto/eesper1.html
4. Horror vacui? Torricelli's barometric experiment · Museo Galileo, Florence https://www.imss.fi.it/vuoto/eesper2.html
5. Horror vacui? The void within a void · Museo Galileo, Florence https://imss.fi.it/vuoto/eesper3.html
6. Barometers · Encyclopedia.com https://www.encyclopedia.com/earth-and-environment/atmosphere-and-weather/meteorological-instruments/barometers
7. Al-Jazari, Badi al-Zaman (Dictionary of Scientific Biography) · Encyclopedia.com https://www.encyclopedia.com/science/dictionaries-thesauruses-pictures-and-press-releases/al-jazari-badi-al-zaman-abu-l-izz-ismail-ibn-al-razzaz
8. Georgius Agricola, De re metallica, Book VI (Hoover translation, 1912) · Project Gutenberg https://www.gutenberg.org/ebooks/38015
9. Mine Pumping in Agricola's Time and Later (R. P. Multhauf, 1959) · Smithsonian Institution, via Project Gutenberg https://www.gutenberg.org/ebooks/31024
10. Hand pumps for water lifting · Practical Action https://samplecontents.library.ph/en-practical_action/Energy/Mechanical%20Power/KnO-100411_Human-powered%20handpumps/page5.html
11. No. 6 pump (public-domain handpump specification) · Rural Water Supply Network https://www.rural-water-supply.net/en/implementation/public-domain-handpumps/no-6-pump
12. Water lifting devices, chapter 3.5: reciprocating displacement pumps · Food and Agriculture Organization of the United Nations https://www.fao.org/4/ah810e/ah810e06.htm
13. India Mark II handpump specification · Rural Water Supply Network https://www.rural-water-supply.net/en/implementation/public-domain-handpumps/india-mark-ii
14. How three handpumps revolutionised rural water supplies: the India Mark II · Rural Water Supply Network https://rwsn.blog/2013/03/19/how-three-handpumps-revolutionised-rural-water-supplies-the-india-mark-ii/
15. A history of UNICEF work on water, sanitation and hygiene in India · UNICEF India https://www.unicef.org/india/stories/history-unicef-work-water-sanitation-and-hygiene-india
16. ASME Landmark: Newcomen Engine · Engineering and Technology History Wiki https://ethw.org/ASME-Landmark:Newcomen_Engine
17. Fire Engine (Newsham, patented 1721) · Colonial Williamsburg Foundation https://history.org/primary-content/fire-engine/
18. Suction pump · Wikipedia https://en.wikipedia.org/wiki/Suction_pump

Fact-checked on 2026-10-14

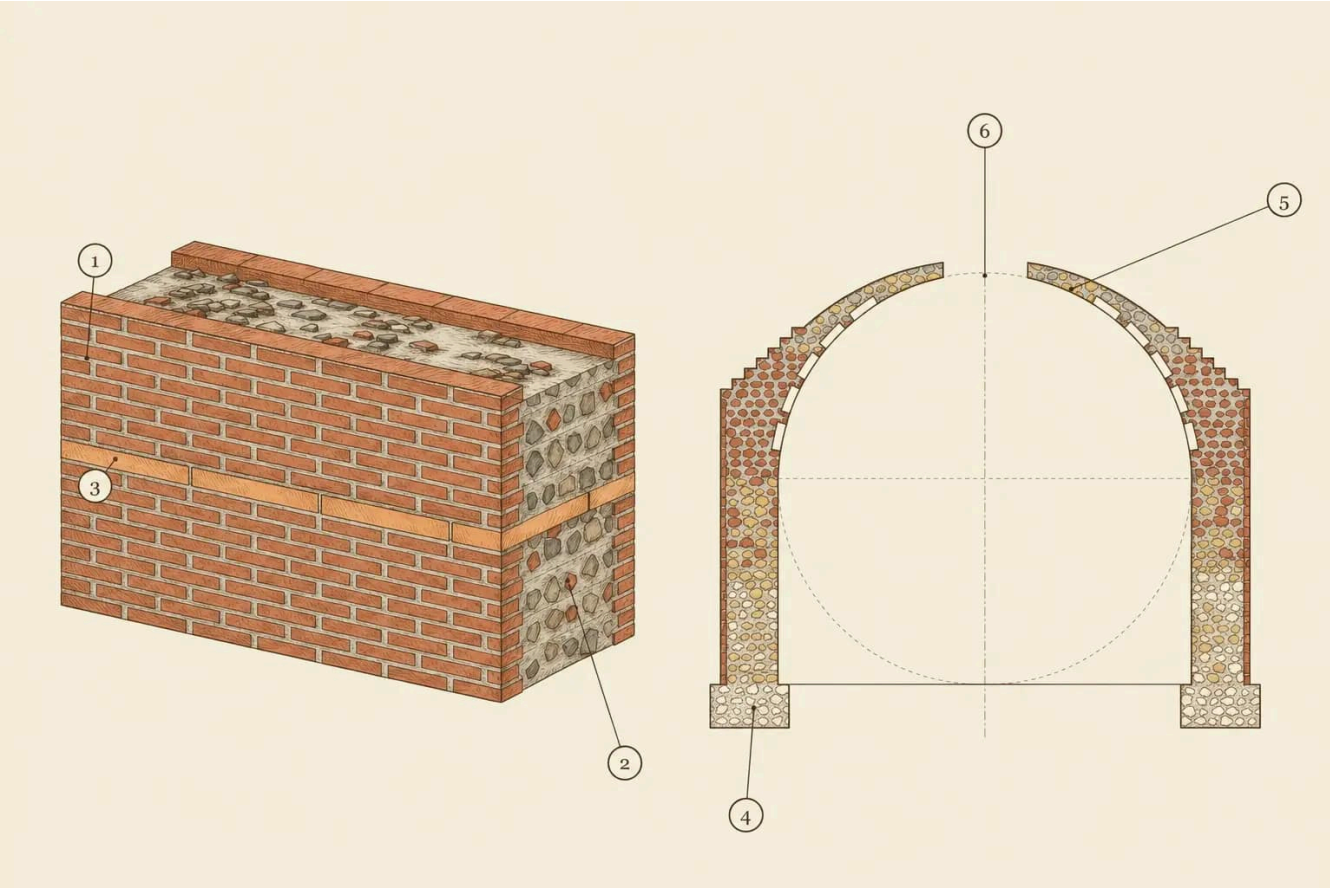
Roman Concrete

Lime, volcanic ash and rubble

c. 200 BCE · Antiquity · Crafts & cities

Requires: Bricks (p. 39), Control of Fire (p. 9), Lime and lime mortar (p. 30)

Leads to: Portland Cement (p. 250)



1 Brick facing 2 Core of rubble in mortar 3 Bonding course of large flat tiles 4 Heavy travertine in the foundations 5 Light pumice and tuff in the upper dome 6 Oculus

Roman concrete is lime mortar packed around lumps of stone or broken brick; in its best-known form the mortar contains volcanic ash. The ash makes it set hard even under water, and it carried the vaults of Rome, its harbours and the unreinforced dome of the Pantheon, still the largest of its kind.

What it is

Roman concrete, opus caementicium, is a mass of stone fragments bound by a lime mortar, which in many Roman works contained volcanic ash. The Romans called the fragments caementa, from which the word cement comes. From the second century BCE it let builders raise walls, vaults and domes of a size that cut stone alone could not reach, at lower cost and with less skilled labour.

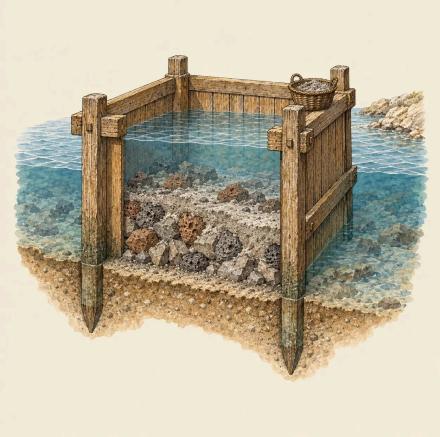
Two things set it apart from a plain lime mortar: volcanic ash, which lets it harden even under water, and a way of building in layers of rubble between faces of brick or small stones.

How it works

The binder starts as limestone. Burnt in a kiln, it gives off carbon dioxide and becomes quicklime; mixed with water, the quicklime swells and heats up and becomes slaked lime. A mortar of pure air lime hardens slowly, as it takes back carbon dioxide from the air, and it stays soft wherever air cannot reach.

A lime kiln: the limestone is stacked on an arch above the fire and comes out as white quicklime.

Volcanic ash changes that. The ash of the Bay of Naples, named pozzolana after the town of Pozzuoli, is rich in silica and alumina in a reactive, glassy form. It reacts with the lime and water and forms new binding minerals, so the mortar hardens by reacting with water rather than with air, even when it is submerged. Vitruvius, writing about 25 BCE, noted that this volcanic sand from around Baiae and Vesuvius, mixed with lime and rubble, hardened under water as well as on land.



Marine concrete: builders filled timber boxes standing in the sea with ash mortar and rubble.

For harbours, builders drove timber piles into the sea bed, tied them together into an enclosure and filled it with mortar and lumps of tuff straight into the water; Vitruvius also describes enclosures that were pumped dry before filling. Pliny the Elder described such piers as a single stone mass “every day stronger”. In 2017 a team led by the geologist Marie Jackson found that seawater slowly dissolves parts of the ash and that new minerals, among them the rare aluminous tobermorite and phillipsite, grow in its pores. The team argues that these interlocking crystals help the concrete resist cracking.

Workers built Roman concrete up in layers. They spread a layer of hand-sized stones or broken brick, rammed mortar into it, and repeated the process course after course; baskets of mortar were carried to the wall by hand. The faces of brick or small squared stones served as permanent formwork. Courses of large flat tiles ran through the wall at intervals and tied the two faces to the core.

In 2023 a team at MIT led by Admir Masic studied the small white lumps of lime found in Roman concrete. They concluded that the builders mixed some of the lime as quicklime, which heats the mix as it reacts. The lumps act as a reserve: when water enters a crack, it dissolves lime from them and deposits calcium carbonate that seals the gap. The team then made modern test mortars with added quicklime, cracked them and ran water through them; according to MIT’s report the cracks sealed within about two weeks, while a control made without quicklime did not heal.

The white lumps are lime clasts. Where a crack crosses one, water can dissolve the lime and refill the crack with calcite.

Roman concrete is weaker in compression than modern Portland cement concrete and gains strength slowly. Builders allowed for this: in the Pantheon, brick arches buried in the walls carried loads while the concrete cured.

How to build it

A small test block, about 30 cm long, shows how the material behaves. Treat it as a demonstration only, not as a load-bearing part of a building. Use materials sold for lime work and restoration.

Gather the materials. You need hydrated lime powder, a natural pozzolana or another pozzolan sold for lime mortars, and aggregate: clean broken brick or stones from walnut to egg size. Wear gloves and eye protection from the start, work in a well-ventilated place and keep dust down.

Mix the mortar. Use the proportions by volume that the pozzolan supplier gives for hydrated lime. Put on a fitted particulate respirator, as the product data sheets specify, and mix the powders dry. Add water little by little until the mortar is stiff and sticky, not runny.

Build the faces. Dampen the bricks and the broken-brick aggregate beforehand, without leaving water standing on them, so that they do not suck the water out of the fresh mortar. Lay two short, thin skins of brick in lime mortar, a hand's height at a time. They act as the formwork and stay in place.

Fill the core. Spread a layer of mortar between the skins, press the aggregate into it, then ram more mortar into the gaps with a wooden tamper until no voids remain. Work in layers about 6 to 8 cm deep, so that mortar surrounds every piece, and finish with a course of flat tiles laid right across the block.

Cure it slowly. Keep the work damp and shaded for at least two weeks, covered with wet sacking, and protect it from frost. Lime and pozzolan go on gaining strength for months; break the block open after a few months to see how far it has set.

> **Safety.** Lime is caustic. It burns skin and can blind: wear gloves, long sleeves and sealed goggles, and rinse any splash with plenty of clean water at once, then get medical help for the eyes. Wear a fitted particulate respirator when tipping or mixing dry lime and pozzolan. Do not slake quicklime or try the Roman "hot mixing" yourself: quicklime and water react violently, boil and spit. This home mix is not tested for strength: do not use it for steps, walls or anything that must carry a load.

History and evolution

Lime mortars were used around the Mediterranean long before Rome; Roman builders turned them into a structural material. Concrete was in wide use by about 150 BCE, and some scholars place its beginning a century earlier. Concrete that sets under water was probably developed around the Bay of Naples, where the ash is found, by the end of the second century BCE; which surviving harbour works are the oldest is debated.

Under the empire it carried most large buildings. Herod's harbour at Caesarea, built from about 22 BCE, was made with ash shipped from Italy. The Pantheon, rebuilt under Hadrian between about 117 and 125 CE, has a dome 43.3 m across with a round opening about 9 m wide at the top. Its walls are about 6 m thick, and the aggregate changes from heavy travertine in the foundations to tuff, brick, and light pumice and tuff in the upper dome. It remains the largest unreinforced concrete dome in the world.

After the western empire fell, large concrete construction faded and lime mortar went back to binding masonry. Modern concrete, made with Portland cement and often reinforced with steel, sets faster and is stronger, but in seawater it can crack, and its steel can corrode, within decades if it is poorly made or poorly protected. Researchers now study Roman harbour cores and lime clasts to make concrete that lasts longer and emits less carbon dioxide.

Key figures

Binder
Lime, often with volcanic ash (pozzolana)

Mix for work under water
About 1 part lime to 2 of ash (Vitruvius)

Pantheon dome
43.3 m across, no reinforcement, completed c. 125 CE

Density of the Pantheon's concrete
About 2,200 kg/m^3 in the foundations, 1,350 kg/m^3 near the top

Sources

1. Vitruvius, The Ten Books on Architecture, Book II (lime and pozzolana) · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/2*.html
2. Vitruvius, The Ten Books on Architecture, Book V, chapter 12 (harbours) · LacusCurtius, University of Chicago https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/5*.html
3. Hot mixing and the durability of ancient Roman concrete (news release, 6 January 2023) · MIT News https://news.mit.edu/2023/roman-concrete-durability-lime-casts-0106
4. How seawater strengthens ancient Roman concrete (news release, 3 July 2017) · University of Utah, via EurekAlert! https://www.eurekalert.org/news-releases/778694
5. The Pantheon: crown jewel of Roman concrete (David Moore, Constructor, 2002) · Associated General Contractors of America (Constructor magazine) https://www.ancientportsantiques.com/wp-content/uploads/Documents/ETUDESarchivees/Ma%c3%a7onnerie/B%c3%a9tonRomain/RomanConcretePantheon-Moore2002.pdf
6. Roman concrete · Wikipedia https://en.wikipedia.org/wiki/Roman_concrete
7. A comparison of the chemical and engineering characteristics of ancient Roman hydraulic concrete with a modern reproduction of Vitruvian hydraulic concrete (Gotti, Oleson et al., Archaeometry 50, 2008) · University of Oxford / Wiley (Archaeometry) https://www.ancientportsantiques.com/wp-content/uploads/Documents/ETUDESarchivees/Ma%C3%A7onnerie/B%C3%A9tonRomain/RomanConcrete-Gotti2008.pdf
8. Building for Eternity: the History and Technology of Roman Concrete Engineering in the Sea (J. P. Oleson ed., 2014) · Oxbow Books https://www.ancientportsantiques.com/wp-content/uploads/Documents/AUTHORS/Oleson2014-BuildingforEternity.pdf
9. Building a Roman pila: the ROMACONS experiment at Brindisi, September 2004 · J. P. Oleson, University of Victoria https://web.uvic.ca/~jpoleson/Harbour%20Concrete/ROMACONS04Pila.html
10. FEM static and dynamic modeling of Roman vaulted monuments in opus caementicium (R. Perucchio, 2012) · University of Rochester, via SAHC Masters https://msc-sahc.org/wp-content/uploads/2020/07/5-fem-roman-vaults-guimaraes-1oct2012.pdf

Fact-checked on 2026-10-12

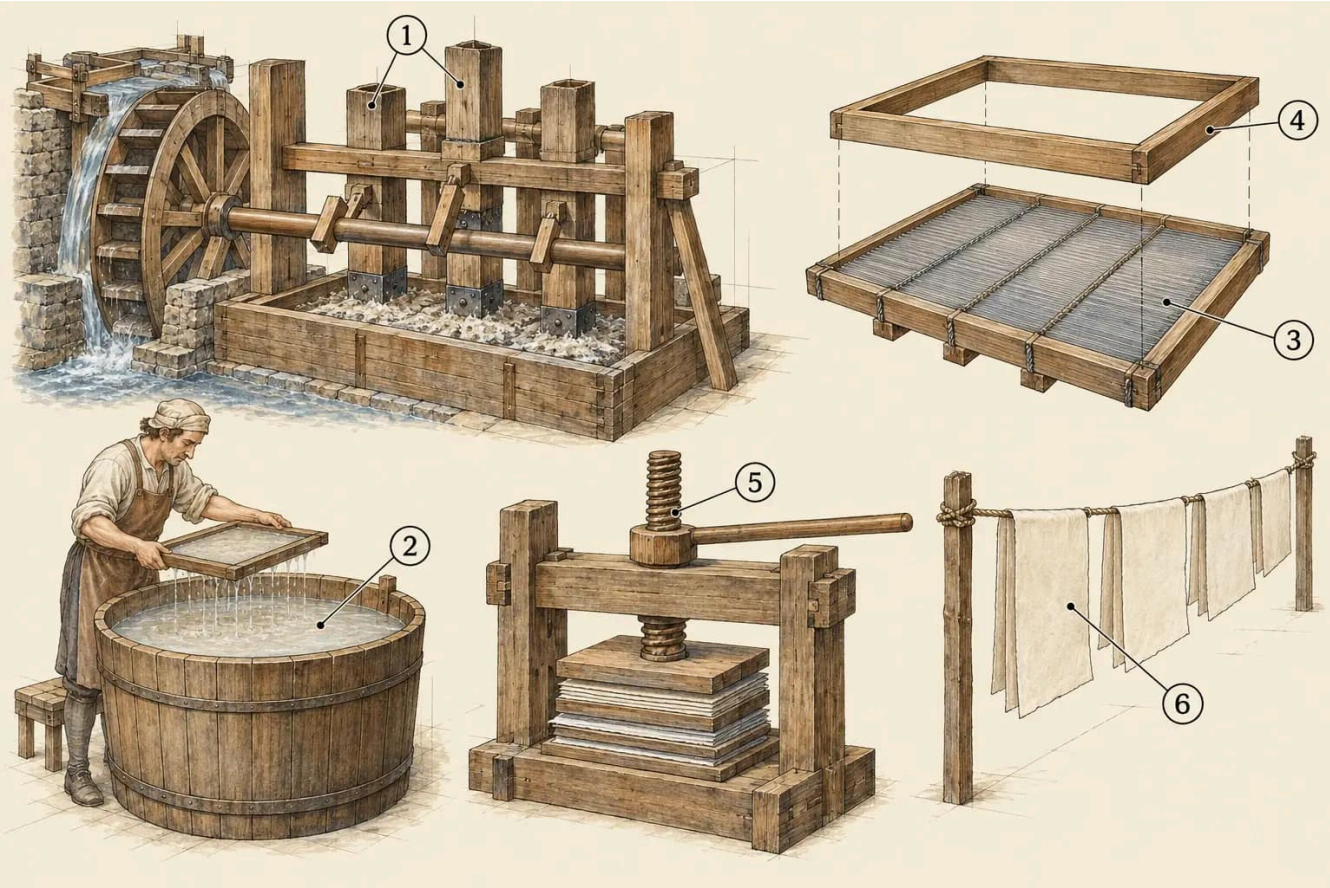
Paper

A cheap surface for memory

c. 150 BCE · Antiquity · Crafts & cities

Requires: Pottery (p. 22)

Leads to: Hot-Air Balloon (p. 225), Printing Press (p. 200)



1 Stampers beating rags into pulp 2 Vat of pulp 3 Mould 4 Deckle 5 Screw press with a post of felts and sheets 6 Sheets hung up to dry

Paper is a thin mat of plant fibres, beaten in water, caught on a screen and dried until the fibres bond to one another. Lighter than bamboo slips and cheaper than silk or parchment, it carried writing and then print from Han China to the rest of the world.

What it is

Paper is a sheet of plant fibres that have been separated, mixed into water and left to settle into a thin mat. When the mat dries, the fibres hold together with no glue. Papyrus, by contrast, is made of strips of pith from the papyrus sedge pressed crosswise, and parchment is animal skin.

It can even be made from waste such as rags and worn fishing nets. For about two thousand years it has carried writing, print, money and maps.

The plate shows the European hand method, used until machines took over in the nineteenth century.

How it works

Paper owes its strength to cellulose, the long molecule of plant cell walls. Beaten in water, the fibres swell and split into fine fibrils. As the wet mat dries, the water pulls the fibres into close contact and hydrogen bonds form wherever they touch. Soaking undoes them, which is why wet paper tears so easily.

First the raw material becomes pulp. In China, bark, hemp and later bamboo were soaked, boiled and pounded. In Europe, linen and hemp rags were left to rot for some weeks, then beaten in troughs by wooden stampers lifted by cams on a waterwheel shaft.

The pulp is stirred into a vat of water until it looks like thin milk. The vatman dips the mould, a wooden frame strung with fine wires, and brings it up level. A loose frame called the deckle sits on top and sets the edge of the sheet. As the water drains, he gives the mould a short shake both ways so the fibres settle in every direction and lock together.

The coucher turns the mould over onto a woollen felt, and the wet sheet stays on the felt. Felts and sheets pile up into a post, which goes into a screw press to squeeze out most of the water. The sheets then dry on lines. For pen and ink, European sheets were dipped in animal gelatine, without which ink spreads as on blotting paper.

Fine laid wires, heavier chain wires and a watermark sewn on in wire.

How to make it

Bark, hemp, rags and old nets: the materials named in Cai Lun's report of 105.

Cotton or linen rags, hemp and the inner bark of mulberry are the easiest fibres. Wood needs grinding machines or chemical cooking.

Prepare the fibre. Cut rags into small pieces. Soak them for several days, then beat them with a pestle or a mallet on a flat stone until a pinch shaken in a jar of water opens into a loose cloud with no threads left. Bark is first boiled for a few hours in water with wood ash, in an iron or stainless steel pot (never aluminium), then rinsed until the water runs clear and the fibre no longer feels slippery, and beaten.

Make the mould and deckle. Build two identical frames of straight-grained wood, the size of the sheet you want. Over one, stretch a fine screen: brass wire, closely woven cloth, or thin bamboo or grass stems tied side by side, as papermakers in Asia did. The bare frame is the deckle.

Form the sheet. Fill the tub with water and add pulp until it is cloudy. Hold mould and deckle together, slide them in at the far side, bring them up flat and shake gently as the water runs out.

Couch and press. Lift off the deckle, turn the mould face down onto a damp felt and press along the back so the sheet stays behind. Lay another felt on top and repeat. Press the stack between weighted boards or in a screw press.

Dry and size. Hang the sheets over a line, or brush them onto a smooth board. To write on them in ink, dip the dry sheets in warm, thin gelatine or starch paste and let them dry again.

> **Safety.** Lye made from wood ash burns skin and eyes: wear gloves and eye protection, and boil fibre outdoors. The floor around a vat stays wet and slippery. Water-driven stampers and screw presses can crush fingers: before reaching in, disconnect the waterwheel, lock the stampers so they cannot fall and slacken the press.

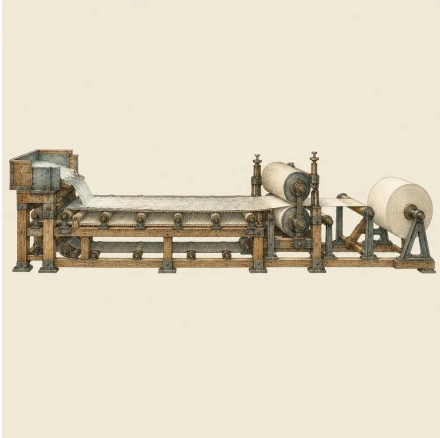
History and evolution

For centuries the invention was credited to Cai Lun, an official at the Eastern Han court, who in 105 CE reported to the emperor a way of making paper from bark, hemp waste, rags and fishing nets. Archaeology has moved the date back: a fragment with a map drawn on it, from a tomb at Fangmatan in Gansu, dates from the second century BCE. Cai Lun most likely improved the process and made it practical for writing.

Papermaking reached Korea, Vietnam and, by the early seventh century, Japan. The story that Chinese prisoners taken at Talas in 751 brought it to Samarkand is doubted, since paper was used there earlier. From the Islamic world the craft reached Spain, where Xàtiva was making paper by the twelfth century.

In the thirteenth century the mills of Fabriano in Italy added water-driven stampers, gelatine sizing and watermarks. Ulman Stromer set up the first documented paper mill in German lands at Nuremberg in 1390.

In 1799 the Frenchman Louis-Nicolas Robert patented a machine that formed paper on an endless moving wire. The Fourdrinier brothers financed its development in England, and modern machines keep the same layout. In the 1840s Friedrich Gottlob Keller in Saxony and Charles Fenerty in Nova Scotia showed that ground wood could replace rags. Wood pulp made paper much cheaper and helped newspapers grow, but much of it was acidic, and many nineteenth-century books have turned yellow and brittle while fifteenth-century rag paper is still supple.



On the paper machine the mould became an endless wire belt and the sheet became a continuous web.

Key figures

Oldest known fragment
Map from Fangmatan, Gansu, 179–141 BCE

First paper mill in German lands
Nuremberg, 1390

First paper machine patent
Louis-Nicolas Robert, France, 1799

Cai Lun's report to the emperor
105 CE

Output of one vat crew by hand
About 1,000 to 4,500 sheets in a long working day

Sources

1. History of paper · Wikipedia https://en.wikipedia.org/wiki/History_of_paper
2. The oldest paper on Earth to be displayed (Fangmatan map) · Hong Kong SAR Government https://www.info.gov.hk/gia/general/199809/05/0904159.htm
3. Cai Lun invents paper · EBSCO Research Starters https://ebsco.com/research-starters/history/cai-lun-invents-paper
4. Topics in Preservation Science: Fabriano paper · Library of Congress https://loc.gov/preservation/outreach/tops/albro/index.html
5. The history of papermaking · Confederation of European Paper Industries (CEPI) https://cepi.org/?p=768
6. Magnolia PaperWeight: an app for hand papermakers and paper conservators · Magnolia Editions (Donald Farnsworth) https://www.magnoliaeditions.com/wp-content/uploads/2021/05/PaperWeight-article-V2.1.pdf
7. Cranberry Corner No. 5 · Guild of Book Workers Newsletter (Edward H. Snider) https://guildofbookworkers.org/sites/default/files/newsletter/gbw115/paper.html
8. European Papermaking Techniques 1300–1800 · University of Iowa (Timothy Barrett) https://paper.lib.uiowa.edu/european.php
9. Chain lines · Mills Archive https://millsarchive.org/glossary/a-z-glossary/2794

Fact-checked on 2026-10-11

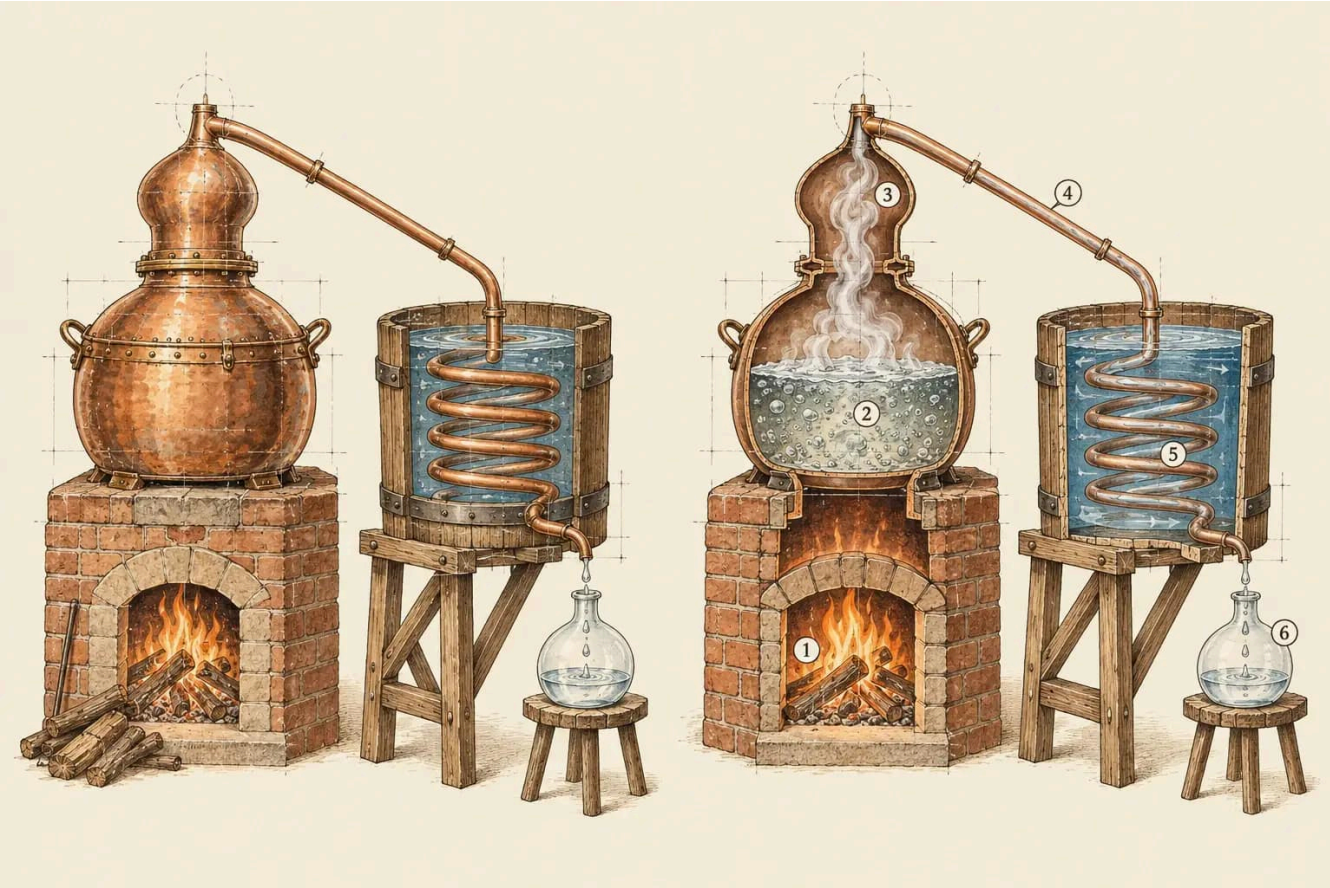
Distillation

Separating liquids by boiling and condensing

c. 300 · Antiquity · Crafts & cities

Requires: Pottery (p. 22), Control of Fire (p. 9)

Leads to: Hygiene & Antisepsis (p. 290), Internal Combustion Engine (p. 303), Refrigeration (p. 274)



1 Fire in the furnace 2 Pot of boiling liquid 3 Still head 4 Vapour pipe 5 Worm in a tub of cold water 6 Receiving flask

Distillation separates the parts of a liquid by heating it until part of it turns to vapour, then cooling that vapour back into liquid in another vessel. Described in Roman Egypt around 300 CE, it has given pure water, perfumes and essential oils, alcohol for medicine and, since the nineteenth century, the fuels refined from crude oil.

What it is

Distillation separates substances by evaporating and condensing them. A liquid is heated, usually to boiling, until part of it turns to vapour, the vapour is led away and cooled, and it becomes liquid again in another vessel. Whatever does not evaporate stays in the pot: salt, mud, dyes, most germs.

Apothecaries used it for medicines and scented waters, perfumers to take the fragrance out of flowers, physicians to make the strong alcohol they used as a solvent and on wounds. Laboratories and hospitals use distilled water because it carries almost no dissolved minerals, and lead-acid batteries are topped up with it for the same reason.

The plate shows a pot still of the early sixteenth century, as drawn in the first printed books on distilling: a copper pot on a small furnace, a domed head, and a pipe that winds through a tub of cold water before dripping into a flask.

How it works

Every liquid gives off vapour, more of it as it gets hotter, and it boils when the pressure of that vapour equals the pressure of the air. At sea level water boils at 100 °C, ethanol, the alcohol in wine, at about 78 °C, and methanol at about 65 °C. Salts barely evaporate at all, so boiling seawater and condensing the steam gives fresh water.

The fire heats the pot and the vapour rises into the head. It runs down a pipe into the worm, a coil standing in cold water, which takes its heat away. The vapour condenses inside the copper and trickles out into the receiving flask.

Essential oils are taken out by steam distillation. Steam passed through flowers, leaves or peel carries away their fragrant oil. Oil and water do not mix, so each adds its own vapour pressure and the pair boils below 100 °C, even when the oil alone would boil above 250 °C. The oil comes over without scorching and settles as a separate layer in the receiver.

In a Florentine flask the oil floats on the water, which drains away through the side tube.

When two liquids in the pot both evaporate and mix, as water and alcohol do, the separation is only partial. The vapour is richer in the more volatile one, so distillers passed the product through the still again. A fractionating column repeats this many times in one pass: rising vapour meets liquid running back down, called reflux, and at each level part of it condenses and boils again. Refineries use such columns to split crude oil into gas, petrol, kerosene, diesel and heavy residue by boiling range.

How to build

This section covers one thing only: drinkable water from salty or muddy water. It does not describe making alcohol. Distilling spirits at home is illegal without a licence in many countries, and a badly run still can concentrate methanol, which blinds and kills in small amounts and cannot be detected by taste or smell.

Solar still. Put a few centimetres of the water in a shallow dark basin in full sun. Cover it with clean glass or with clear, heat-tolerant food-grade plastic, tilted so that drops run down its underside to a gutter along the low edge, which leads to a covered glass jar. Seal the edges so that vapour cannot escape. In tropical sun a well-built still gives about two to three litres per square metre a day; expect less elsewhere, and less again with makeshift materials.

Pot and lid. Half fill a large metal pot and set it over a fire. Stand a small clean metal bowl on a stone in the middle, its rim well above the water. Put a metal lid on upside down, handle pointing at the bowl, and keep it cool with snow, cold water or a wet cloth; never cool a glass lid this way, as it can shatter. Keep a gentle boil: hard bubbling splashes raw water into the bowl.

Watch for leaks. Dry a few drops of the collected water on a clean dark plate. A white crust means raw water is splashing or leaking into the collector. A clean plate proves nothing more: it shows neither that the still separates well nor that the water is safe, since clear water can carry harmful chemicals and only a laboratory test can tell.

With the lid upside down, the water that condenses on it runs to the handle and drips into the bowl.

Know the limits. Distillation leaves behind salt, metals such as lead, nitrate and germs. It does not reliably remove substances that boil near or below the boiling point of water, such as some solvents and fuels, and some other chemicals are carried over with the steam: if the source may be chemically polluted, find another. Store the water in clean, covered glass, stainless steel or food-grade plastic containers, because germs return easily. Avoid glazed pottery, whose glaze may release lead.

> **Safety.** Steam scalds worse than boiling water: lift lids away from your face. Never seal a vessel that is being heated or tie its lid down; the vapour needs a way out, or the pot can burst. Ordinary glass cracks on a flame or under sudden cold. Watch the fire, keep it away from dry grass and keep children at a distance. Never distil fuel, alcohol or unknown liquids: their vapours catch fire, and any methanol in a fermented liquid comes over into the distillate.

History and evolution

At Tepe Gawra in northern Iraq, pots of the fifth and fourth millennia BCE have a channel around the rim that may have collected condensed liquid. Replicas tested in experiments published in 2020 produced scented water, but their original use is still debated.

The first clear descriptions of stills come from Roman Egypt. Around 300 CE the alchemist Zosimos of Panopolis wrote about stills with one or several pipes and credited some of them to Maria the Jewess. Alchemists and physicians of the Islamic world took up the apparatus, and its Arabic name, al-anbiq, became “alembic”. In the ninth century the philosopher al-Kindi wrote a book on perfume and distillation with over a hundred recipes.

The tribikos of the Alexandrian alchemists sent the vapour through three spouts into three flasks.

In Bologna in the 1270s, physicians described aqua vitae, “water of life”, alcohol distilled from wine and used as a remedy. In Strasbourg the surgeon Hieronymus Brunschwig published the first printed manual on distilling medicinal waters in 1500, then a larger book in 1512.

In 1830 the Irishman Aeneas Coffey patented a two-column still that ran continuously instead of in batches. Around 1854 Samuel Kier of Pittsburgh ran one of the first oil refineries, distilling crude oil into lamp kerosene. In 2011 distillation still accounted for about a third of installed desalination capacity worldwide, often in plants that use the waste heat of power stations.

Key figures

Boiling points at sea level
Water 100 °C, ethanol about 78 °C, methanol about 65 °C

Earliest clear description of a still
Zosimos of Panopolis, Egypt, about 300 CE

Simple solar still
About 2.3–3 litres per square metre per day in tropical sun

Continuous column still
Patented by Aeneas Coffey in 1830

Desalination in 2011
About a third of world capacity by distillation, 60% by reverse osmosis

Sources

1. Ancient Distillation and Experimental Archaeology about the Prehistoric Apparatuses of Tepe Gawra (Belgiorno, 2020) · EXARC Journal https://exarc.net/ark:/88735/10508
2. Zosimos of Panopolis · Complete Dictionary of Scientific Biography, via Encyclopedia.com https://www.encyclopedia.com/science/dictionaries-thesauruses-pictures-and-press-releases/zosimos-panopolis
3. Classic kit: Mary's bath (Sella, 2009) · Chemistry World, Royal Society of Chemistry https://www.chemistryworld.com/opinion/classic-kit-marys-bath/3004925.article
4. Distillation · Foundation for Science, Technology and Civilisation (Muslim Heritage) https://muslimheritage.com/distillation/
5. Al-Kindī's Attack on Alchemy and His Perfume Making (Inoue, 2017) · Orient 52, Society for Near Eastern Studies in Japan https://www.jstage.jst.go.jp/article/orient/52/0/52_72/_article
6. Aqua vitae (Wondrich) · The Oxford Companion to Spirits and Cocktails, Oxford University Press https://www.spiritsanddistilling.com/dictionary/acref-9780199311132-e-1030
7. Coffey, Aeneas · The Oxford Companion to Spirits and Cocktails, Oxford University Press https://www.spiritsanddistilling.com/dictionary/id/acref-9780199311132-e-1328
8. Distilling reliable remedies: Hieronymus Brunschwig's Liber de arte distillandi (1500) (Taape) · Ambix 61, Apollo repository, University of Cambridge https://www.repository.cam.ac.uk/handle/1810/260374
9. Liber de arte Distillandi de Compositis (Brunschwig, 1512) · Science History Institute https://digital.sciencehistory.org/works/1jcqz5i
10. Steam Distillation: Separation Theory (Nichols) · LibreTexts Chemistry https://chem.libretexts.org/Courses/SUNY_Oneonta/Chem_221%3A_Organic_Chemistry_I_(Bennett)/2%3ALab_Textbook_(Nichols)/05%3A_Distillation/5.05%3A_Steam_Distillation/5.5C%3A_Separation_Theory
11. Drinking Water Treatment: Distillation (G1493) · University of Nebraska–Lincoln Extension https://extensionpubs.unl.edu/publication/g1493/html/view
12. Solar distillation · Practical Action https://samplecontents.library.ph/en-practical_action/Energy/Solar%20energy/solar-distillation/page5.html
13. Some Petroleum Pioneers of Pittsburgh (Mann, 2009) · Heinz History Center https://www.heinzhistorycenter.org/wp-content/uploads/2022/08/4-Petroleum-Pioneers.pdf
14. Modern technology and economical developments in desalination on emphasis of nuclear methodology (Abdallah) · Acta Technica Corviniensis, 2018 https://acta.fih.upt.ro/pdf/2018-2/ACTA-2018-2-08.pdf
15. Thermophysical properties of seawater: a review of existing correlations and data (Sharqawy, Lienhard and Zubair, 2010) · Desalination and Water Treatment 16, via DSpace@MIT https://dspace.mit.edu/handle/1721.1/69157

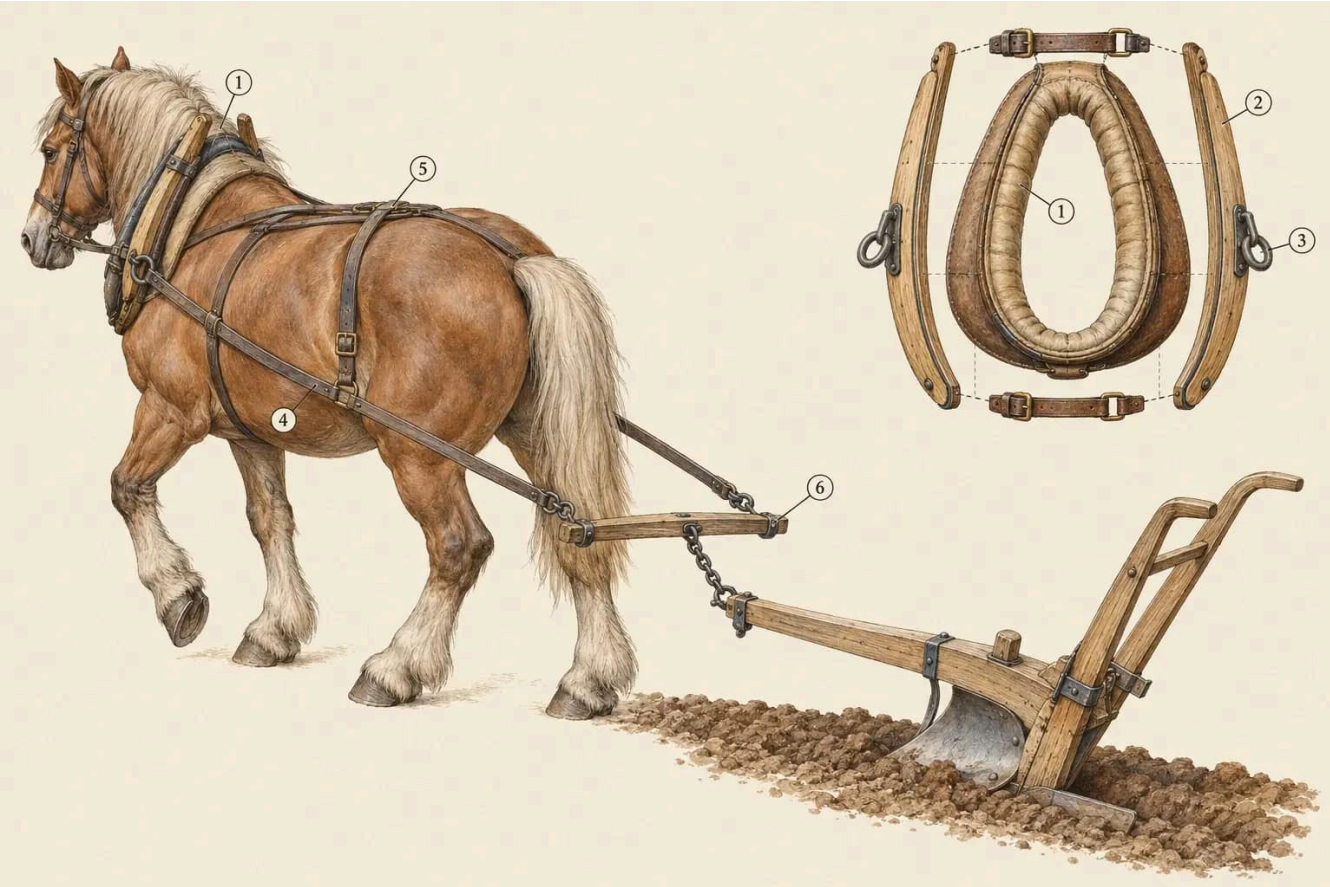
Fact-checked on 2026-10-14

Horse Collar

The horse pulls with its shoulders

c. 480 · Antiquity · Crafts & cities

Requires: Leather Tanning (p. 98), Rope & Cordage (p. 13)



1 Padded collar 2 Hames 3 Hame tug 4 Trace 5 Back band 6 Whippletree

The horse collar is a stiff, padded ring that rests against a horse's shoulders, with the traces hooked to it near the shoulder joints. The horse can throw its weight into the load without pressing on its windpipe, and in medieval Europe it took over much of the ploughing and hauling once done by oxen.

What it is

A horse collar is a stiff ring of leather packed with straw, shaped to sit at the base of the neck against the front of the shoulders. Two curved bars of wood or metal, the hames, are strapped into a groove around it, and the traces that pull the load hook onto them. A back band keeps the traces level, and a wooden crossbar, the whippletree, joins their ends to the plough or cart.

In this harness a horse pushes with its chest and shoulders, the way a person leans into a handcart. With the nailed horseshoe and the heavy plough, the collar helped horses replace oxen on many farms of medieval northern Europe.

How it works

Horses were first put to a yoke, like oxen. The pole of a chariot ran to a yoke on the pair's necks or withers, the ridge above the shoulders, held by a strap around each neck. Egyptian chariot horses wore forked yoke saddles that bore on the shoulders, and Greek and Roman teams pulled largely against a chest strap. Richard Lefebvre des Noëttes reconstructed all of this as a strap that rode up and pressed on the windpipe. Later experiments disagree with him (see History).

The "throat-and-girth" harness as historians long drew it: a yoke on the withers, a neck strap and a girth.

Oxen suit a yoke better. Their neck is short and thick, and many breeds have a hump or ridge of muscle in front of the withers for the beam to push against. A head yoke is lashed to the horns; a withers yoke rests on the neck in front of the shoulders. A horse has a long neck with the windpipe just under the skin.

Oxen under a neck yoke: the beam bears on the neck in front of the shoulders, and wooden bows close it underneath.

The breast strap came first: a broad band across the chest, below the windpipe, with the traces running back from its ends. It is light and still serves for light carriages, but under a heavy, jerky load it slips and rubs.

The collar spreads the push over a larger, stiffer surface. Its face lies on the muscles in front of the shoulder blades and leaves a gap at the throat. The hames make a rigid frame, so each trace pulls on the whole collar. For draught cattle, W. Micuta of the Bellerive Foundation estimated the contact of a padded collar at about 1,200 cm^2 over both shoulders, against about 200 cm^2 for a neck yoke.

The line of draught matters as much as the padding. The tugs on the hames sit a little above the point of the shoulder, and each trace should leave at a right angle to the slope of the shoulder. If the traces climb towards a high hitch, they lever the collar up against the throat. The whippletree pivots at its centre, so the horse can swing its shoulders as it walks without jerking the load.

How to build

Collars are stitched by harness makers, with a hard roll of straw at the front and a smooth face against the horse. A sound second-hand collar, carefully fitted, is usually a better choice than a home-made one.

Choose the size. Collars are measured inside, from top to bottom: 16 inches (41 cm) or less for a pony, 24 inches (61 cm) or more for a heavy draught horse. A thick-necked horse also needs a collar that is wider at the top.

Check the fit. Press the collar back onto the shoulders, as if under load. At the sides your fingers should slide in flat between rim and neck, but not your whole hand. Leave about 5 cm at the throat. A collar that is too short rides up and chokes; one that is too long drops onto the point of the shoulder and rubs.

Fit the hames. They should lie flat in the groove along their whole length. Fasten the bottom strap first, then pull the top strap straight across.

Set the traces. The back band carries the traces at the right height, and the belly band stops them rising under load. Adjust both so each trace leaves its tug at a right angle to the shoulder, and hitch low enough that the traces never pull the collar upwards.

Watch for sores. Hair worn short on the shoulder is the first warning: correct the fit before the skin breaks, and rest a sore horse until it heals. A horse that loses weight will need a pad or a smaller collar. At each halt, lift the collar to let the shoulders cool; at night, clean both collar face and shoulders.

Check the gap at the throat with the collar pressed back onto the shoulders.

> **Safety.** A draught horse can weigh close to a tonne and can kick, bolt or pin you against the vehicle. Learn from an experienced teamster, and have a helper hold the horse while you hitch or unhitch. Follow the hitching and unhitching sequences your teacher showed you, the same way every time. Never step over a trace or stand between horse and load, and never tie a line from the load to your body. Speak before you touch the hindquarters. Give rests and water, and stop if the horse is distressed or the harness slips.

History and evolution

China left the yoke behind first. A lacquer box from the state of Chu, painted in the fourth century BCE, shows horses pulling against a bar across the chest, and the softer breast strap is common on Han dynasty reliefs. The earliest clear image of a collar harness is a mural in Mogao cave 257 at Dunhuang, dated 477–499 CE, though its padding is not drawn clearly. Pita Kelekna places both the breast strap and the collar in the first millennium BCE.

The collar reached Europe in the early Middle Ages, probably by way of Central Asia. Lynn White placed it in Carolingian lands around 800; W. Micuta gives the eleventh century. By the twelfth it was common. With horseshoes for wet ground and oats from the three-field rotation, horses took over ploughing in parts of the north, working faster than oxen.

For decades historians held that ancient harness strangled horses. Lefebvre des Noëttes tested a reconstruction in 1910 and found that two horses could pull little more than 500 kg. In experiments published in 1977, Jean Spruytte rebuilt Egyptian, Greek and Roman harnesses, showed that the earlier reconstruction was wrong, and pulled about a tonne on sand with one of them. This work leaves the collar a useful advance for slow, heavy pulling such as ploughing, and it removes the idea that ancient horses were choked by their harness.

Key figures

Earliest clear image
Mogao cave 257, Dunhuang, China, 477–499 CE

In Europe
From about 800 CE (Carolingian lands); widespread by the 11th–12th centuries

Collar sizes
About 16 to 24 inches (41–61 cm), measured inside, top to bottom

Throat clearance
About 5 cm when the collar is pressed back onto the shoulders

Bearing surface (draught cattle)
About 1,200 cm^2 for a padded collar over both shoulders, against about 200 cm^2 for a neck yoke (W. Micuta's estimate)

Sources

1. Technology in the Middle Ages (Lynn White Jr., in Technology in Western Civilization, 1967) · Oxford University Press (course reading, Manchester University) https://users.manchester.edu/facstaff/ssnaragon/kant/lp/Readings/White,%20Plow.html
2. L'attelage dans l'Antiquité. Le prestige d'une erreur scientifique (Marie-Claire Amouretti, 1991) · Annales. Économies, Sociétés, Civilisations 46-1 https://www.persee.fr/doc/ahess_0395-2649_1991_num_46_1_278939
3. Roman Traction Systems: the dorsal yoke (Judith A. Weller) · Roman Science and Technology, humanist.de https://humanist.de/rome/rts/dorsal.html
4. The Lefebvre des Noëttes review page · Roman Science and Technology, humanist.de https://humanist.de/rome/ldn/index.html
5. The Swiss collar for developing countries (W. Micuta) · FAO https://www.fao.org/4/V0600T/v0600T0j.htm
6. Collars, Hames and Harness Fitting (Horse & Mule Association of America, Leaflet 276, 1944) · Small Farmer's Journal https://smallfarmersjournal.com/collars-hames-and-harness-fitting/
7. Hitching Safely (Jenifer Morrissey, with Doc Hammill) · Rural Heritage https://ruralheritage.com/hitching-safely/
8. Horse Collar Harnessing: Ancient Carriage Tech · Science and Technology Daily https://www.stdaily.com/web/English/2025-10/24/content_420664.html
9. Efficient equine transport (Pita Kelekna) · Cambridge University Press blog https://cambridgeblog.org/2009/05/efficient-equine-transport/
10. Horse collar · Wikipedia https://en.wikipedia.org/wiki/Horse_collar

Fact-checked on 2026-10-14

Gunpowder

The explosive behind guns and mining

c. 850 · Middle Ages · Crafts & cities

Requires: Control of Fire (p. 9), Charcoal (p. 62)

1 Mill house 2 Water wheel 3 Wooded bank between the buildings 4 Powder keg with copper hoops 5 Horn powder flask 6 Saltpetre crystals

Gunpowder, or black powder, is a mixture of saltpetre, charcoal and sulfur that burns extremely fast, giving off hot gas and a cloud of solid smoke. Chinese alchemists came across it in the ninth century, and over the following five hundred years it became the propellant of rockets, guns and cannon, then a tool for mining and building.

What it is

Gunpowder is the oldest known chemical explosive. It is a black or dark grey powder made of three substances: saltpetre (potassium nitrate), charcoal and sulfur. Most fuels need air to burn, but gunpowder carries its own oxygen, so it burns in a closed space. In a fraction of a second, much of its mass becomes hot gas, and the pressure of that gas can drive a bullet out of a barrel or split rock.

Until the nineteenth century it was the only explosive in common use and the propellant of every gun. Today it is called black powder, to set it apart from the smokeless powders that replaced it in firearms from the 1880s. It is still used in fireworks, in safety fuses, in muzzle-loading guns and in some quarrying.

The plate shows an eighteenth-century powder works from the outside. The mills stood far apart along a river that drove their wheels, with earth banks and trees between them, so that an explosion in one was less likely to set off the next. On the Brandywine in Delaware, many had heavy stone walls on three sides and a light roof and river front, so that the blast of an explosion went out over the water. Beside the scene are a keg with copper hoops, chosen because copper is far less likely than iron to strike sparks, a horn flask in which soldiers and hunters carried their powder, and crystals of saltpetre.

How it works

Burning is a reaction between a fuel and oxygen. In a wood fire the oxygen comes from the air, and the fire can only burn as fast as air reaches the wood. In gunpowder the oxygen is held in the saltpetre, which is mixed closely with the fuel. When the powder is heated, the saltpetre breaks down and gives up its oxygen right against the fuel particles, and the reaction does not wait for air.

Each ingredient has its own job. Saltpetre is the oxidiser, and it makes up most of the mass. Charcoal is the main fuel; it is porous, so a little of it offers a large surface to the oxygen. Sulfur is a fuel too, but it matters mostly because it lowers the temperature at which the mixture catches fire and makes it burn faster. The purity of the saltpetre and the kind of wood the charcoal came from changed how a powder behaved, which is why powder makers took such care over both.

The products are partly gases, mainly carbon dioxide, nitrogen and carbon monoxide, and partly solid potassium salts. A little under half the mass becomes gas. The rest leaves as thick white smoke and as a residue that fouls the barrel of a gun, which had to be cleaned often.

Gunpowder deflagrates: it burns very fast, but the reaction passes from grain to grain by heat. Loose powder in the open burns with a flash and a cloud of smoke. Confined in a barrel, the gas cannot escape, the pressure rises, the powder burns faster still, and the gas drives the shot out. High explosives such as TNT or dynamite detonate instead. A shock wave races through them at several kilometres per second, faster than sound travels in the material, and the reaction is over almost at once, with a shattering blow. Gunpowder gives a longer, softer push. That suits a propellant, which has to speed up a bullet without bursting the barrel, and it is why quarrymen long used it to split and lift blocks of stone that dynamite would have shattered.

A spark, a flame, friction, a blow or static electricity can set gunpowder off, and explosions in powder mills killed many workers. Making, storing and transporting it are controlled by explosives laws almost everywhere.

History and evolution

Chinese alchemists of the Tang dynasty heated saltpetre, sulfur and many other substances in their search for elixirs of long life. A Taoist text usually dated to the mid-ninth century warns alchemists against certain mixtures containing saltpetre: some who had heated them burned their hands and faces, and even their house. Historians debate whether an earlier text of 808 already describes a similar mixture. The mixture came to be called *huoyao*, “fire medicine”.

Chinese armies soon took it to war. The *Wujing Zongyao*, a military compendium completed in 1044, describes incendiary and smoke weapons and contains the oldest surviving written formulas. A silk banner from Dunhuang, painted in the mid-tenth century, shows a fire lance, and Song troops used fire lances at the siege of De’an in 1132. In the thirteenth century, Jin and Song defenders hurled gunpowder bombs from their walls at besieging Mongol armies, and the tube of the fire lance was made of metal and loaded with projectiles. The bronze hand cannon

found in Heilongjiang province carries no date, but its find site links it to fighting recorded in 1288, which makes it one of the oldest guns known to survive.

Early Chinese hand guns were short bronze tubes fixed to a wooden pole.

The fire lance, a tube of powder lashed to a spear, threw out flame for a few seconds at close range.

Knowledge of the powder spread west across the Mongol empire and the Islamic world in the thirteenth century. In the Mamluk sultanate, the treatise of the Syrian Hasan al-Rammah, written in the late thirteenth century, describes incendiaries and rockets, and the English friar Roger Bacon mentioned the powder in 1267. The first European records and pictures of guns date from the 1320s: in 1326 the city of Florence ordered metal cannon and their ammunition, and a treatise that Walter de Milemete wrote for the young Edward III in 1326–1327 contains a drawing of a gun. Twenty years later the English probably used a few small guns at the battle of Crécy. By the fifteenth century, siege guns could bring down high medieval walls in weeks, and military engineers answered with low, thick walls and angled bastions.

Saltpetre was the ingredient that was hard to get. In Europe, saltpetre men had the right to dig up the floors of stables, dovecotes and cellars, and later governments set up nitre beds where it formed in heaps of earth and manure. In the seventeenth century the European trading companies bought large quantities in India, in Gujarat, Bihar and Bengal. In 1775 the chemist Antoine Lavoisier became one of the four commissioners of the new French royal powder administration and, from his laboratory at the Paris Arsenal, worked to improve the supply and quality of French powder. In the nineteenth century, deposits of sodium nitrate in the Chilean desert supplied the explosives and fertiliser industries, until German chemists learned to make nitrogen compounds from the air in the early twentieth century.

Saltpetre forms slowly where organic waste rots in damp soil, and for centuries it was scraped from walls and floors like these.

Powder mills were among the most dangerous workplaces of the industrial age. The du Pont mills on the Brandywine in Delaware, opened in 1802, had 288 explosions and at least 228 deaths before they closed in 1921. Workers were searched at the gates for matches and for metal on their clothes and shoes. Gunpowder dug canals, tunnels and mines: one of the earliest records of blasting in a mine comes from Banská Štiavnica, in the Kingdom of Hungary, in 1627. From the 1870s dynamite replaced it for most blasting work, and smokeless powders made from nitrocellulose replaced black powder in firearms in the 1880s and 1890s. It survives in fireworks, in fuses and among people who shoot historical guns.

Key figures

Early written warning
Mid-9th century, a Taoist alchemical text, China

Oldest surviving written formulas
1044, the Wujing Zongyao military compendium

One of the oldest surviving guns
Heilongjiang bronze hand cannon, dated from its context to about 1288

First European picture of a gun
1326–1327, manuscript of Walter de Milemete, England

Du Pont powder mills, Delaware (1802–1921)
288 explosions, at least 228 deaths

Sources

1. China in 1000 CE, Song dynasty module: gunpowder · Asia for Educators, Columbia University https://afe.easia.columbia.edu/songdynasty-module/tech-gunpowder.html
2. Christ Church MS 92: Walter of Milemete, De nobilitatibus, sapientiis et prudentiis regum (1326–1327) · Christ Church, Oxford (manuscript catalogue) https://www.chch.ox.ac.uk/sites/default/files/2023-09/MS-92.pdf
3. Eleutherian Mills (Hagley), National Register of Historic Places nomination form · U.S. National Park Service https://npgallery.nps.gov/NRHP/GetAsset/NHLS/66000259_text
4. Powder Yard Trail · Hagley Museum and Library https://www.hagley.org/pyt
5. Antoine-Laurent Lavoisier · Science History Institute https://www.sciencehistory.org/education/scientific-biographies/antoine-laurent-lavoisier/
6. History of gunpowder · Wikipedia https://en.wikipedia.org/wiki/History_of_gunpowder
7. Heilongjiang hand cannon · Wikipedia https://en.wikipedia.org/wiki/Heilongjiang_hand_cannon

Fact-checked on 2026-10-12

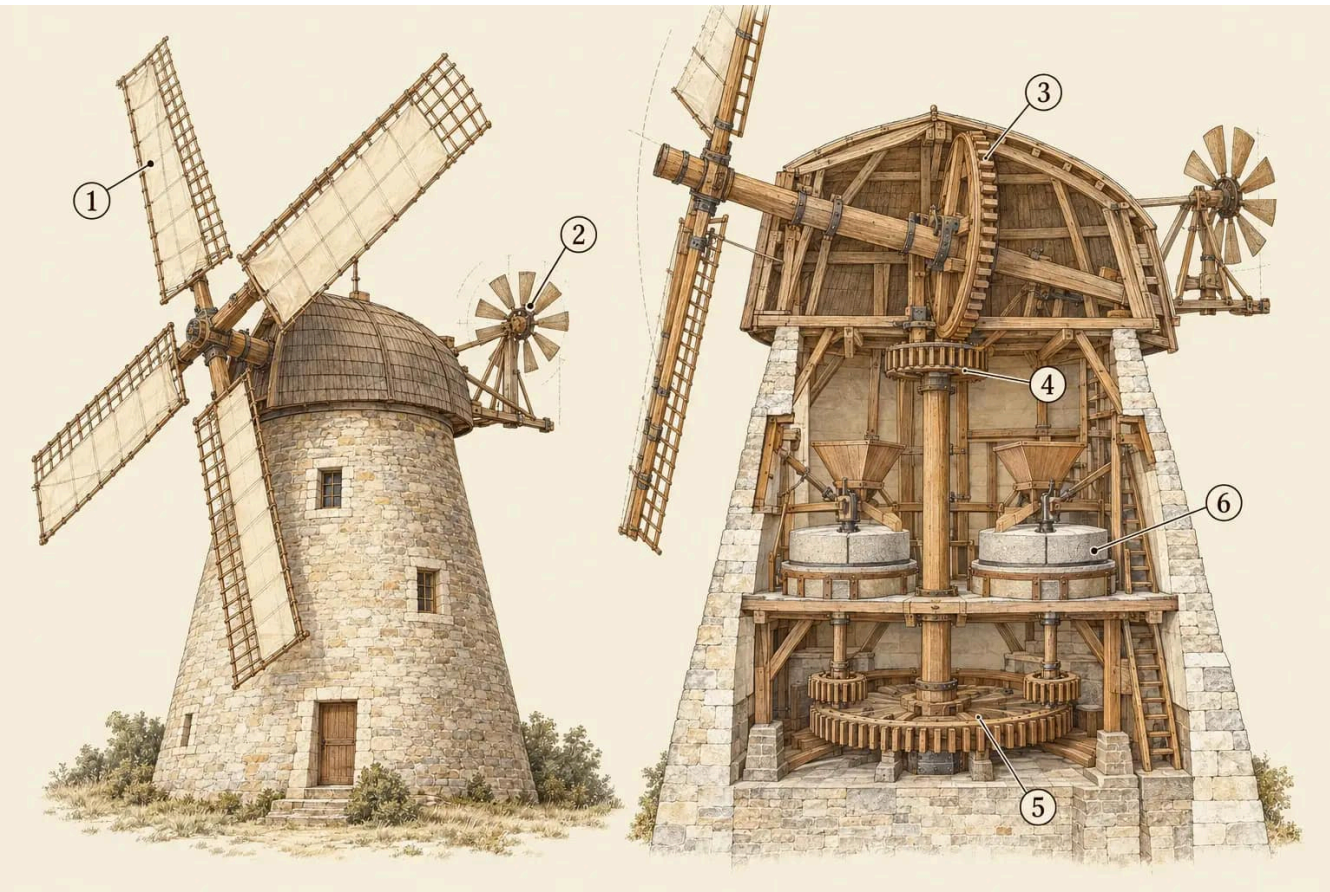
Windmill

Wind turned into flour

c. 900 · Middle Ages · Crafts & cities

Requires: Gears (p. 149), Water Wheel (p. 153), Rope & Cordage (p. 13)

Leads to: Wind Turbine (p. 326)



1 Sails 2 Fantail 3 Brake wheel 4 Wallower 5 Great spur wheel 6 Millstones

A windmill catches the wind with large sails and passes that energy, through a train of wooden and iron gears, to a millstone that grinds grain. From the twelfth century to the coming of steam it was, with the water wheel, the main source of mechanical power in Europe.

What it is

A windmill is a machine that turns moving air into rotation, and that rotation into useful work. For most of its history the work was grinding grain into flour. Windmills also drained polders, sawed timber, pressed oil seeds and crushed pigments.

The mill drawn here is a tower mill: a fixed tower of stone with a cap that turns to face the sails into the wind. The design spread across Europe from the late Middle Ages, because a masonry tower can carry large sails and heavy machinery under cover.

How it works

The wind pushes on the sails, which are slightly twisted and set at an angle. They behave like the blades of a propeller: part of the push becomes torque that turns the windshaft, a heavy, nearly horizontal shaft carried in the cap.

A post mill turns as a whole on its post; in a tower mill only the cap turns.

The windshaft carries the brake wheel, a large wheel with its cogs set into one face. It meshes with the smaller wallower on the vertical main shaft, so the drive turns from horizontal to vertical and gains speed. Lower down, the great spur wheel drives a small stone nut on each stone spindle. At Gedney Dyke mill in Lincolnshire, a brake wheel of 96 cogs drove a wallower of 68, and a spur wheel of 120 cogs drove stone nuts of 18: together the two stages made the stones turn about nine times faster than the sails.

The runner sits on the rynd at the top of the iron spindle, which comes up through the fixed bed stone.

The stone spindle rises through the fixed bed stone. On its top sits the rynd, an iron bar or cross that fits into recesses in the eye of the upper runner stone and carries its whole weight. In some mills the spur wheel sits above the stones and the drive comes down through a short iron shaft called the quant, but the runner still rests on the spindle below. Grain runs from a hopper into the eye. Furrows dressed into both stones cut it and sweep the meal outwards to the rim, where it leaves as flour. The miller raises or lowers the spindle with the tentering gear, and that gap decides how fine the flour will be.

The power carried by the wind grows with the cube of its speed, so a wind twice as strong carries eight times the energy. No rotor can extract more than 59.3% of it, a limit Albert Betz published in 1920. Traditional mills stay far below that figure.

How to build it

A windmill needs an organised community: carpenters, masons, a smith, and a miller who knows how to dress stones. The stages below give the order of work and the choices that matter; the dimensions belong to the millwright.

Pick the site. An open rise, away from trees and buildings, facing the prevailing wind. Downwind of a tree or a house, the air stays turbulent for roughly twenty times its height, so keep obstacles well away on the windward side.

Raise the tower. A tapering tower of stone or brick, with thick walls at the base. The top carries a level curb of timber or iron on which the cap turns on rollers.

Shape the shaft and wheels. The windshaft is hewn from an oak trunk and bound with iron where it wears; from the late eighteenth century many were cast in iron. The wheels are hardwood, and the cogs are separate pieces, often hornbeam or apple wood, replaced as they wear.

Make the sails. Four arms each carry a lattice of laths with canvas spread over it. With the mill stopped and the sails chained, the miller spreads more or less cloth on each sail to suit the wind, much as a sailor reefs a sail.

Choose the stones. The stone must be hard and porous. French burr stone from La Ferté-sous-Jouarre was prized across Europe. It was usually built up from several pieces set in plaster and bound with iron hoops.

Fit the brake. A wooden brake band clamps the rim of the brake wheel. It has to hold the sails in a strong wind, so try it first in a light breeze, and have a millwright confirm that it and the sail chains can hold the mill in a gale before it does any work.

> **Safety.** Never walk through the path of the sails, even when they turn slowly, and never touch a sail before the brake is on and the sails are chained. Watch the weather: take in the cloths and secure the mill before a storm arrives, because in a gale nobody can work on the sails. Inside, keep hands, hair and loose clothes away from turning gears and shafts. An overheated brake can set the cap alight, and many mills burned that way. Flour dust in the air is flammable, so naked flames are never allowed inside.

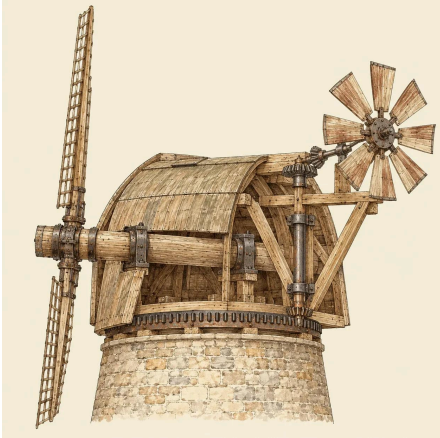
History and evolution

The first well-documented windmills stood in Sistan, on today's border between Iran and Afghanistan. Arab geographers describe them in the tenth century, and they may be older. Their sails turn about a vertical axis inside walls that funnel the wind.

The horizontal-axis windmill appears in Europe at the end of the twelfth century. One of the earliest dated records is a post mill at Weedley in Yorkshire, listed in an inventory of Templar lands in 1185. The tower mill, where only the cap turns, spread later and allowed much larger mills.

In 1745 the English blacksmith Edmund Lee patented the fantail, a small bladed wheel at the back of the cap. When the wind shifts, the fantail starts to turn and winds the cap round until the sails face the wind again. In 1772 the Scottish millwright Andrew Meikle introduced spring sails, made of shutters that open by themselves in a gust.

The Netherlands had between nine and ten thousand windmills in the middle of the nineteenth century, used for milling and above all for draining land. Steam engines and then electric motors replaced them, and about a thousand survive there today. Modern wind turbines use the same rotor physics to drive generators.



The fantail drives the cap round on its toothed curb until the sails face the wind again.

Key figures

Sail speed
About 10–15 rpm in a working wind

Runner stone speed
About 100–150 rpm

Power
Grows with the cube of wind speed

Theoretical ceiling
59.3% of the wind's energy (Betz limit)

Sources

1. Windmill · Wikipedia https://en.wikipedia.org/wiki/Windmill
2. Betz's law · Wikipedia https://en.wikipedia.org/wiki/Betz%27s_law
3. Fantail (windmill) · Wikipedia https://en.wikipedia.org/wiki/Fantail_(windmill)
4. Technical descriptions of English windmills · The Mills Archive Trust https://millsarchive.org/2019/09/13/technical-descriptions-of-english-windmills/31
5. Weedley windmill site (R. Gregory) · The Mills Archive Trust https://millsarchive.org/library/index/?which=8434
6. First Windmill Use · Environment & Society Portal, Rachel Carson Center https://www.environmentandsociety.org/taxonomy/term/5347

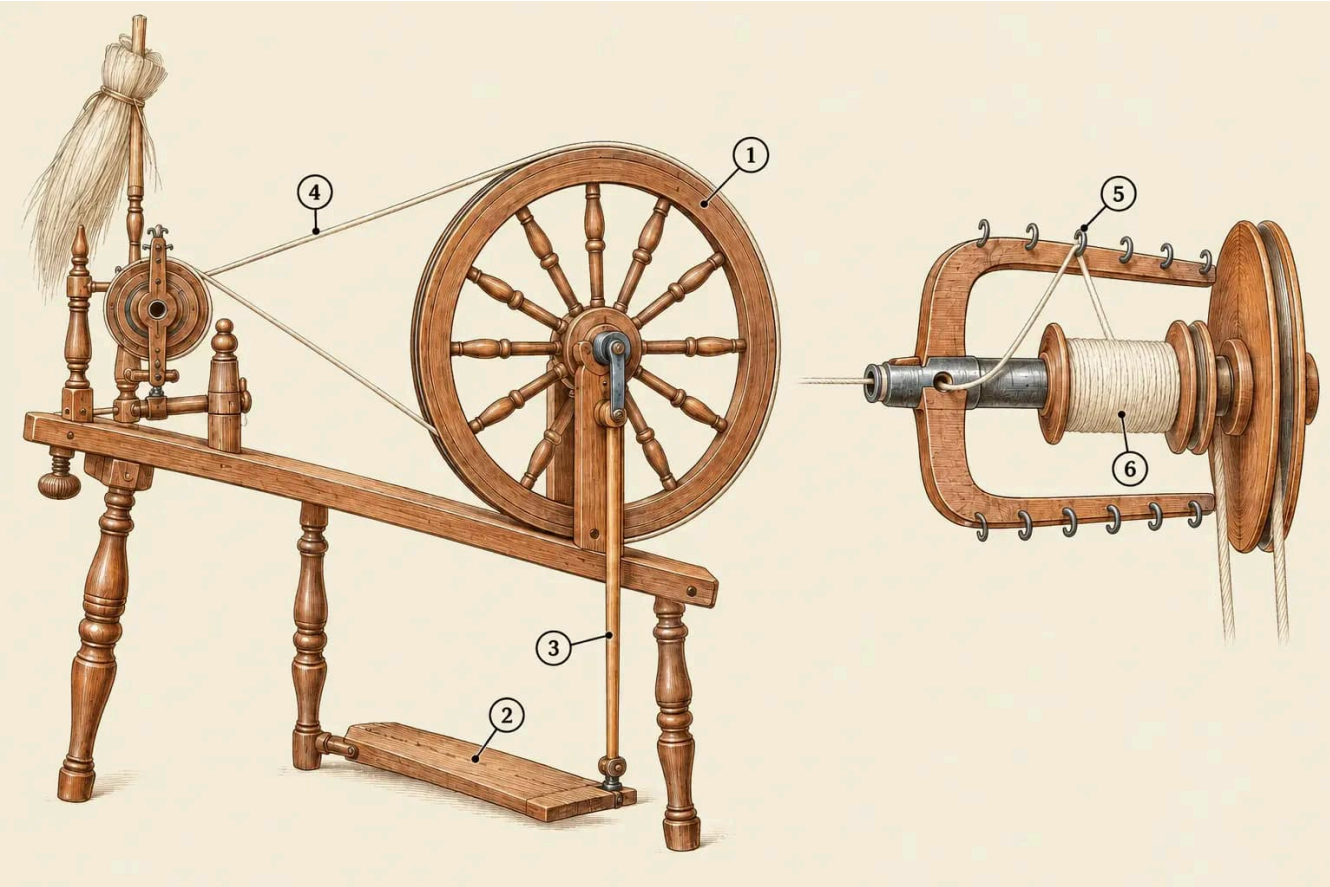
Fact-checked on 2026-10-11

Spinning Wheel

Fibre into thread, faster

c. 1000 · Middle Ages · Crafts & cities

Requires: Wheel & Axle (p. 78), Rope & Cordage (p. 13)



1 Drive wheel 2 Treadle 3 Footman (connecting rod) 4 Drive band 5 Flyer with hooks 6 Bobbin

A spinning wheel twists loose fibre into yarn with a spindle driven by a large wheel, much faster than a hand spindle. The wheel with a flyer, known in Germany by about 1480, also winds the yarn onto a bobbin while it spins, so that spinning and winding no longer alternate.

What it is

Spinning turns a mass of short fibres, such as wool, flax or cotton, into a continuous thread. Two things happen at once: the fibres are drawn out into a thin, even strand, and the strand is twisted so that the fibres grip each other. Twist is what gives yarn its strength.

For thousands of years this was done with a hand spindle, a stick weighted with a whorl, set spinning by the fingers. The spinning wheel puts the spindle on a frame and drives it with a large wheel by a cord. One turn of the big wheel turns the small spindle many times, so it twists far faster than a hand could.

The plate shows a Saxony wheel, a treadle wheel with a flyer of the kind used across Europe from the sixteenth century, here as an eighteenth-century model.

How it works

On a great wheel, an early type, the spindle simply points at the spinner. The spinner turns the wheel, holds the fibre at an angle to the spindle tip, and walks backwards drawing out a length of yarn while the twist runs into it. Then the spinner stops, holds the yarn square to the spindle and turns the wheel again to wind the finished length on. Spinning and winding alternate.

Before the wheel: a hand spindle and a distaff. The whorl keeps the spindle turning.

The flyer removes that pause. The yarn enters a hollow spindle through a hole at its front end, the orifice, comes out through a side hole, runs along one arm of a U-shaped flyer and over one of its hooks, and goes onto a bobbin that sits loose on the spindle. Flyer and bobbin each have their own grooved pulley, of different sizes. One continuous drive band goes twice round the big wheel and once round each pulley, so the smaller bobbin pulley turns a little faster than the flyer.

The flyer's turning twists the yarn. The small difference in speed between bobbin and flyer winds the twisted yarn on as fast as it is made. Now and then the spinner stops the wheel and moves the yarn to another hook so that the bobbin fills evenly, and adjusts a tension screw that moves the flyer assembly along the bench to tighten or slacken the band.

Hand cards: wool is brushed between two cards and rolled into rolags ready for spinning.

The treadle frees both hands. A crank on the wheel's axle is linked by a wooden rod, the footman, to a hinged board under the spinner's foot. Each press of the foot gives the wheel a push. One hand feeds fibre from a distaff or from a rolag of carded wool, the other controls the twist. Saxony wheels were used above all for long fibres such as flax and wool. Flax is dressed onto a distaff and drawn from it a few fibres at a time. Wool is first brushed between a pair of hand cards and rolled into a soft tube, the rolag, so that the fibres lie loosely and draw out evenly.

How to build it

A flyer wheel needs turned parts and careful fitting, a project for a skilled woodworker with a lathe. A simpler wheel of the oldest type shows the principle and spins wool.

Make the bench. A solid board about 1 m long on three or four legs, high enough to sit or stand at. At one end, fix an upright post to carry the wheel; at the other, a shorter post for the spindle head.

Fit the wheel. Any large, true-running wheel with a grooved rim will do: a wooden wheel built from a hub, spokes and rim, or an old bicycle wheel with its tyre removed. Mount it on an axle in the post and add a handle near the rim to turn it.

Make the spindle head. Two small uprights on the short post hold a straight steel rod, pointed at one end, in loops of leather or in small bearings. Fix a small grooved pulley on the rod between the uprights. The rod lies

across the bench, parallel to the wheel's axle, with its pulley exactly in line with the groove of the wheel so that the band runs straight; its point faces the side where you stand.

Fit the drive band. Tie a loop of strong cotton cord round the wheel rim and the spindle pulley, tight enough to drive the spindle without slipping. With a wheel about ten times the diameter of the pulley, the spindle turns about ten times for each turn of the wheel.

Spin. Tie a leader of yarn to the spindle shaft, wind on a few turns, then spiral it up to the tip so that it leaves over the point. Overlap its end with carded wool, turn the wheel slowly and draw back at an angle to the tip, letting twist run into the fibre. To wind on, turn the wheel back a little to free the spiral, hold the yarn square to the spindle and turn forward; then spiral the yarn back up to the tip for the next length. When the spindle is full, wind the yarn onto a niddy-noddy, tie the skein loosely in several places, take it off and wash it to set the twist.

A niddy-noddy: spun yarn is wound into a skein of known length before washing and dyeing.

> **Safety.** Keep fingers, hair and loose sleeves away from the turning wheel, the drive band and the spindle, stop the wheel before clearing a snag, and fit a cover over the sharp spindle tip when the wheel is not in use. Check that a bicycle wheel or wooden wheel is firmly fixed and does not wobble before turning it fast. Keep small children away from a turning wheel.

History and evolution

Where the spinning wheel was invented is disputed. Some historians place it in India between about 500 and 1000 CE, others in China, where it was in wide use by about 1090, or in the Islamic world, where it is recorded by about 1030 and clearly illustrated in Baghdad in the 1230s. It reached Europe in the thirteenth century; European pictures of it date from about 1280, and the guild rules of Speyer, in Germany, mention it at the end of the thirteenth century (in 1280 or 1298, depending on the source). Wheel and spindle were long used side by side in Europe.

The flyer appears in a German illustration of about 1480, and Leonardo da Vinci also drew one. A treadle was added in the sixteenth century; a story credits a Brunswick craftsman with it in 1533. Compared with the hand spindle, the wheel greatly raised a spinner's output. The historian Lynn White linked the larger supply of linen rags, and so of cheap paper for printing, to the wheel.

In the 1760s James Hargreaves built the spinning jenny, which drove many spindles at once, and Richard Arkwright's water frame and Samuel Crompton's mule of 1779 moved spinning into mills. In the twentieth century Mahatma Gandhi made the charkha, a simple hand-turned wheel, the emblem of Indian self-reliance, and hand spinners still use treadle wheels today.

Key figures

Earliest wheels
Disputed: India, China or the Islamic world, by the 11th century CE

Early record in Europe
Guild rules of Speyer, Germany, late 13th century

Earliest flyer
German illustration of about 1480

Treadle
Added in the 16th century

Sources

1. Spinning Wheel, British (Saxony wheel with flyer) · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co44835
2. Spinning (Bette Hochberg, Encyclopedia of Clothing and Fashion) · Encyclopedia.com (Gale) https://www.encyclopedia.com/fashion/encyclopedias-almanacs-transcripts-and-maps/spinning
3. Saxon wheel; spinning wheel · Horniman Museum and Gardens https://www.horniman.ac.uk/object/11.40
4. Spinning wheel · Aotea Utanganui, Museum of South Taranaki https://museumofsouthtaranaki.wordpress.com/2016/03/11/spinning-wheel/
5. Spinning wheel · Wikipedia https://en.wikipedia.org/wiki/Spinning_wheel
6. Choosing the whorl to make the yarn you want (Rudy Amann) · Spin Off https://spinoffmagazine.com/choosing-the-whorl-to-make-the-yarn-you-want/
7. Sliding hook flyer, double drive: assembly instructions · Ashford Wheels & Looms https://ashford.co.nz/instructions/SHFDD.pdf
8. DRS spinning wheels revisited · A Fisherman Knits http://gansey.blogspot.com/2018/07/drs-spinning-wheels-revisited.html

Fact-checked on 2026-10-12

Magnetic Compass

A needle that points north

c. 1088 · Middle Ages · Crafts & cities

Requires: Iron Smelting (p. 133), Steel (p. 137)

Leads to: Celestial Navigation (p. 205)

1 Gimbal rings 2 Bowl 3 Compass card 4 Magnetized needle 5 Pivot pin 6 Lodestone

A magnetic compass is a magnetized needle, free to turn, that lines itself up with the Earth's magnetic field and so shows north in any weather. Described in China in the eleventh century and at sea in Europe by about 1190, it let sailors hold a course out of sight of land and under cloud.

What it is

A compass is a small magnet that can turn freely. Left alone, it settles along the lines of the Earth’s magnetic field, one end towards magnetic north and the other towards magnetic south. A navigator who knows where north is can read every other direction from it, at night, in fog or out of sight of land.

The plate shows a mariner’s compass of the sixteenth century. The needle is glued under a paper card painted with a wind rose, so the whole card turns with it. The card balances on a pin in a wooden bowl, and the bowl hangs in gimbals so it stays level when the ship rolls.

How it works

The Earth behaves roughly like a huge bar magnet. Its field is weak, about half a gauss at the surface, but a light needle on a good pivot needs very little force to turn. The needle swings until its own field lines up with the horizontal part of the Earth's field, then stops.

The needle has to be magnetized first. In iron and steel, tiny regions called domains each act as a magnet, but they point every which way and cancel out. Stroking the needle in one direction with a lodestone, a naturally magnetic piece of magnetite, lines many of them up, and the needle keeps that order. Hard steel holds it best. Soft iron loses it quickly, and before the mid-eighteenth century sailors had to touch up their needles with a lodestone kept on board.

Stroked along a lodestone, a steel needle becomes a magnet in its own right.

An early method: a needle on a float, turning freely on still water.

Magnetic north is not the geographic pole, and the angle between them, the declination, changes from place to place and slowly over the years. The field is also tilted: in the northern hemisphere it pulls the north end of the needle downwards, in the southern hemisphere the south end, most steeply near the magnetic poles, so compass makers balance the needle with a small weight. On a ship, iron fittings and cargo pull the needle aside too, an error called deviation.

On the plate, the pointed pin and the small cap on the needle keep friction low. The card lets the helmsman read the heading against a fixed mark on the bowl. The glass cover keeps out wind, and the gimbals stop the card from tipping when the ship rolls.

How to build it

Make the needle. Use a steel sewing needle or a thin strip of hard steel about 5 cm long. Iron that is too soft will not stay magnetized.

Magnetize it. Stroke the needle from the middle to one end with one pole of a lodestone or magnet, lifting the stone away in a wide arc at the end of each stroke. Repeat twenty or thirty times, always in the same direction.

Test it on water. Push the needle through a short piece of cork or dry reed and float it in a bowl of still water, away from iron. Find which end points north and mark it. North of the tropics, check it against the pole star at night or the shortest shadow at local solar noon, which then points north; south of the tropics the noon shadow points south.

Give it a pivot. Press a small cone into a scrap of thin brass to make a cap and fix it to the centre of the needle. Set a sharp needle point upright in the bottom of a wooden bowl and rest the cap on it. Balance the needle with a dab of wax until it lies level.

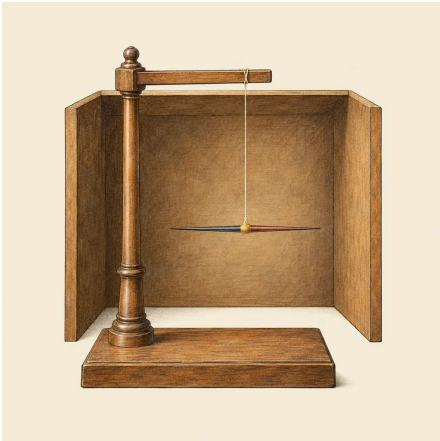
Add a card and a cover. Glue the needle under a light card marked with the points of the compass, its north mark over the north end of the needle. Paint a fixed mark, the lubber line, inside the bowl and line it up with the bow of the boat: the heading is read on the card against it. A pane of glass over the bowl keeps draughts away.

Hang it. For a model of a ship's compass, mount the bowl in two rings pivoted at right angles to each other. A home-made compass is a demonstration: do not navigate by it before checking it against a proven compass.

History and evolution

People knew in both China and Greece more than two thousand years ago that lodestone attracts iron. Han-dynasty texts mention a south-pointing device used in divination, perhaps a lodestone spoon, though historians disagree about what it was.

The military manual *Wujing Zongyao*, compiled around 1044, describes a thin iron fish heated red-hot, cooled lying north to south and then floated on water, where it pointed south. Around 1088 Shen Kuo described needles magnetized by rubbing them on lodestone, floated on water or hung from a silk thread. He also noted that the needle points slightly east of due south, an early record of declination. Between 1111 and 1117, Zhu Yu wrote that ship pilots watched the needle when clouds hid the sun and stars.



Shen Kuo judged a needle hung from a single silk thread the best mounting.

In Europe the English scholar Alexander Neckam described sailors using a magnetized needle around 1190. A Persian text of 1232 gives the first mention in the Islamic world. In 1269 Petrus Peregrinus described a pivoted dry compass, and around 1300 the dry box compass with a card spread through the Mediterranean.

Liquid-filled compasses, which damp the card's swinging, took over in the nineteenth and early twentieth centuries, and the gyrocompass, which finds true north without magnetism, followed in the first decade of the twentieth century.

Key figures

Iron fish floated on water
Wujing Zongyao, c. 1044

Needle compass and declination described
Shen Kuo, c. 1088

First recorded use at sea
China, between 1111 and 1117

First European mention
Alexander Neckam, c. 1190

Strength of the Earth's field
About 0.5 gauss (50 microtesla)

Sources

1. History of the compass · Wikipedia https://en.wikipedia.org/wiki/History_of_the_compass
2. Compass · Wikipedia https://en.wikipedia.org/wiki/Compass
3. Shen Kuo: first Renaissance man · AAAS https://www.aaas.org/shen-kuo-first-renaissance-man
4. Lodestone, c. 1700–1720 (NAV0710) · Royal Museums Greenwich https://www.rmg.co.uk/collections/objects/rmgc-object-42922
5. Dry card compass, 1838 (ACO0005) · Royal Museums Greenwich https://www.rmg.co.uk/collections/objects/rmgc-object-7085

Fact-checked on 2026-10-11

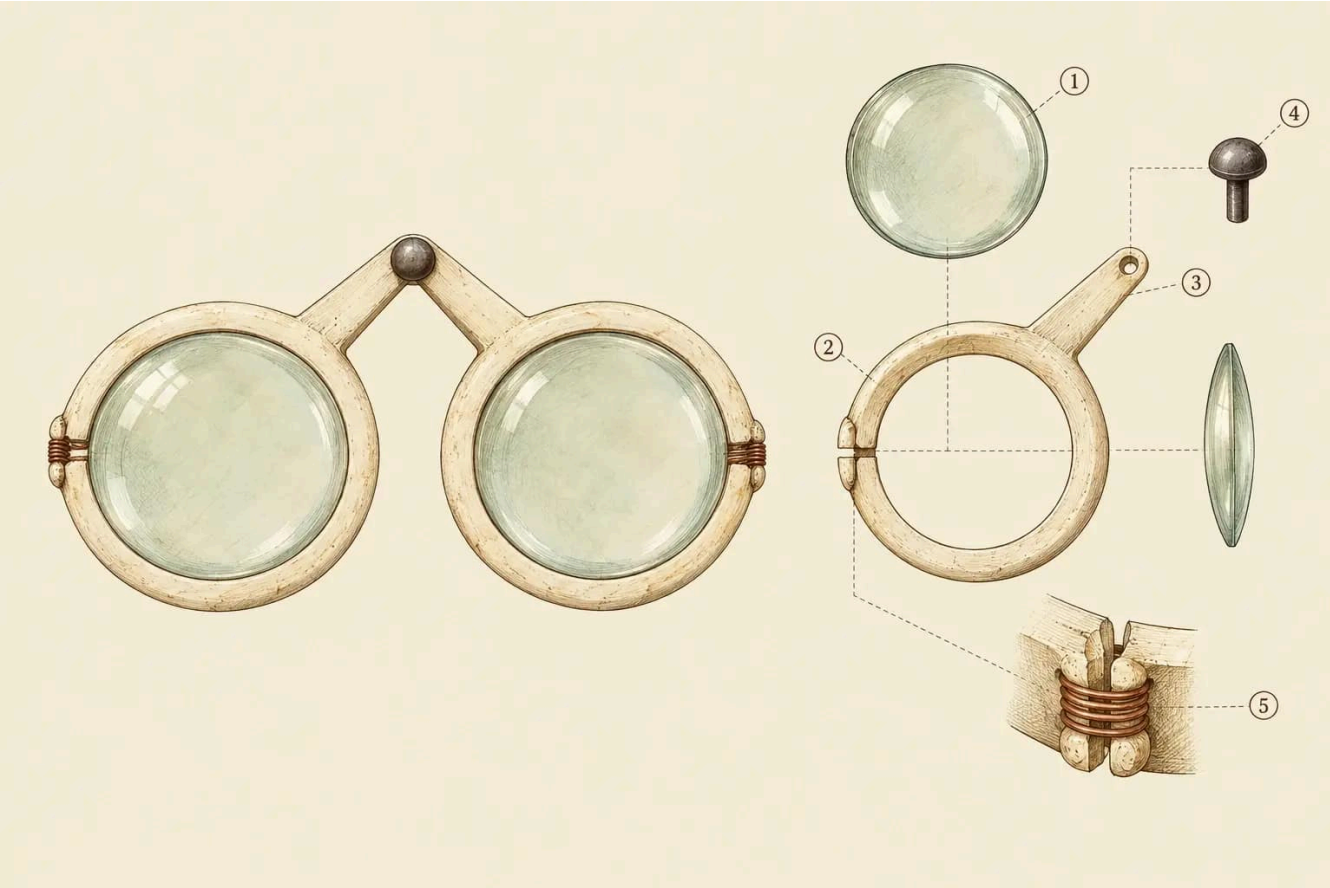
Eyeglasses

Lenses that extend a working life

c. 1286 · Middle Ages · Crafts & cities

Requires: Glass (p. 129)

Leads to: Microscope (p. 209), Telescope (p. 213)



1 Biconvex glass lens 2 Bone rim 3 Handle 4 Iron rivet 5 Copper wire binding

Eyeglasses are a pair of lenses held in a frame in front of the eyes to correct long sight, short sight or astigmatism. They appeared in Italy in the 1280s as reading aids for older people; lenses for short sight followed in the fifteenth century and side arms in the eighteenth.

What it is

Eyeglasses, or spectacles, put a lens in front of each eye so that the light reaches the retina already bent by the right amount. The first ones helped people in their forties and older to read and to do fine work, once focusing at reading distance had become hard.

The pair on the plate is the oldest type, the rivet spectacles of the fourteenth and fifteenth centuries. Each glass lens sits in a ring carved from bone, wood or horn. A short handle sticks out from each ring, and the two handles are joined by a single rivet. The pair has no side arms: the rivet rests on the bridge of the nose and the rims pinch the nose on either side, so the wearer has to keep the head level or hold the spectacles with one hand.

How it works

Inside the eye, a soft lens changes shape to bring near or distant things into focus. With age it hardens, and the closest point the eye can see sharply moves away: a few centimetres from a child's face, it ends up out of reach of the arms for most people of sixty. This is presbyopia, and it is why reading glasses were the first ones made.

A reading stone, a dome of crystal or glass laid on the page, was the magnifier that came before spectacles.

A convex lens, thicker in the middle than at the edge, makes the light converge a little before it enters the eye, and so does part of the work that the eye's own lens can no longer do. Opticians measure this power in dioptres, the inverse of the focal length in metres. A reading lens of +2 dioptres brings parallel light to a point 50 cm behind it.

Short sight is a different focusing problem, and it can come on top of presbyopia. The eyeball is a little too long, or its optics too strong, and distant things blur. A concave lens, thinner in the middle, spreads the light slightly before it enters the eye and pushes the image back onto the retina. Lenses of this kind were being ground in Florence in the fifteenth century. In astigmatism the eye's power differs between two perpendicular directions, so lines at one angle blur more than lines at another. Correcting it needs a lens curved more in one direction than the other, and such lenses came much later.

How to build it

A pair of rivet spectacles like the one on the plate takes two lenses, a piece of bone or hardwood, copper wire and one small rivet.

The glass blank, fixed with pitch to a wooden handle, was worked with wet abrasive in a bronze tool, then polished on leather.

Get the lenses. For a pair you will actually look through, take two lenses from a cheap pair of modern reading glasses. Grinding your own is a historical demonstration: as a spectacle maker did, rub a disc of glass about 4 cm across with wet abrasive powder inside a tool hollowed to the curve you want, finishing with finer and finer grits, then polish it with rouge on leather or felt. For a +2 dioptre lens made of ordinary glass, both faces need a radius of curvature of about 50 cm, a very shallow curve. Hand-ground lenses will not have an exact power, and their optical centres will not be lined up with your pupils.

Cut the rims. Mark two circles on a flat piece of bone or boxwood with dividers, a little larger than the lenses, and saw them out with a fine saw, leaving a short tab on each ring for the handle. Cut a V-shaped groove around the inside of each rim to hold the edge of the lens.

Split and bind. Saw through each rim on the side opposite the handle. Spring the ring open, slide the lens into the groove and close the split by wrapping thin copper wire several times around two small lobes left on either side of it.

Rivet the handles. Drill a small hole near the end of each handle, overlap them and set a copper or iron rivet, peened just tight enough that the two halves can still be folded. File small notches along the inner edges where the rims meet the nose, so they grip better.

> **Safety.** Grind glass wet and wear a dust mask: dry glass and abrasive dust harm the lungs. Wear eye protection when drilling bone and cutting wire, and handle cut glass with care. Never look at the Sun through a lens, and never leave one in sunlight near paper or wood, because it can start a fire. This pair is a replica: do not use it in place of glasses prescribed and fitted by an optometrist, and never drive with it.

History and evolution

Polished crystals and glass had been used to enlarge writing long before spectacles. The step of setting a lens in a frame in front of each eye came in Italy around 1280 to 1290. Where exactly is not known: Pisa and Florence are often proposed, and a Venetian ordinance of 1300 already punished glassmakers who sold glass “discs for the eyes” as rock crystal. In a sermon given in Florence in 1306, the Dominican friar Giordano da Pisa said that the art of making spectacles was not yet twenty years old and that he had spoken with the man who first made them. Nobody knows his name.

The oldest known painting of spectacles is a fresco of 1352 by Tommaso da Modena in the chapter house of San Nicolò in Treviso, which shows a Dominican cardinal reading with rivet spectacles. Real frames rarely survive. A bone pair from the fifteenth century was found at Trig Lane, by the Thames in London, at a time when thousands of spectacles a year were imported into London from the Low Countries. In 1466 the Duke of Milan ordered two hundred pairs graded by age, a sign that lens strengths had become fairly standard.

By the early sixteenth century spectacles could correct short sight as well as long sight, and bridges of leather or whalebone replaced the rivet. Around 1730 the London optician Edward Scarlett is credited with adding rigid side arms, or temples, that pressed against the sides of the head. In letters of 1784 and 1785 Benjamin Franklin described his “double spectacles”, with half of each lens for distance and half for reading. Pince-nez, held by a spring on the nose, followed in the nineteenth century, then in the twentieth plastic frames, lighter plastic lenses and, later, thinner high-index lenses.

Double spectacles of the late eighteenth century: a distance lens above, a reading lens below.

Key figures

Early Venetian record
Ordinance of 2 April 1300 on glass "discs for the eyes"

Testimony on the date
Sermon by Giordano da Pisa, Florence, 1306: the art was "not yet twenty years" old

First painted spectacles
1352, fresco by Tommaso da Modena in Treviso

A typical reading lens
+2 dioptres, a focal length of 50 cm

Side arms (temples)
Credited to the London optician Edward Scarlett, about 1730

Sources

1. History of spectacles · College of Optometrists, British Optical Association Museum https://www.college-optometrists.org/history-of-spectacles
2. Spectacles (bone rivet spectacles from Trig Lane) · London Museum https://www.londonmuseum.org.uk/collections/v/object-407684/spectacles/
3. Medieval Eyeglasses: Wearable Technology of the Thirteenth Century · Medievalists.net https://www.medievalists.net/2016/03/medieval-eyeglasses-wearable-technology-of-the-thirteenth-century/
4. The Earliest Depiction of Eyeglasses in a Painted Work of Art · HistoryofInformation.com https://www.historyofinformation.com/detail.php?id=1447
5. A Venetian ordinance on the production of lenses (2 April 1300) · HistoryofInformation.com https://historyofinformation.com/detail.php?id=2217
6. Renaissance Vision from Spectacles to Telescopes (Vincent Ilardi, 2007), book description · American Philosophical Society, via Goodreads https://www.goodreads.com/book/show/1685277.Renaissance_Vision_from_Spectacles_to_Telescopes
7. Benjamin Franklin invents bifocal glasses · HISTORY.com https://www.history.com/this-day-in-history/may-23/benjamin-franklin-invents-bifocal-glasses
8. University Physics Volume 3, 2.5 The Eye · OpenStax, Rice University https://openstax.org/books/university-physics-volume-3/pages/2-5-the-eye
9. Presbyopia · EyeWiki, American Academy of Ophthalmology https://eyewiki.org/Presbyopia
10. A Review of Depth of Focus in Measurement of the Amplitude of Accommodation (Burns, Allen, Edgar and Evans, Vision 2, 2018) · MDPI, via PubMed Central https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6835437/
11. Optics of the Human Eye (Atchison and Smith, 2nd edition, 2023) · CRC Press https://www.routledge.com/Optics-of-the-Human-Eye/Atchison/p/book/9781003128601
12. Schematic eyes: Gullstrand, Gullstrand-Emsley and reduced eyes (lecture notes) · Al-Mustaqbal University https://www.uomus.edu.iq/img/lectures21/MUCLecture_2024_11210775.pdf

Fact-checked on 2026-10-12

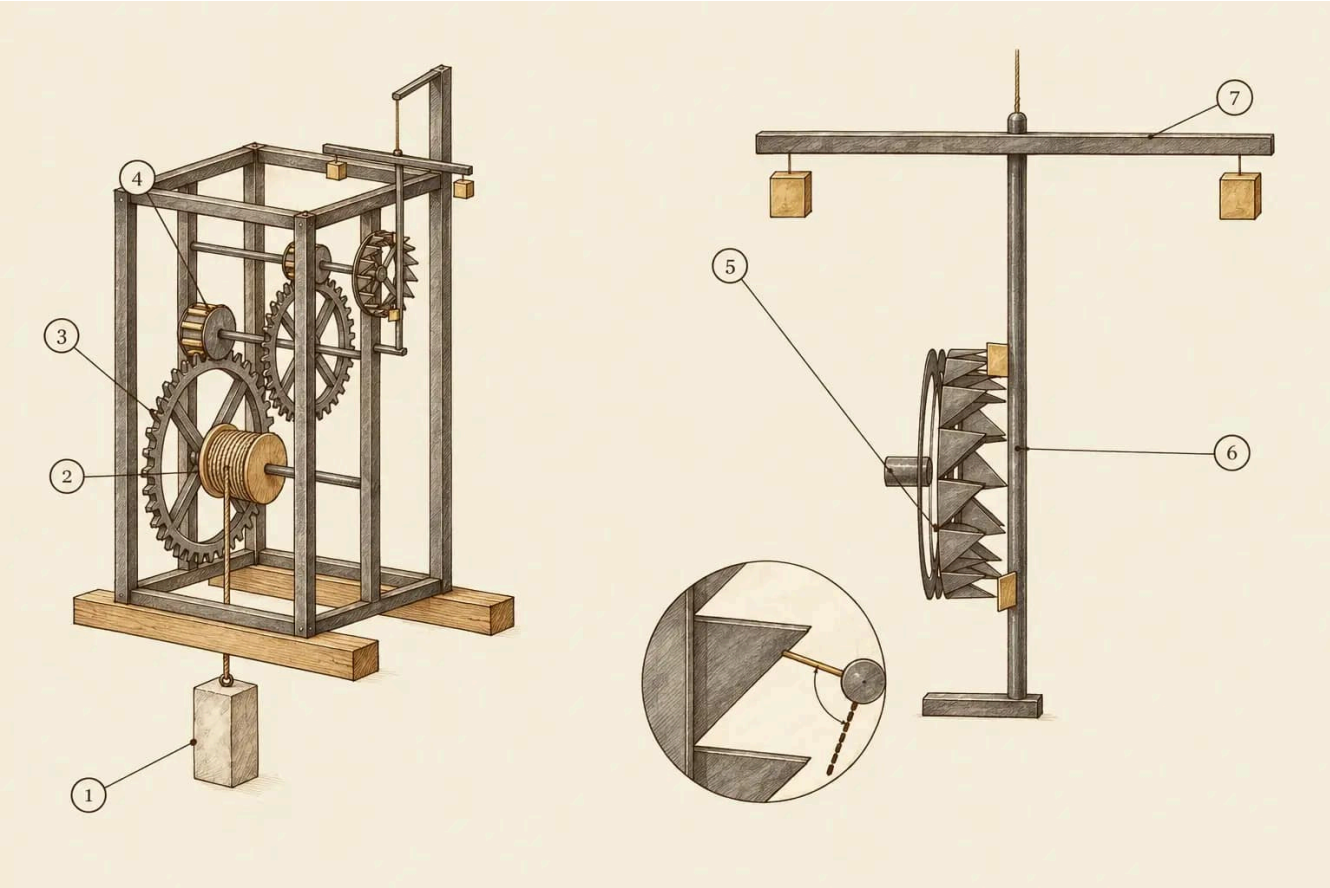
Mechanical Clock

Time cut into equal beats

c. 1300 · Middle Ages · Crafts & cities

Requires: Gears (p. 149), Iron Smelting (p. 133)

Leads to: Celestial Navigation (p. 205)



1 Driving weight 2 Barrel and rope 3 Great wheel 4 Lantern pinion 5 Crown wheel 6 Verge and pallets 7 Foliot and its weights

A mechanical clock lets a falling weight turn a train of gears, and an escapement lets the train move forward only one small step at a time. The first ones were built in Europe at the end of the thirteenth century, large iron machines in church towers that struck the hours on a bell.

What it is

A mechanical clock divides time into equal beats and counts them with gears. The earliest kind, made from the end of the thirteenth century, was a large frame of wrought iron in a church or town tower. It was driven by a heavy stone weight and controlled by a verge and foliot, a rocking bar that let the wheels turn only in small, regular steps. Many had no dial at all: they struck a bell at the hours, and people learned the time by ear.

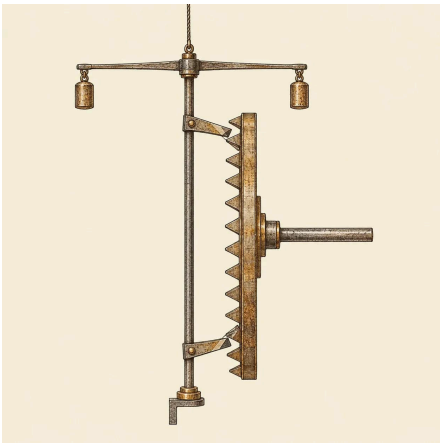
At Salisbury Cathedral a clock of this type still runs in the nave. It is usually identified with a clock mentioned there in 1386, and on that basis it is often called the oldest working clock in the world; the dating rests on indirect evidence, and other clocks are put forward for the title. Its wheels sit in a four-post iron frame held together with

wedged tenons instead of bolts. One weight drives the going train, which keeps time; another drives the striking train, which rings the bell.

How it works

The weight hangs on a rope wound round a wooden barrel. As it slowly falls, it turns the barrel and the great wheel fixed to the same arbor. The great wheel drives a small pinion on the next arbor, which carries another wheel, and so on up to the escape wheel. Each step from wheel to pinion makes the next arbor turn faster.

Left to itself the weight would spin the train and fall in seconds. The escapement stops that. The escape wheel is a crown wheel, with saw-shaped teeth standing out from one face. In front of it hangs the verge, an upright rod with two small flags, the pallets, one meeting the teeth at the top of the wheel and one at the bottom, set at roughly a right angle to each other. A tooth pushes the upper pallet aside and turns the verge; that brings the lower pallet into the path of a tooth on the far side of the wheel, which pushes it back the other way. The verge therefore rocks to and fro, and the wheel advances by half a tooth at each swing one way, a whole tooth for each swing there and back.



The verge escapement seen from the side, where the teeth round the crown wheel's rim line up in one column: the wheel pushes the two pallets in turn, and the weighted foliot swings back and forth on top of the verge.

The foliot is a horizontal bar fixed across the top of the verge, with a small weight hung near each end. Its inertia slows each swing. Moving the weights outward makes the beat slower and the clock lose; moving them in makes it gain. The foliot has no natural period of its own, so the rate also changes with the force of the driving weight, with friction and with the state of the oil, and a typical error was around a quarter of an hour a day. The keeper reset the clock against a sundial and wound up the weights every day.

How to build it

A working model of a verge-and-foliot escapement in plywood and hardwood dowel can be made with hand tools. It ticks and shows how the escapement controls a falling weight; with no dial it does not tell the time. What follows is an overview of the stages: for tooth shapes and arbor spacings, work from a published, dimensioned plan for a wooden escapement model.

A lantern pinion: round rods between two discs, easy to make by hand, mesh with the teeth of the larger wheel.

Build the frame. Two uprights about 40 cm tall joined by cross-bars, with holes for three horizontal arbors one above the other at the spacings given by the plan. Use dowels as arbors and line the holes with short pieces of brass tube so they turn freely. Screw the frame to a heavy base or a wall bracket so it cannot tip.

Make the train. On the bottom arbor go a drum for the cord and the great wheel; on the middle arbor a lantern pinion of dowel rods and a second wheel; on the top arbor another lantern pinion and the crown wheel. Each wheel must mesh with its pinion without binding or slipping, so cut the teeth to the plan's profile and file them smooth.

Make the escapement. The crown wheel needs an odd number of teeth, 15 is common, standing out from one face: cut them on the edge of a

short ring of thin plywood or hardwood and glue the ring to the face of a disc. Mount the verge, a straight dowel, vertically in front of the wheel, with two thin pallets about 90 degrees apart at the heights of the top and bottom of the wheel. The odd number of teeth means one pallet meets a tooth tip while the other faces a gap. Fit the foliot, a light bar about 30 cm long with two sliding weights, across the top of the verge.

Adjust without the weight. Turn the train by hand with a finger on the drum and check that the pallets alternate: a tooth at the top escapes, then a tooth at the bottom catches the other pallet, with no tooth skipped and nothing jamming. Bend or file the pallets only while the weight is off. Then wind a cord rated well above the load round the drum, tie its end to the drum and hang the weight your plan specifies, often 1 to 2 kg for a small wooden model. To set the beat, lift the weight off or support it, slide the foliot weights a little, let it hang again and count the ticks over a minute; repeat until the beat is steady.

> **Safety.** If a pallet slips, the train runs away and the weight drops: always lift the weight off or support it before touching the escapement, and let the weight run inside a closed guide, such as a tube or a box, that stops at the floor. Keep hands, feet and pets out of its path. Clamp the work and keep hands behind the blade when cutting teeth, and wear eye protection when drilling.

History and evolution

Water clocks and sundials had measured time for thousands of years before mechanical clocks. The decisive step, a mechanism that let a weight fall in regular jerks, was taken somewhere in Europe in the late thirteenth century, and large public clocks are recorded in Italian cities in the first half of the fourteenth. Clocks appear in the records of cathedrals and abbeys from that time, but the same Latin word, horologium, served for water clocks too, so the first mechanical clock cannot be named. By the end of the fourteenth century large iron clocks were at work in many cathedrals; the movement of the Wells Cathedral clock, of 1392, is now in the Science Museum in London, while its dial is still in the cathedral.

The striking train pulls the wire, the hammer swings against the bell, and the hours are heard across the town.

The great change came in 1656 to 1657, when Christiaan Huygens, following an idea of Galileo's, used a pendulum to regulate a clock. A pendulum swings in almost the same time whatever the drive. Huygens's first pendulum clock erred by less than a minute a day, and his later ones by less than ten seconds. Many tower clocks were converted; Salisbury's and Wells's both lost their foliots for a pendulum, and Salisbury's was given a reproduction verge and foliot when it was restored in 1956. Around 1675 a spiral balance spring gave watches a regulator with a period of its own; it brought their error down to some ten minutes a day, far behind a pendulum clock but much better than before.

Key figures

First mechanical clocks
Europe, late 13th century

Oldest working clock (claimed)
Salisbury Cathedral, about 1386; no dial, strikes the hours

Error of a verge-and-foliot clock
Roughly a quarter of an hour a day, depending on make and care

Pendulum clock (Huygens)
1656; under a minute a day at first, later under 10 seconds

Sources

1. What to see: the world's oldest clock · Salisbury Cathedral https://www.salisburycathedral.org.uk/discover/what-to-see/
2. Wells Cathedral clock, 1392 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co1347/wells-cathedral-clock-1392
3. A walk through time: the revolution in timekeeping · National Institute of Standards and Technology https://www.nist.gov/pml/time-and-frequency-division/popular-links/walk-through-time/walk-through-time-revolution
4. Clocks in the Scientific Revolution · World History Encyclopedia https://www.worldhistory.org/article/2315/clocks-in-the-scientific-revolution/
5. Oldest clock · Guinness World Records https://guinnessworldrecords.com/world-records/oldest-clock
6. Model of verge escapement with foliot regulator · Museo Galileo, Florence https://catalogue.museogalileo.it/object/ModelVergeEscapementWithFoliotRegulator.html
7. Salisbury Cathedral clock · Wikipedia https://en.wikipedia.org/wiki/Salisbury_Cathedral_clock
8. Dynamics of the verge and foliot clock escapement (P. Hoyng and A. C. T. Nieuwenhuizen) · arXiv https://arxiv.org/abs/1604.06681
9. Turret clock, Cotehele (c. 1490) · National Trust Collections https://www.nationaltrustcollections.org.uk/object/347888
10. Cotehele clock · Wikipedia https://en.wikipedia.org/wiki/Cotehele_clock
11. Before Big Ben (Jonathan Betts) · Building Conservation https://buildingconservation.com/articles/bigben/bigben.html

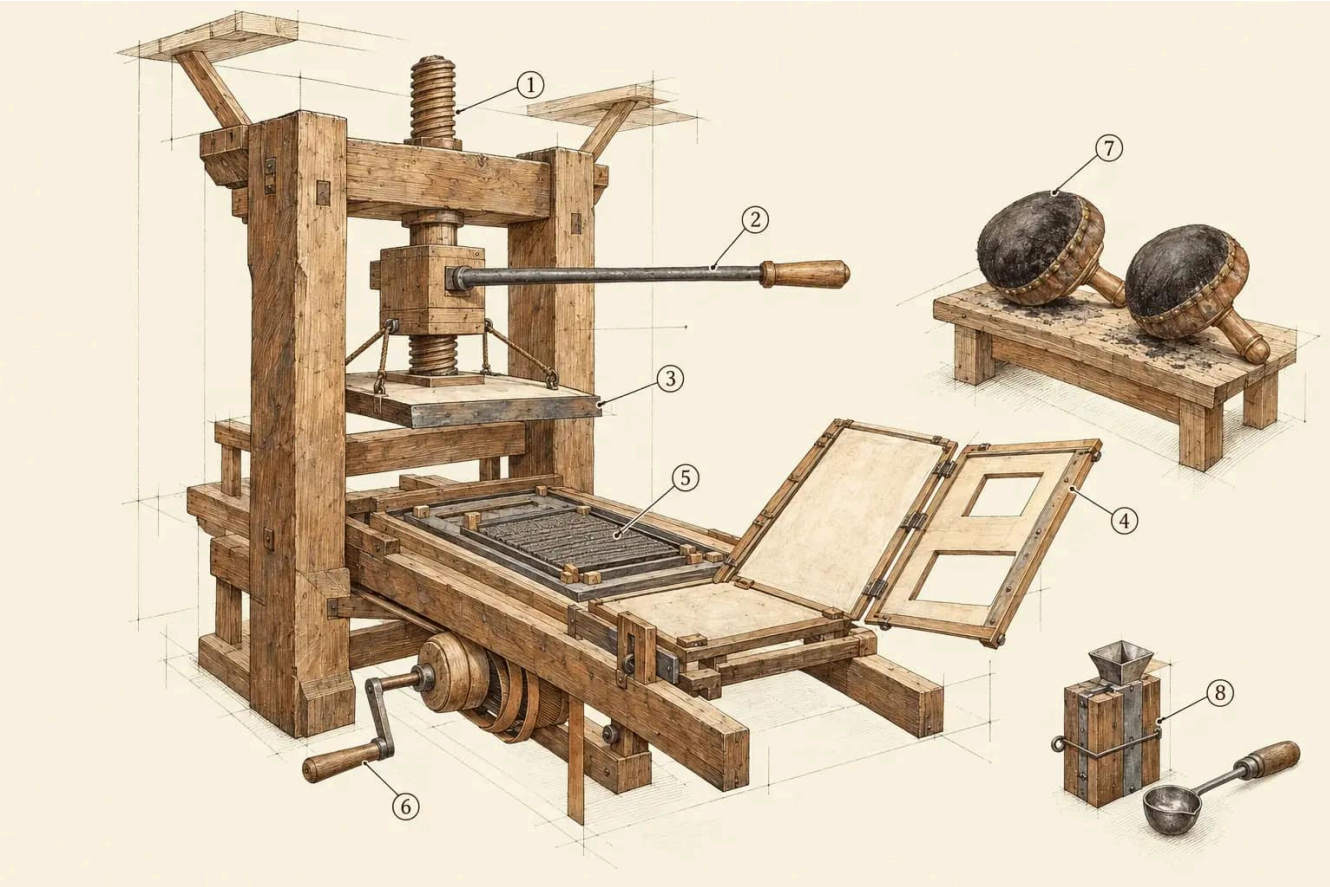
Fact-checked on 2026-10-12

Printing Press

Movable type, copied by the thousand

c. 1440 · Middle Ages · Crafts & cities

Requires: Paper (p. 165), Iron Smelting (p. 133), Writing (p. 82), Steel (p. 137)



1 Screw 2 Bar 3 Platen 4 Tympan and frisket 5 Forme of type on the bed 6 Rounce 7 Ink balls 8 Hand mould for casting type

The printing press presses inked metal type onto damp paper with a wooden screw, so one page of text can be copied hundreds of times in a day. Gutenberg combined it with cast movable type and oil-based ink around 1440, and within fifty years printing had spread across Europe.

What it is

A printing press puts ink on paper by pressure. Letters cast in metal are set side by side to form a page, inked, covered with a damp sheet and squeezed under a flat plate. Lifted off, the sheet carries a mirror image of the type, which reads the right way round.

The machine itself was an old idea. Screw presses had squeezed grapes and olives since Roman times, and papermakers used them to press wet sheets. What was new was the combination of the press with reusable metal type that could be cast quickly and to exact sizes, an ink that stuck to metal, and cheap paper.

How it works

The work starts with the type. A punchcutter files the shape of a letter, in reverse, on the end of a steel bar. The punch is struck into a small block of copper, leaving a hollow letter: the matrix. The matrix goes into the bottom of a hand mould, the caster pours in molten metal, and a moment later he opens the mould and drops out a sort, a small bar with the letter standing on its end.

The two halves of the hand mould slide to fit the width of each letter, while the height of every sort stays the same.

Gutenberg's mould could be adjusted for a narrow "i" or a wide "M" without changing the height of the type. That is what lets thousands of separate sorts stand together and print evenly. The metal, an alloy of lead, tin and antimony, melts at a low temperature, fills fine detail and wears slowly.

Ink balls were stuffed with wool or horsehair and dabbed onto the type.

The compositor picks sorts from a case, sets them line by line in a composing stick and builds up the pages. The pages are then locked tightly in an iron frame, the chase, with wedges. The result is the forme, which lies on a flat stone bed in the carriage of the press.

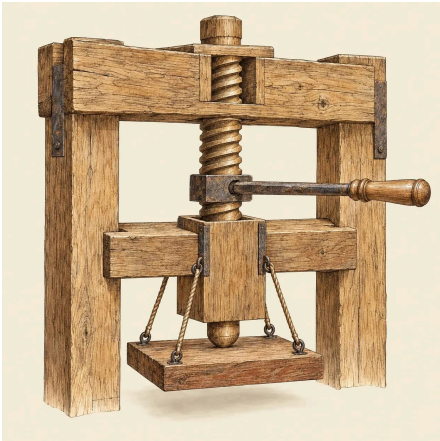
A pressman dabs the type with two ink balls loaded with ink made from soot and linseed oil. His partner lays a damp sheet on the tympan, a hinged frame covered with parchment, and folds the frisket over it to keep the margins clean. Tympan and frisket fold down onto the forme. Turning the rounce winds the carriage in under the platen. A pull on the bar turns the screw a fraction of a turn, the platen presses down, and the sheet is printed.

How to build it

A working press needs a carpenter, a smith and someone who can cut letters.

Build the frame. Join two heavy upright cheeks of oak with a head at the top and a cross piece lower down, and brace the whole to the floor and ceiling. If the frame flexes, the impression blurs.

Make the screw and platen. A wooden screw of hard, close-grained wood such as box or pear, cut with a coarse thread, runs in a nut set in the head. Below the nut the screw turns inside a square wooden sleeve, the hose, which slides through a guide board, the till, and cannot rotate. The flat platen hangs from the hose on cords, so it moves straight down without turning.



The hose slides through the till without turning, so the platen hung from it on cords comes straight down.

Fit the carriage. A smooth stone set in a wooden box slides on rails under the platen. A rounce, a spindle with a handle and leather straps, pulls it in and out.

Cast type. This is skilled foundry work. Cut steel punches, strike them into copper and cast in a two-part mould, with the precautions below.

Without a proper foundry, letters carved in hardwood end grain will print, though slowly and less evenly.

Make ink. Grind lampblack into linseed-oil varnish, oil already thickened by heating, until it is as thick as honey. Buy the varnish ready-made or have it made by someone experienced, because heating oil is a fire hazard.

Dampen the paper. Slightly damp paper takes ink much better. Stack it between wet sheets overnight.

> **Safety.** Cast type only in a workshop set up for molten lead, with a temperature-controlled melting pot, fume extraction, a face shield, a leather apron and gloves. Molten metal splashes violently if it touches water or a damp tool, so preheat ladles and moulds. Lead is poisonous: never eat while working, keep dross and dust in closed containers and wash your hands afterwards. Rags soaked in linseed oil can catch fire by themselves as they dry, so spread them flat outdoors or keep them in a closed metal tin of water. Keep clear of the swing of the bar.

History and evolution

Movable type was first made in China. In the 1040s Bi Sheng printed with baked clay characters, a method recorded by Shen Kuo. Korean printers later cast type in bronze, and the oldest surviving book printed from metal type, the *Jikji*, dates from 1377. Printing Chinese characters, in China as in Korea, needs thousands of different sorts, which kept the method expensive.

Johannes Gutenberg, a Mainz craftsman trained in metalwork, worked on printing in Strasbourg from about 1437 to 1444. Witnesses in a lawsuit of 1439 speak of a press, lead and forms used in a secret venture, usually taken to be early printing. Back in Mainz, with money from Johann Fust, he printed the 42-line Bible between about 1452 and 1455. About 180 copies were made, most on paper and the rest on vellum; 48 or 49 survive.

The trade spread fast. By 1480 printers were at work in about 110 places, and by 1500 in about 270 towns, which had turned out over twenty million copies.

Around 1800 the Stanhope press, built entirely of iron, doubled the output. In 1814 Friedrich Koenig's steam-driven cylinder press printed *The Times* at 1,100 sheets an hour.

Key figures

Gutenberg's first printing experiments
Late 1430s, probably Strasbourg

Type metal
Lead, tin and antimony

Printing towns in Europe by 1500
About 270

42-line Bible
c. 1455, about 180 copies, 48 or 49 surviving

Output of a wooden press, c. 1600
About 1,500 to 3,600 impressions per working day

Sources

1. Printing press · Wikipedia https://en.wikipedia.org/wiki/Printing_press
2. The Gutenberg Bible · Library of Congress https://www.loc.gov/exhibits/bibles/interactives/gutenberg/index.html
3. Johannes Gutenberg (Scientist of the Day) · Linda Hall Library https://www.lindahall.org/about/news/scientist-of-the-day/johannes-gutenberg/
4. Shen Kuo · Wikipedia https://en.wikipedia.org/wiki/Shen_Kuo
5. Joseph Moxon, Mechanick Exercises on the Whole Art of Printing (1683): the press · Transcription by R. Holme https://rholme.taths.org.uk/texpic/20/20_02a/20_02a.htm
6. Making Books: the Renaissance and Today, glossary of the Beaver Press · MIT OpenCourseWare https://ocw.mit.edu/courses/21h-343j-making-books-the-renaissance-and-today-spring-2016/pages/end-view

Fact-checked on 2026-10-11

IV

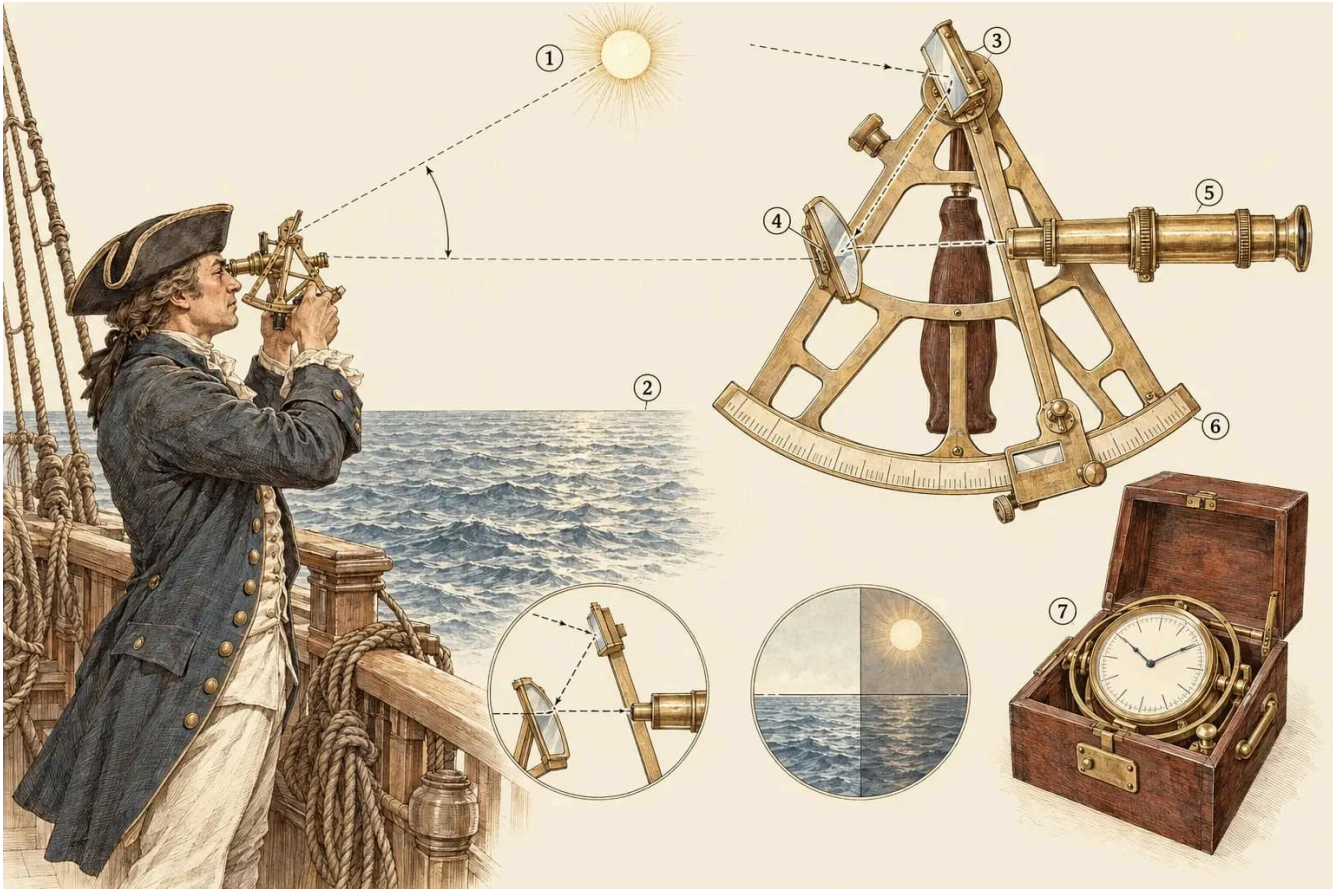
Science & industry

Celestial Navigation

A ship's position read from the sky

c. 1460 · Renaissance · Science & industry

Requires: Magnetic Compass (p. 189), Sail (p. 86), Positional Numerals (p. 94), Measures and standards (p. 124), Mechanical Clock (p. 196)



1 Sun 2 Sea horizon 3 Index mirror 4 Horizon mirror, half silvered 5 Sighting telescope 6 Graduated arc 7 Marine chronometer

Celestial navigation finds a ship's position from the height of the Sun, Moon and stars above the horizon. Latitude comes from the Pole Star, which Portuguese pilots measured with a quadrant around 1460, or from the noon Sun; longitude needs the time at a home meridian, which chronometers and lunar tables supplied from the 1760s.

What it is

Out of sight of land, compass and estimated speed hold a course, but errors pile up. The sky gives a check, because the height of a star or of the Sun above the horizon depends on where the observer stands.

Latitude, the distance north or south of the equator, came first: Indian Ocean pilots took it from the Pole Star with fingers or a kamal, and Europeans brought quadrants and astrolabes to sea in the fifteenth century. Longitude depends on time and stayed a hard problem until the eighteenth. The plate shows a sextant and a marine chronometer from that later period.

How it works

The Pole Star sits close to the point of the sky above the Earth's axis. At the North Pole it stands close to overhead; on the equator, close to the horizon. In between, its height is roughly the latitude. In Columbus's time it was 3.5° off the pole, so pilots corrected their readings; today the gap is under a degree.

South of the equator, navigators use the Sun at local noon, when it stands highest. Its angle from the celestial equator, the declination, swings between about 23.4° N and 23.4° S over the year and can be tabulated in advance. With the noon Sun to the south, latitude is 90° minus its altitude, plus the declination, south counting as negative. With the Sun to the north, as always south of the tropics, latitude is the declination minus (90° minus altitude).

On the early quadrant, a plumb line hangs across a scale while the star is sighted along one edge. The mariner's astrolabe hangs from a ring; for the Sun, the navigator turns its sight rule until a beam passes through the upper pinhole onto the lower one. Both swing on a rolling deck, and errors of several degrees were common.

The mariner's astrolabe was cast heavy and open so the wind would not swing it.

The octant and sextant measure from the sea horizon instead. Sunlight strikes the index mirror on the moving arm, reflects to the horizon mirror, then into the telescope. Half of the horizon mirror is clear, so the horizon is seen straight through it beside the reflected Sun. With dark shades swung in, the navigator moves the arm until the Sun's lower edge touches the horizon and reads the arc. Tables then correct for the eye's height, refraction and half the Sun's diameter, about 16′. The double reflection doubles the angle, so an arc of one sixth of a circle reads up to 120°.

For longitude: the Earth turns 15° an hour. If the Sun crosses the local meridian when a clock kept on Greenwich time shows 15:00, the ship is about 45° west of Greenwich, before the correction for the equation of time: the Sun runs up to 16 minutes early or late over the year. The hard part was a clock that stays true at sea. The other method, the lunar distance, compares the Moon's measured angle to a bright star with printed tables to find the home time.

Between sights, a dead reckoning from compass, log line and clock is plotted on the chart; each fix corrects it.

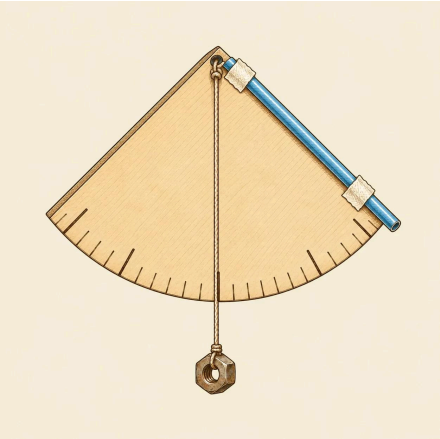
How to build it

A card quadrant finds your latitude within a degree or two, 100 to 200 km.

Make the quadrant. Cut a quarter circle of stiff card about 15 cm in radius. With a protractor, mark degrees along the curve, from 0 at one straight edge to 90 at the other. Tape a straw along the 90 edge. Hang a thread weighted with a nut from the corner. The thread then reads the straw's angle above the horizontal.

Measure the Pole Star. On a clear night in the northern hemisphere, follow the two end stars of the Plough's bowl to Polaris, about five times their spacing away. Sight it through the straw, let the thread settle and read. Five readings averaged give an approximate latitude.

Or measure the noon Sun by a shadow. Never sight the Sun. Plant a straight stick on level ground and check it is vertical with the plumb line. Around midday, mark the shadow's tip every five minutes: the shortest shadow is local noon, rarely 12:00 by the clock. The Sun's altitude is the angle whose tangent is the stick's height divided by that shadow; or draw the triangle to scale and measure the angle with the protractor.



Sight along the straw and read where the thread crosses the scale.

Correct for the date. Look up the day's solar declination in an almanac, positive when north. North of the tropics, latitude = 90° − altitude + declination. On 11 April the declination is about +8°. If a 100 cm stick casts a shortest shadow of 77 cm, the altitude is about 52.4° and the latitude 90 − 52.4 + 8 = 45.6° N, close to Lyon's 45.8°. Then compare with a map.

> **Safety.** Never look at the Sun, with the naked eye or through a straw, tube, binoculars or any sight, even briefly; sunglasses do not protect, and the damage is permanent. At night go with someone, carry a torch, and keep away from cliff edges, quays, riverbanks and open water.

History and evolution

Pacific navigators sailed without instruments, steering by where stars rise and set and judging latitude by the height of the Southern Cross. In 1976 Mau Piailug guided the canoe Hōkūleʻa from Hawaiʻi to Tahiti this way.

With the kamal of Indian Ocean pilots, a knot held in the teeth set the distance to a small board whose edges spanned horizon and star. Ahmad ibn Majid of Oman recorded this lore in 1490.

The kamal: each knot matched the Pole Star's height at a known port.

Diogo Gomes wrote that he took the Pole Star with a quadrant on a Guinea voyage around 1460; his dates are uncertain. Past the equator, crossed in the 1470s, the Portuguese used the noon Sun, the astrolabe and Abraham Zacuto's declination tables, printed at Leiria in 1496. The cross-staff and John Davis's backstaff of about 1594 followed. John Hadley described his octant to the Royal Society in 1731. John Harrison's watch H4 was tried at sea in 1761; Nevil Maskelyne's Nautical Almanac, first issued in 1766 for 1767, carried lunar tables. Regular radio time signals began in 1904, and GPS reached full operation in 1995.

Key figures

One degree of latitude
About 111 km (60 nautical miles)

Earth's turn
15° of longitude per hour, 1° every 4 minutes

Sun's declination
Between about 23.4° N and 23.4° S over the year

Pole Star measured with a quadrant at sea
Diogo Gomes, around 1460

Hadley's octant
Described to the Royal Society on 13 May 1731

Sources

1. What is a mariner's astrolabe? · Royal Museums Greenwich https://www.rmg.co.uk/stories/space-astronomy/what-mariners-astrolabe
2. Quadrant · The Mariners' Museum and Park https://exploration.marinersmuseum.org/object/quadrant/
3. Mariner's astrolabe · The Mariners' Museum and Park https://exploration.marinersmuseum.org/?p=211
4. Back staff · The Mariners' Museum and Park https://exploration.marinersmuseum.org/object/back-staff/
5. Martin Behaim: his life and his globe (E. G. Ravenstein, 1908), pp. 15–17 · Universitätsbibliothek Freiburg https://dl.ub.uni-freiburg.de/diglit/ravenstein1908/0029/ocr
6. Martin Behaim: his life and his globe, Zacuto's Almanach · Universitätsbibliothek Freiburg https://dl.ub.uni-freiburg.de/diglit/ravenstein1908/0031/ocr
7. The navigator Ahmad ibn Majid · AramcoWorld https://archive.aramcoworld.com/issue/200504/the.navigator.ahmad.ibn.majid.htm
8. The Star Compass · Polynesian Voyaging Society https://worldwidevoyage.hokulea.com/education-at-sea/polynesian-navigation/the-star-compass/
9. Wayfinding revival · Science Learning Hub, University of Waikato https://www.sciencelearn.org.nz/resources/631-wayfinding-revival
10. John Hadley · MacTutor, University of St Andrews https://mathshistory.st-andrews.ac.uk/DNB/Hadley.html
11. Octant / sextant · Museo Galileo https://catalogue.museogalileo.it/multimedia/OctantSextantBis.html
12. Who was John Harrison? · Royal Museums Greenwich https://www.rmg.co.uk/discover/explore/longitude-found-john-harrison
13. John Harrison · Linda Hall Library https://www.lindahall.org/about/news/scientist-of-the-day/john-harrison
14. Nevil Maskelyne and the lunar method · Royal Museums Greenwich https://www.rmg.co.uk/stories/topics/longitude-found-nevil-maskelyne-lunar-method
15. The Evolution of Time Measurement, Part 5: Radio Controlled Clocks (M. A. Lombardi, 2012) · NIST https://tf.nist.gov/general/pdf/2536.pdf
16. The System: Celebrating 20 Years of GPS · GPS World https://www.gpsworld.com/the-system-celebrating-20-years-of-gps/
17. Longitude and Local Noon · ESO, Sea and Space https://www.eso.org/public/outreach/eduoff/seaspace/navigation/navastro/navastro-5.html
18. Declination of the Sun · Plymouth State University https://vortex.plymouth.edu/dept/tutorials/sun/sun4a.html
19. The American Practical Navigator (Pub. 9), chapter 14: Instruments for celestial navigation · National Geospatial-Intelligence Agency https://thenauticalalmanac.com/2019_Bowditch-_American_Practical_Navigator/Volume-_1/05-%20Part%203-%20Celestial%20Navigation/Chapter%2014-%20Instruments%20For%20Celestial%20Navigation.pdf
20. The American Practical Navigator (Pub. 9), appendix B: Calculations and conversions (dip of the horizon) · National Geospatial-Intelligence Agency https://thenauticalalmanac.com/2019_Bowditch-_American_Practical_Navigator/Volume-_1/13-%20Appendices/Appendix%20B-%20Calculations%20and%20Conversions.pdf
21. Mate sextant, Kelvin & Hughes, 1967 (NAV1204) · Royal Museums Greenwich https://www.rmg.co.uk/collections/objects/rmgc-object-43416
22. The calculation of astronomical refraction in marine navigation (G. G. Bennett, 1982) · Journal of Navigation https://doi.org/10.1017/S0373463300022037
23. General Solar Position Calculations · NOAA Global Monitoring Laboratory https://gml.noaa.gov/grad/solcalc/solareqns.PDF

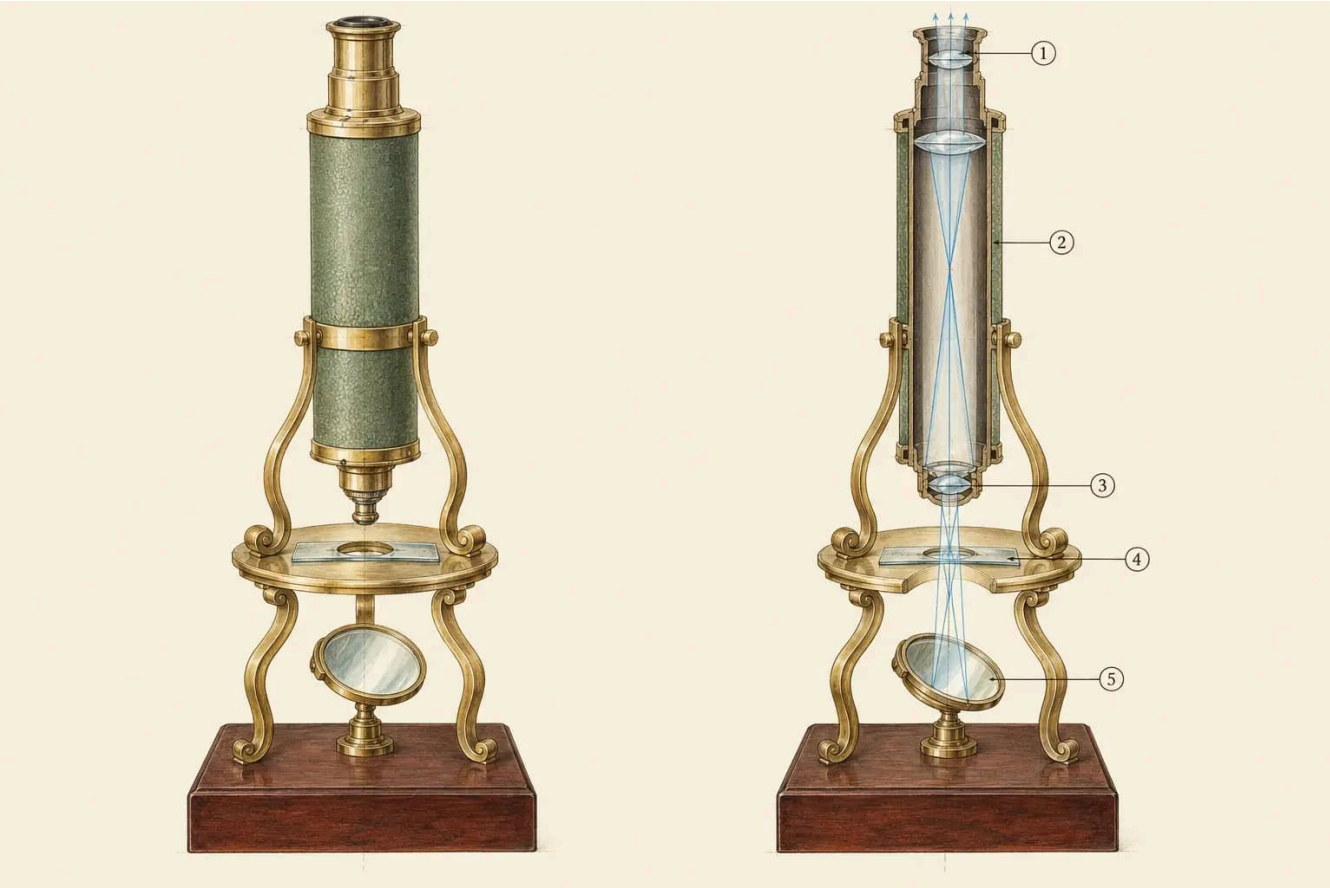
Fact-checked on 2026-10-14

Microscope

A world too small to see

c. 1590 · Renaissance · Science & industry

Requires: Eyeglasses (p. 192)
Leads to: Hygiene & Antisepsis (p. 290)



1 Eyepiece 2 Body tube 3 Objective lens 4 Stage and slide 5 Concave mirror

A microscope uses one or more lenses to show things too small for the eye to see. Compound instruments with two lenses in a tube appeared in the Netherlands around 1600, and in the 1670s Antoni van Leeuwenhoek's single tiny lenses showed bacteria and single-celled life for the first time.

What it is

A microscope shows details too small for the unaided eye to make out, from a tenth of a millimetre down to a few thousandths of one. The simplest kind, the simple microscope, is a single strong lens held close to the eye. The compound microscope uses two lenses or groups of lenses in a tube: the first makes an enlarged image and the second enlarges that image again.

The instrument on the plate is a compound microscope of the type the London instrument maker Edward Culpeper developed around 1725 to 1730. Three curved brass legs on a wooden base carry the stage; three more carry the sleeve in which the body tube slides up and down for focusing. A concave mirror below the stage gathers daylight or candlelight and sends it up through the specimen.

How it works

The specimen, often a thin slice or a drop of liquid on a glass slide, sits over a hole in the stage. The mirror throws light up through it. Just above the slide, the objective lens, small and strongly curved, forms a real, enlarged and upside-down image of the specimen inside the tube. The eyepiece at the top works like a magnifying glass on that image. In the plate, a field lens just below the eye lens widens the area that can be seen at once.

The two enlargements multiply. An objective that magnifies ten times and an eyepiece that magnifies ten times give a hundred times in all. Moving the tube up or down brings the specimen into focus; at high power the depth that is sharp is only a few thousandths of a millimetre.

More magnification does not always show more. Early lenses bent each colour by a slightly different amount and blurred the image with coloured fringes. Joseph Jackson Lister solved much of this around 1830 with objectives that combined two kinds of glass. Later in the century Ernst Abbe, working with the Zeiss firm in Jena, showed that the wave nature of light itself sets a limit: a conventional light microscope cannot separate two points much closer than about 0.2 µm, roughly half the wavelength of visible light, and the exact figure depends on the colour of the light and the aperture of the objective. Smaller things need electron microscopes or special fluorescence methods.

Leeuwenhoek's instrument, seen from the side: the long screw raises the specimen pin, the short one pushes it toward or away from the lens.

How to build it

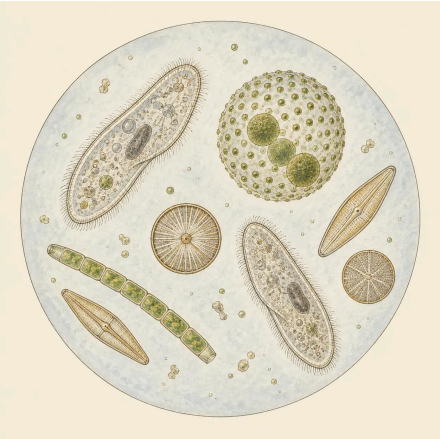
A single-lens microscope of Leeuwenhoek's type is within reach of a careful amateur and can reach 100× or more.

Make the lens. The easiest lens is a glass or sapphire ball 2 to 3 mm across, sold for optics or for fibre couplers. A ball 2 mm across made of ordinary glass has a focal length of about 1.5 mm, measured from its centre, and magnifies about 150 times. The specimen has to sit only about half a millimetre from the glass surface. Leeuwenhoek also made lenses by melting glass; heating the tip of a thin glass rod until a round bead forms works, but it needs a gas flame and is best left to people trained in lampworking.

Mount it. In two thin strips of brass or aluminium about 5 by 2.5 cm, drill a hole about half the diameter of the ball, which serves as the aperture and cuts out the blurred edge of the lens. Countersink the inner side of each hole so the ball sits in it, sandwich the lens between the strips and rivet or bolt them together near the edges. File off every burr and round the corners.

Add the specimen holder. Fix a small block behind the plate on a long screw passing through a bracket, so that turning the screw raises and lowers it. Fit a pin, or a glass coverslip with finished edges, to the block to hold the specimen just behind the lens, and a second screw through the block, pressing on the plate, to adjust the distance. Use fine threads: the specimen must be brought to within half a millimetre of the lens and moved by hundredths of a millimetre.

Use it. Hold the lens close to your eye without touching it, with the specimen on the far side, and look toward a bright, diffuse light such as a white wall or an overcast sky. A drop of pond water on a coverslip will show moving protozoa and algae.



A drop of pond water seen at about a hundred times: paramecia, a Volvox colony, diatoms and a green alga.

> **Safety.** Never point any microscope or its mirror at the Sun: concentrated sunlight can cause permanent eye damage in an instant. Hot glass looks the same as cold glass, so let beads and rods cool on a heatproof surface, and keep gas flames away from anything flammable. Wear eye protection when drilling metal. Treat pond water as unclean and wash your hands after handling it.

History and evolution

Spectacle makers in the Netherlands were the first to put two lenses in a tube, around 1590 to 1620. Later claims credited Zacharias Janssen of Middelburg, but they rest mostly on statements made decades afterwards by his son, and Cornelis Drebbel and others built similar instruments. In 1624 Galileo sent one of his “occhialini” to Federico Cesi, and the next year Johannes Faber, a member of Cesi’s Accademia dei Lincei, proposed calling it a microscope.

Robert Hooke’s Micrographia, published by the Royal Society in 1665, made the compound microscope famous. Its thirty-eight engravings showed a flea, a louse and a thin slice of cork, whose empty compartments Hooke called cells. In Delft the cloth merchant Antoni van Leeuwenhoek saw finer detail with a single lens. He made several hundred small microscopes, some magnifying more than 250 times, and from 1673 sent letters to the Royal Society describing blood cells, sperm and swarms of “little animals”. In a letter of 1676 about water in which pepper had been steeped he described organisms now recognised as bacteria, the first ever seen, and in 1683 he found similar ones in the plaque from his teeth.

Hooke’s microscope of the 1660s: a globe of water gathers the light of an oil lamp onto the specimen.

The compound microscope only overtook the simple lens in the nineteenth century, when Lister’s achromatic objectives and Abbe’s theory turned it into a precise laboratory instrument. Electron microscopes, built from the 1930s, look far below the limit of light, and since the 1990s some fluorescence methods have let optical microscopes get past it.

Key figures

First compound microscopes
Netherlands, about 1590–1620; the inventor is disputed

Leeuwenhoek's best lenses
About 70× to over 250×, resolving about 1 µm

Limit of a conventional light microscope
About 0.2 µm, half the wavelength of visible light

The name
Proposed by Johannes Faber of the Accademia dei Lincei in 1625

Hooke's Micrographia
1665, 38 engraved plates; first use of "cell" in biology

Sources

1. Museum of Microscopy: The Leeuwenhoek Microscope · Molecular Expressions, Florida State University https://micro.magnet.fsu.edu/primer/museum/leeuwenhoek.html
2. Culpeper microscope with boxfoot made by George Adams in 1738 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co119233
3. Johannes Faber (biography) · Museo Galileo https://catalogue.museogalileo.it/biography/JohannesFaber.html
4. Galileo and the microscope: timeline (estoria04) · Museo Galileo (IMSS) https://brunelleschi.imss.fi.it/esplora/microscopio/dswmedia/storia/pdf/estoria04.pdf
5. Fleas, mould and plant cells: under a 17th-century microscope · British Library https://www.bl.uk/stories/blogs/posts/fleas-mould-and-plant-cells-under-a-17th-century-microscope
6. History of the achromatic and aplanatic microscope · Antique Microscopes (Brian Stevenson) https://www.microscope-antiques.com/hxachromatic.html
7. De microscoop van Antoni van Leeuwenhoek · Koninklijke Nederlandse Vereniging voor Microbiologie https://www.knvm.org/outreach/mijlpalen-in-de-microbiologie/de-microscoop-van-antoni-van-leeuwenhoek
8. Robert Hooke (Museum of Microscopy) · Molecular Expressions, Florida State University https://micro.magnet.fsu.edu/primer/museum/hooke.html
9. Hooke's Microscope · Lens on Leeuwenhoek https://lensonleeuwenhoek.net/node/7761
10. Museum of Microscopy: Culpeper microscope · Molecular Expressions, Florida State University https://micro.magnet.fsu.edu/primer/museum/culpeper.html
11. Culpeper tripod microscope · The Golub Collection, University of California, Berkeley https://golubcollection.berkeley.edu/thumb181
12. Descriptive Catalogue of the Collection of Microscopes in charge of the Utrecht University Museum (P. H. van Cittert, 1934) · Utrecht University Library https://objects.library.uu.nl/download/1874-307223/fulltext
13. University Physics Volume 3, 2.8 Microscopes and Telescopes · OpenStax, Rice University https://openstax.org/books/university-physics-volume-3/pages/2-8-microscopes-and-telescopes
14. Resolution · Nikon MicroscopyU https://www.microscopyu.com/microscopy-basics/resolution

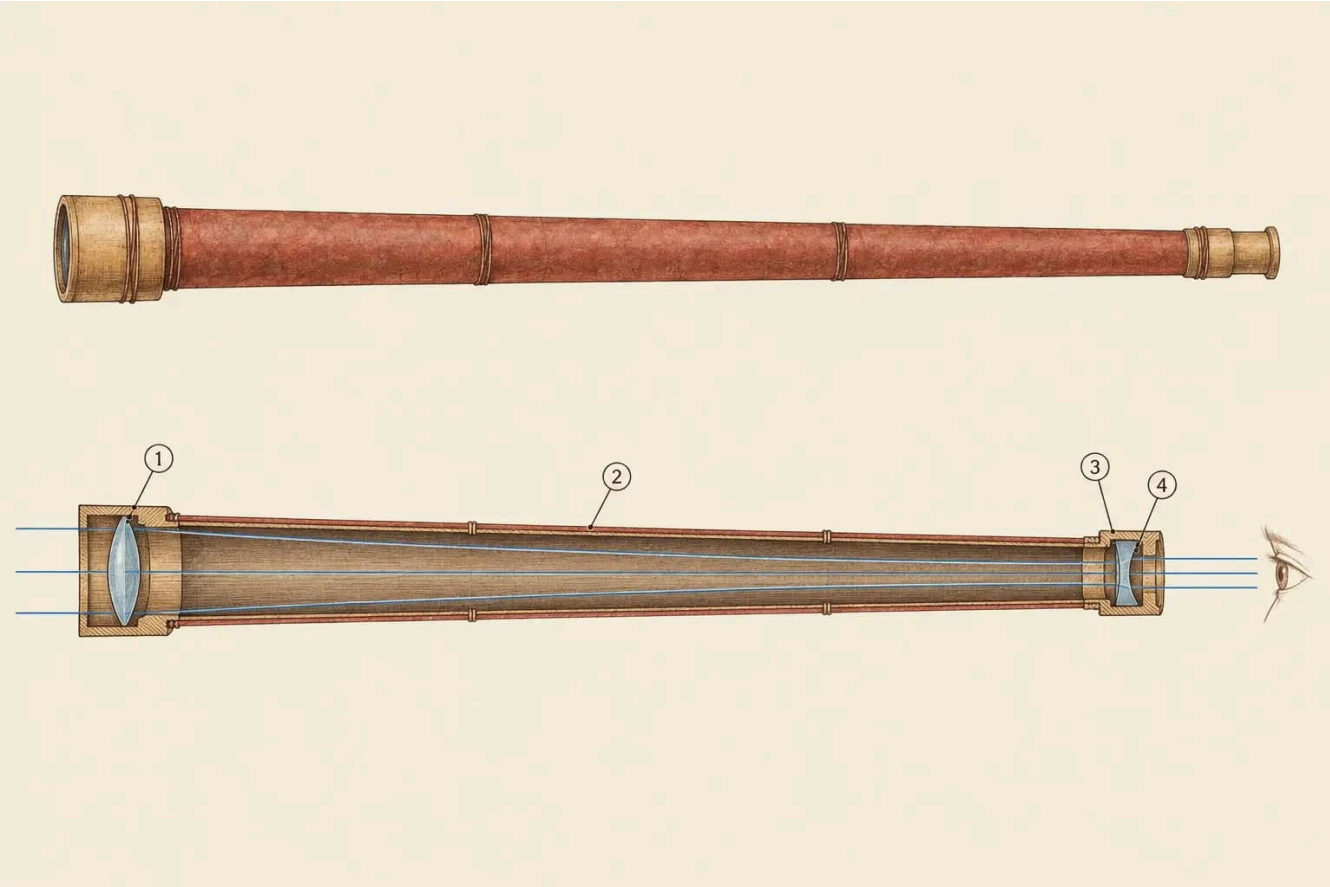
Fact-checked on 2026-10-12

Telescope

Bringing the distant close

1608 · Renaissance · Science & industry

Requires: Eyeglasses (p. 192)



1 Convex objective lens 2 Main tube 3 Eyepiece housing 4 Concave eyepiece lens

A telescope gathers light from a distant object with a lens or a mirror and enlarges the image it forms. Spectacle makers in the Netherlands made the first ones in 1608, and Galileo's improved instruments showed mountains on the Moon in late 1609 and four moons circling Jupiter in January 1610.

What it is

A telescope makes distant things look nearer. Its main light-gathering element, called the objective, collects far more light than the pupil of the eye and forms an image of the distant object. In a refractor the objective is a lens at the front of the tube; in a reflector it is a curved mirror at the back; a smaller eyepiece lens then enlarges that image for the eye.

The telescope on the plate is one of the two surviving instruments made by Galileo Galilei, kept in the Museo Galileo in Florence. Its main tube is made of two wooden half-tubes held together with copper wire and covered with paper. A short housing at the front holds the objective, a convex lens 51 mm across with a focal length of 1,330 mm. Another at the back holds the eyepiece, a small concave lens. The instrument magnifies 14 times and shows a patch of sky only a quarter of a degree wide, about half the width of the full Moon.

How it works

Light from a star or a distant tower arrives as an almost parallel beam. The convex objective bends that beam so that it converges toward a point, the focus, 1,330 mm behind the lens in Galileo's telescope. On its own, the objective would form a small, upside-down image there.

In the Galilean design the concave eyepiece intercepts the converging light before it reaches the focus. It spreads the rays just enough to make them parallel again, but they now travel at steeper angles than when they arrived, so the eye sees the object larger and the right way up. The magnification is the focal length of the objective divided by that of the eyepiece, leaving aside the eyepiece's minus sign: 1,330 mm divided by 94 mm gives about 14.

In 1611 Johannes Kepler proposed a convex eyepiece instead. The Keplerian telescope gives an upside-down image, which does not matter to an astronomer, and a much wider field of view, and it became the standard astronomical refractor. A lens also bends each colour by a slightly different amount, which surrounds bright objects with coloured fringes. Isaac Newton avoided this by gathering the light with a concave mirror, which reflects every colour alike.

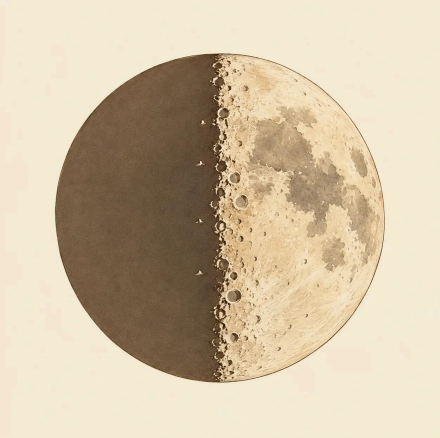
Newton's reflector replaced the objective lens with a curved metal mirror at the bottom of a short tube; a small flat mirror sends the light out to the side.

How to build it

A Galilean telescope like Galileo's needs two lenses and a tube about a metre long.

Choose the lenses. For the objective, a convex lens of about +1 dioptre (focal length 1,000 mm) and 40 to 50 mm across; a single lens works, an achromatic doublet from an optics supplier gives a sharper image. For the eyepiece, a concave lens of about −10 dioptres (focal length −100 mm) and 20 to 25 mm across. This pair magnifies 1,000 ÷ 100 = 10 times.

Make the tube. The lenses must sit about 900 mm apart: the objective's focal length minus the eyepiece's, counted without its minus sign. Use two cardboard or plastic tubes that slide one inside the other, so that the length can be adjusted by a few centimetres. Paint or line the inside matt black to stop stray reflections.



At first quarter, peaks catching the sunlight beyond the shadow line showed Galileo that the Moon had mountains.

Mount the lenses. Hold the objective at the front end between two rings of card or wood, square to the tube. Fit the eyepiece in a short cap at the back with the hollow side toward the eye.

Focus and use. Rest the tube on something firm, such as a camera tripod or a fence, and slide the tubes until a distant chimney looks sharp. At night it shows craters on the Moon and, on a steady evening, Jupiter's four largest moons.

> **Safety.** Never point a telescope or any lens at the Sun, even briefly or near sunset, and never leave one where children could do it: focused sunlight can cause immediate, permanent eye damage and can set the tube on fire. Looking at the Sun through a telescope needs a filter made for that purpose that covers the whole front opening, fixed securely, checked for scratches and holes each time and used as its maker instructs. Eclipse glasses and filters that screw into the eyepiece are not safe behind a telescope.

History and evolution

On 2 October 1608 Hans Lipperhey, a spectacle maker in Middelburg, asked the States General in The Hague for a patent on an instrument for seeing far things as if they were near. Jacob Metius of Alkmaar filed a similar request a few weeks later, others claimed the idea too, and the patent was refused. No telescope from these first makers survives; Lipperhey's probably magnified about three times.

News of the "Dutch perspective glass" spread quickly. Thomas Harriot in England was using a six-power instrument by the summer of 1609, and Galileo in Padua, who ground his own lenses, built a three-power spyglass in the summer of 1609 and showed an eight-power one to the Venetian Senate in August. By the autumn he had reached about twenty; sources differ on whether he first studied the Moon with that instrument or with a weaker one. His second surviving telescope magnifies 21 times. In March 1610 his short book Sidereus Nuncius described mountains on the Moon, countless stars in the Milky Way and four moons orbiting Jupiter. The name telescope was suggested in 1611 by Prince Federico Cesi, founder of the Accademia dei Lincei.

Jupiter and its four large moons lie almost on one line; Galileo watched them change places from night to night in January 1610.

Astronomers then built ever longer refractors to reduce colour blur. Chester Moore Hall made achromatic lenses of two kinds of glass around 1733, and they came into general use after John Dollond began producing them in the late 1750s. Newton's reflector, designed in 1668 and shown in a second version to the Royal Society at the turn of 1672, was the model for the mirror telescopes William Herschel built himself; with one of them he found the planet Uranus in 1781.

Key figures

First written record
Hans Lipperhey's patent application, The Hague, 2 October 1608

Lipperhey's instrument
Probably about 3×

Galileo's telescope in Florence
Objective 51 mm, focal length 1,330 mm, 14×

Sidereus Nuncius
Published in Venice, March 1610

Newton's reflector
Designed 1668; second version shown to the Royal Society in 1671–1672

Sources

1. Galileo's telescope (inv. 2427) · Museo Galileo https://catalogue.museogalileo.it/object/GalileosTelescope.html
2. Instruments: Galileo's telescopes · Museo Galileo (IMSS) https://brunelleschi.imss.fi.it/pencil/eng/html/Tools/01%20Cannocchiale.htm
3. Scientist of the Day: Hans Lipperhey · Linda Hall Library https://www.lindahall.org/about/news/scientist-of-the-day/hans-lipperhey/
4. Galileo's telescope: reflecting telescopes · Museo Galileo (IMSS) https://brunelleschi.imss.fi.it/esplora/cannocchiale/dswmedia/storia/estoria6_st.html
5. History of the achromatic and aplanatic microscope (Hall and Dollond) · Antique Microscopes (Brian Stevenson) https://www.microscope-antiques.com/hxachromatic.html
6. Telescope · The Galileo Project, Rice University https://galileo.library.rice.edu/sci/instruments/telescope.html
7. 7-foot Newtonian (reflector) telescope · Royal Museums Greenwich https://www.rmg.co.uk/collections/objects/rmgc-object-11122
8. Galileo's telescope (inv. 2427): measurements of the lenses · Museo Galileo (IMSS) https://imss.fi.it/news/cielimedicei/01/estrumento2.html
9. Galileo's knowledge of optics and the functioning of the telescope, revised (Y. Zik and G. Hon) · arXiv https://arxiv.org/abs/1307.4963
10. Learning from Galileo's errors (E. Bernieri) · arXiv https://arxiv.org/abs/1206.4244
11. Telescopes of Galileo (V. Greco, G. Molesini and F. Quercioli), Applied Optics 32, 6219–6226 · Optica Publishing Group https://opg.optica.org/ao/abstract.cfm?uri=ao-32-31-6219
12. University Physics Volume 3, 2.8 Microscopes and Telescopes · OpenStax, Rice University https://openstax.org/books/university-physics-volume-3/pages/2-8-microscopes-and-telescopes
13. University Physics Volume 3, 4.5 Circular Apertures and Resolution · OpenStax, Rice University https://openstax.org/books/university-physics-volume-3/pages/4-5-circular-apertures-and-resolution
14. Astronomy 2e, 6.1 Telescopes · OpenStax, Rice University https://openstax.org/books/astronomy-2e/pages/6-1-telescopes

Fact-checked on 2026-10-12

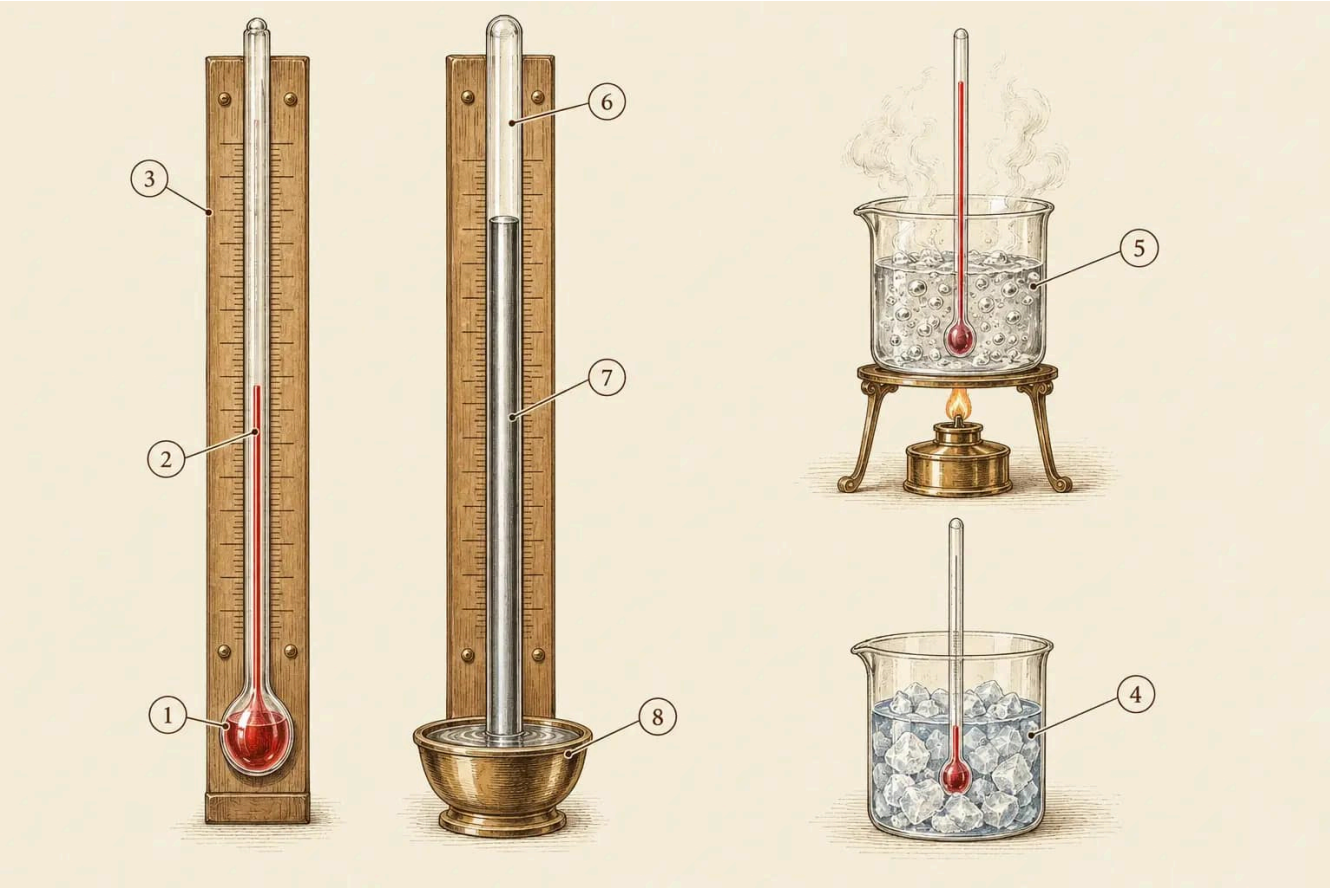
Thermometer and barometer

Temperature and air pressure read on glass

c. 1654 · Renaissance · Science & industry

Requires: Glass (p. 129), Measures and standards (p. 124), Positional Numerals (p. 94)

Leads to: Refrigeration (p. 274)



1 Bulb holding the liquid 2 Fine glass stem 3 Scale 4 Melting ice, lower fixed point (0 °C) 5 Boiling water, upper fixed point (100 °C at 1013.25 hPa) 6 Empty space at the closed top of the tube 7 Mercury column, about 760 mm 8 Open cistern

A thermometer shows temperature as the length of a liquid thread in a fine glass tube, read against a scale fixed by melting ice and boiling water. Its companion, the barometer, weighs the air by the height of the liquid column the atmosphere can hold up: about 760 mm of mercury at sea level.

What it is

A thermometer turns temperature into a length you can read. A glass bulb full of liquid opens into a tube with a very narrow bore. When the liquid warms it expands, and its thread climbs the tube past a scale.

The barometer came out of the same Italian workshops and weighs the air above us by the height of a liquid column. With thermometers built alike, observers in different towns could compare their readings, as the first weather network did from 1654.

How it works

Liquids grow slightly when heated: ethanol by about 0.11% of its volume per degree, mercury by about 0.018%, glass far less. The bore makes this visible, because all the extra volume of the bulb must go into it. A bulb holding a fifth of a cubic centimetre of alcohol gains about 0.2 mm^3 per degree; in a bore 0.2 mm across, that is a step of about 7 mm.

A scale needs points that anyone can reproduce. Pure ice always melts at the same temperature, and pure water always boils at the same temperature under the same air pressure. The Celsius scale calls them 0 and 100, with a hundred equal steps between. On high ground water boils at a lower temperature, roughly one degree less for every 300 m of altitude. Calibrating an instrument means checking it against these points or a trusted reference and noting the error; without that, two thermometers can disagree by several degrees. It matters in the kitchen: British food-safety advice asks for 70 °C held for two minutes at the centre of cooked food.

Plain water shrinks as it warms between 0 and 4 °C and freezes at 0 °C. Early sealed thermometers held alcohol, and from the eighteenth century precision instruments mostly held mercury, which stays liquid over a wide range and does not wet the glass.

Torricelli's barometer was a glass tube about a metre long, closed at one end, filled with mercury and turned over into a bowl of mercury. The column dropped until about 760 mm stood above the bowl, with an almost empty space above it. Its weight balances the push of the air on the open surface. Mercury is 13.6 times denser than water, so a water barometer needs more than 10 m of tube, the same height that limits a suction pump.

Near sea level the column falls by about a millimetre for every 11 m you climb, so a barometer also measures height. A falling barometer often comes before wind and rain, a rising one before fair weather. Aneroid barometers use a sealed metal capsule that flexes instead of a liquid.

How to build

The liquid thermometer is a teaching instrument: compare it with a reference to learn its error, and never use it for food or to check a fever. The jar barometer only shows whether the pressure is rising or falling.

The liquid thermometer. Take a small glass bottle of about 100 ml, a clear drinking straw at least 25 cm long and modelling clay. Mix equal volumes of water and 70% isopropyl alcohol (rubbing alcohol), tinted with food colouring: the mix expands more than water and avoids its odd behaviour near freezing. Fill the bottle to the brim, push the straw well into the liquid and seal the neck with clay, leaving no air bubble. At room temperature the liquid should stand about 8 cm above the clay; add or remove a little through the straw with a dropper. The larger the bottle and the narrower the straw, the bigger the step per degree. Tape a paper strip behind the straw.

The lower fixed point: the bottle stands in melting ice until its thread stops moving.

Fix the points. Stand the bottle in a bowl of crushed ice and a little water, deep enough to cover it up to the neck. Stir, wait until the thread stops moving, which can take a quarter of an hour, and mark 0; the liquid must still show above the clay. Let it come back to room temperature, then put it and a digital kitchen thermometer side by side in a bowl of warm tap water at about 40 °C, stir, wait until both readings stop moving and mark the reference's reading; the thread must not reach the top. If either check fails, change the amount of liquid or the bottle and start both points again. Divide

the gap into equal steps and compare with the reference at room temperature to find your error. Never squeeze the bottle.

A jar barometer: the membrane sinks when the pressure rises, and the straw tip lifts.

The jar barometer. Cut the neck off a balloon, stretch it tight over a wide glass jar and tie it with string so that no air passes. Glue one end of a long straw to the centre of the membrane and let the other overhang the rim, in front of a card. When the outside pressure rises, the membrane sinks and the tip lifts. The trapped air also swells with heat: one degree moves the pointer about as much as 3.5 hPa of pressure. Keep the jar out of the sun in a room whose temperature changes little, and compare its movements with the pressure trend from your weather service.

Reading. Keep your eye level with the top of the thread.

> **Safety.** Never build an instrument with mercury: its vapour is toxic. If an old mercury thermometer breaks, get people and pets out and keep them out, open windows to the outside and shut doors to the rest of the house. Do not vacuum or sweep. On a hard floor, wearing gloves, gather the beads with stiff card, lift them onto a damp paper towel, pick up tiny ones with sticky tape, and seal it all in a labelled bag. On carpet or upholstery, cut out or set aside the soiled part and ask your local health or environmental service. Once the cleanup is done, keep the room aired for at least 24 hours, and take the waste to a hazardous-waste collection as your local authority directs. Isopropyl alcohol is flammable and poisonous: keep it from flames and children. Use hot tap water, never boiling water, and never move glass straight from ice to hot water.

History and evolution

Philo of Byzantium and Hero of Alexandria knew that warmed air swells and pushes water along a tube. Benedetto Castelli later recalled Galileo showing such a thermoscope around 1600, and by 1612 Santorio, a physician in Venice, had given it a scale to follow fevers. Being open, it also reacted to air pressure.

Galileo's thermoscope: as the air in the flask cools, water rises in the neck.

Torricelli described the mercury barometer in a letter of June 1644. In 1648 Pascal's brother-in-law Florin Périer carried one up the Puy de Dôme, where the column stood about 8.5 cm lower than in Clermont below. In Florence, makers working for Grand Duke Ferdinand II sealed alcohol in glass, and in 1654 the duke sent matching thermometers to the first weather network.

Daniel Gabriel Fahrenheit made mercury thermometers in Amsterdam from the 1710s and published his method in 1724. Anders Celsius proposed his scale in 1742 with 0 at boiling and 100 at freezing; it was turned round soon after his death in 1744. In 1848 William Thomson, later Lord Kelvin, proposed an absolute scale, its zero now set at −273.15 °C.

In 1868 Carl Wunderlich, drawing on about 25,000 patients, put the normal mean at about 37 °C and the start of fever near 38 °C. Robert FitzRoy began British storm warnings in 1861 and published the first public forecast in The Times that August. Digital sensors and thermometers filled with other liquids have since largely replaced mercury thermometers, which many countries now restrict.

Key figures

Fixed points (Celsius)
0 °C for melting ice, 100 °C for water boiling at 1013.25 hPa

Air pressure at sea level
About 760 mm of mercury, or about 10.3 m of water

Expansion per degree
Ethanol about 0.11% of its volume, mercury about 0.018%

First weather network
1654, set up by Ferdinand II of Tuscany with sealed alcohol thermometers

Body temperature (Wunderlich, 1868)
About 37 °C on average; 38 °C 'probably febrile'; data from about 25,000 patients

Sources

1. Letter by Castelli on the invention of the thermoscope · Museo Galileo, Florence https://catalogue.museogalileo.it/indepth/LetterByCastelliOnInventionThermoscope.html
2. Medici meteorological network · Museo Galileo, Florence https://catalogue.museogalileo.it/multimedia/MediciMeteorologicalNetworkBis.html
3. Fifty-degree thermometer · Museo Galileo, Florence https://catalogue.museogalileo.it/object/FiftydegreeThermometer.html
4. Thermometers of the Accademia del Cimento · Museo Galileo, Florence https://catalogue.museogalileo.it/section/ThermometersAccademiaCimentoArtScienceGlassware.html
5. Torricellian experiment · Museo Galileo, Florence https://catalogue.museogalileo.it/indepth/TorricellianExperiment.html
6. This Month in Physics History: Torricelli demonstrates the existence of a vacuum · APS News, American Physical Society https://www.aps.org/apsnews/2012/10/torricelli-demonstrates-existence-vacuum
7. Blaise Pascal (Scientist of the Day) · Linda Hall Library https://www.lindahall.org/about/news/scientist-of-the-day/blaise-pascal/
8. On September 19, 1648, Pascal conducted an experiment that proved the existence of atmospheric pressure · Scientific Russia https://en.scientificrussia.ru/articles/under-atmospheric-pressure
9. Fahrenheit, Daniel Gabriel (ADB and NDB entries) · Deutsche Biographie, Bavarian Academy of Sciences https://www.deutsche-biographie.de/sfz14129.html
10. Daniel Gabriel Fahrenheit · Museo Galileo, Florence https://catalogue.museogalileo.it/biography/DanielGabrielFahrenheit.html
11. The Legacy of Anders Celsius · JSTOR Daily https://daily.jstor.org/the-legacy-of-anders-celsius/
12. Kelvin: History · National Institute of Standards and Technology https://www.nist.gov/si-redefinition/kelvin/kelvin-history
13. Wunderlich, Das Verhalten der Eigenwärme in Krankheiten (1868) · HistoryofMedicine.com (Jeremy Norman) https://archive.historyofmedicine.com/id/3542
14. Thermometry and the role of fever in medicine · Healio https://www.healio.com/news/hematology-oncology/20120325/thermometry-and-the-role-of-fever-in-medicine
15. Robert FitzRoy and the early Met Office · Met Office https://www.metoffice.gov.uk/research/library-and-archive/archive-hidden-treasures/robert-fitzroy
16. Air pressure · NOAA JetStream https://www.noaa.gov/jetstream/atmosphere/air-pressure
17. Learning lesson: the "dry" barometer · NOAA JetStream https://www.noaa.gov/jetstream/ll-pressure2
18. Cubical expansion coefficients of liquids · The Engineering ToolBox https://www.engineeringtoolbox.com/cubical-expansion-coefficients-d_1262.html
19. Calibrating your food thermometer · Texas A&M AgriLife Extension https://agrilifeextension.tamu.edu/calibrating-your-food-thermometer
20. High-altitude cooking (Guide E-215) · New Mexico State University Cooperative Extension https://pubs.nmsu.edu/_e/E215/
21. Cooking your food · Food Standards Agency https://www.gov.uk/government/publications/cooking-your-food/cooking-your-food
22. What to do if a mercury thermometer breaks · US Environmental Protection Agency https://www.epa.gov/mercury/what-do-if-mercury-thermometer-breaks

Fact-checked on 2026-10-14

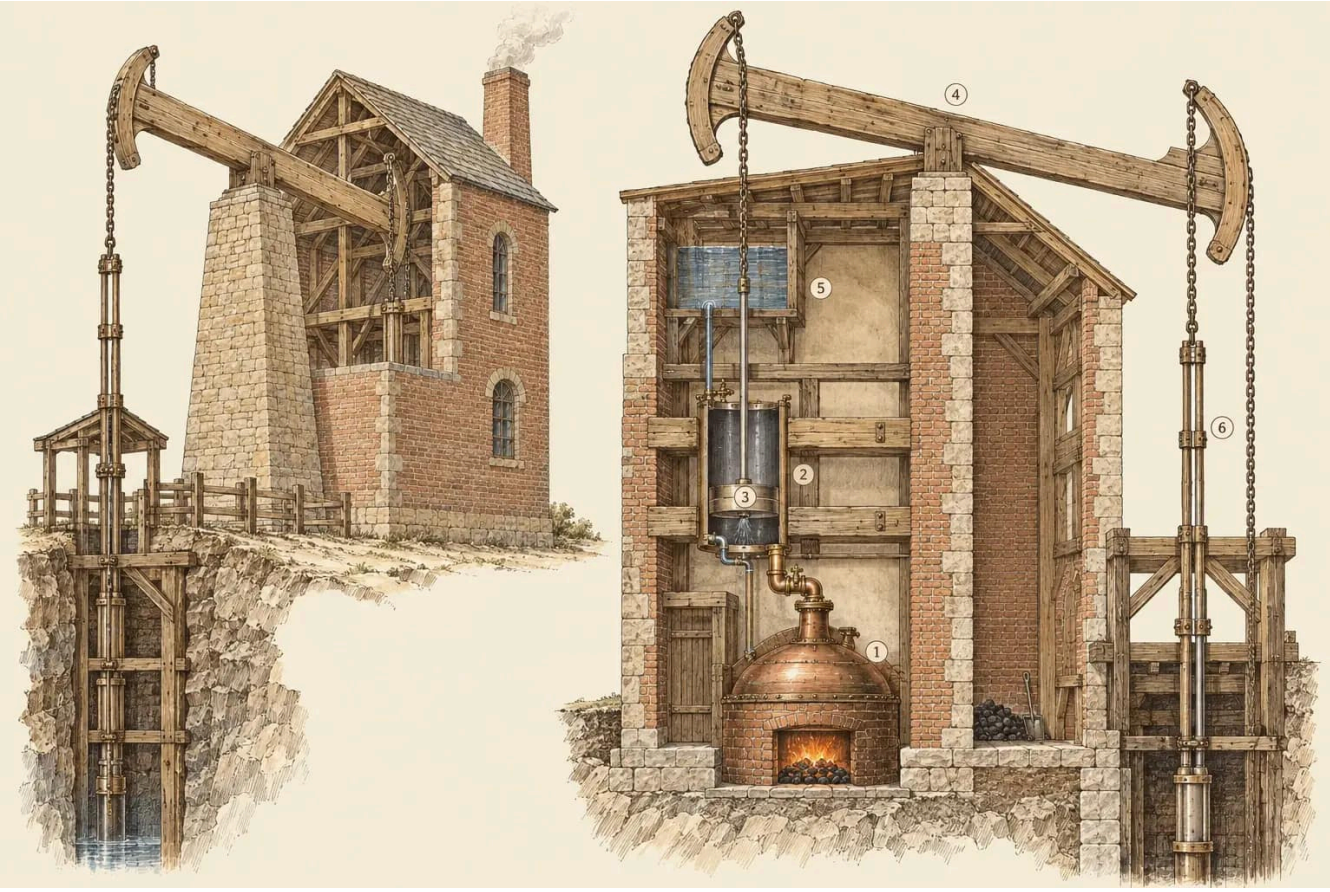
Steam Engine

Heat turned into motion

1712 · Industrial age · Science & industry

Requires: Iron Smelting (p. 133), Gears (p. 149), Piston Pump (p. 157)

Leads to: Internal Combustion Engine (p. 303), Refrigeration (p. 274), Steam Locomotive (p. 238), Steam Turbine (p. 314)



1 Boiler 2 Cylinder 3 Piston 4 Great beam 5 Injection water cistern 6 Pump rods

A steam engine turns the heat of a fire into movement by using steam to drive a piston. Thomas Newcomen's engine of 1712 pumped water out of mines, and James Watt's improvements from 1765 onwards made steam power cheap enough to drive the factories of the Industrial Revolution.

What it is

A steam engine is a machine that uses steam from boiling water to push a piston, and so turns fuel into mechanical work. The first ones pumped water out of mines; later engines drove spinning mills and other machinery, and propelled ships and locomotives.

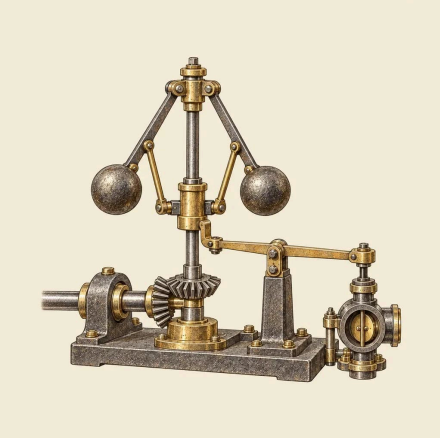
The engine on the plate is the type Thomas Newcomen built in 1712. It is called an atmospheric engine, because the work is done by the pressure of the air outside, while the steam is only used to make a vacuum. The boiler works barely above atmospheric pressure, so it is far less likely to burst than the high-pressure boilers of the nineteenth century.

How it works

Hero of Alexandria's aeolipile, in the first century AD, spun on jets of steam but did no useful work.

The engine is built around a vertical cylinder, open at the top, with a piston inside. The piston hangs by a chain from one end of a great timber beam that rocks on the wall of the engine house. From the other end hang the pump rods, which go down the shaft to the pumps at the bottom of the mine.

The heavy pump rods pull their end of the beam down, which lifts the piston, and steam from the boiler below fills the cylinder. A valve shuts off the steam. A jet of cold water from the cistern sprays into the cylinder, and the steam condenses at once into a little water, leaving a partial vacuum. The air above the piston now presses down harder than the thin steam left beneath it. On a cylinder half a metre across, the pressure difference could in theory reach about 20 kilonewtons, the weight of two tonnes; the useful force was well below that. The piston drops, the beam rocks, and the pump rods rise, lifting water out of the mine.



On later Watt engines, the governor's balls fly outwards as the engine speeds up and partly close the steam valve.

When steam is let in again, it drives air out through a small snifting valve, while the condensed water drains away down a separate pipe with a non-return valve. The cycle repeats about twelve times a minute. A rod hanging from the beam, the plug tree, carries pegs that open and close the valves by themselves.

At every stroke the cold spray chills the cylinder, and the next charge of steam must heat it again before it can fill it. Most of the coal is spent on that reheating.

James Watt's answer was to condense the steam in a separate vessel, kept cold, while the cylinder stayed hot. He later closed the top of the cylinder, used steam pressure on both sides of the piston and added gears to give rotary motion, so the engine could drive machinery as well as pumps.

How to build it

An atmospheric engine needs a coppersmith or boilermaker, a founder able to cast and bore a cylinder, a carpenter for the beam and a mason for the house.

Make the boiler. Historically this was a riveted copper or wrought-iron shell with a domed top, set in brickwork over a firegrate, with a weighted safety valve, cocks to check the water level and a feed pipe. A working reconstruction needs a boiler designed, tested and inspected by a qualified boilermaker; never improvise one.

Cast and bore the cylinder. The cylinder stands just above the boiler, carried on heavy beams set in the walls, and is joined to it only by a short steam pipe. Its bore must be round and smooth along its whole length, or the piston will leak; accurate boring was one of the hardest problems of the eighteenth century.

Fit the piston. Pack the edge of the piston with rope or leather and keep a thin layer of water on top to seal it.

Raise the beam. Make the beam of oak, with curved arch heads at each end so the chains pull straight up and down. Rest its central pivot on a thick wall.

Fit the valves. One valve admits steam and another sprays cold water from a cistern placed high in the house; a snifting valve lets out air, and a pipe with a non-return valve drains the condensed water. Work them by hand at first, then from tappets on a rod hanging from the beam.

> **Safety.** A boiler whose safety valve is blocked, wedged or overloaded can explode: never obstruct or isolate the relief path, and never add weight to the valve. Steam and hot water scald badly. Keep well clear of the beam, chains and pump rods while the engine runs, and fence the shaft.

History and evolution

Hero of Alexandria described a sphere spun by steam jets in the first century AD, but it remained a curiosity. In 1690 Denis Papin showed that condensing steam under a piston could lift a weight. Thomas Savery patented a pump without a piston in 1698. It drew water up by condensing steam in a vessel, then pushed it higher with steam pressure, and it could only manage modest lifts.

Newcomen, an ironmonger from Dartmouth, and his partner John Calley set up the first working engine in 1712 at a coal mine near Dudley Castle. Because Savery's patent covered raising water by fire, Newcomen's engines were built under it until it expired in 1733. More than a hundred were at work in Britain and Europe by the time Newcomen died in 1729.

In 1763 James Watt, an instrument maker at the University of Glasgow, was asked to repair a model Newcomen engine. Two years later he had the idea of the separate condenser, patented in 1769. With Matthew Boulton he began selling engines in 1776. They used about a quarter of the fuel of a Newcomen engine of the same power. Around 1800, as Watt's patent ran out, Richard Trevithick and others turned to high-pressure steam to build smaller, lighter engines, which soon moved onto rails and into ships.

Watt's sun-and-planet gear of 1781 turned the up-and-down motion of the beam into rotation.

Key figures

First working engine
1712, Conygree coal works near Dudley, England

Steam pressure in a Newcomen boiler
About 1 to 2 psi above the atmosphere (0.07 to 0.14 bar)

Working rate
About 12 strokes a minute

Newcomen engines built by 1729
More than 100

Watt's separate condenser
Conceived 1765, patented 1769, about 75% less fuel

Sources

1. Newcomen atmospheric engine · Wikipedia https://en.wikipedia.org/wiki/Newcomen_atmospheric_engine
2. Watt steam engine · Wikipedia https://en.wikipedia.org/wiki/Watt_steam_engine
3. Newcomen atmospheric engine (object 1920-124) · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co50900/newcomen-atmospheric-engine-atmospheric-steam-engine
4. ASME Landmark: Newcomen Engine · Engineering and Technology History Wiki (ASME) https://ethw.org/ASME-Landmark:Newcomen_Engine
5. A new age · Science Museum https://blog.sciencemuseum.org.uk/a-new-age/

Fact-checked on 2026-10-11

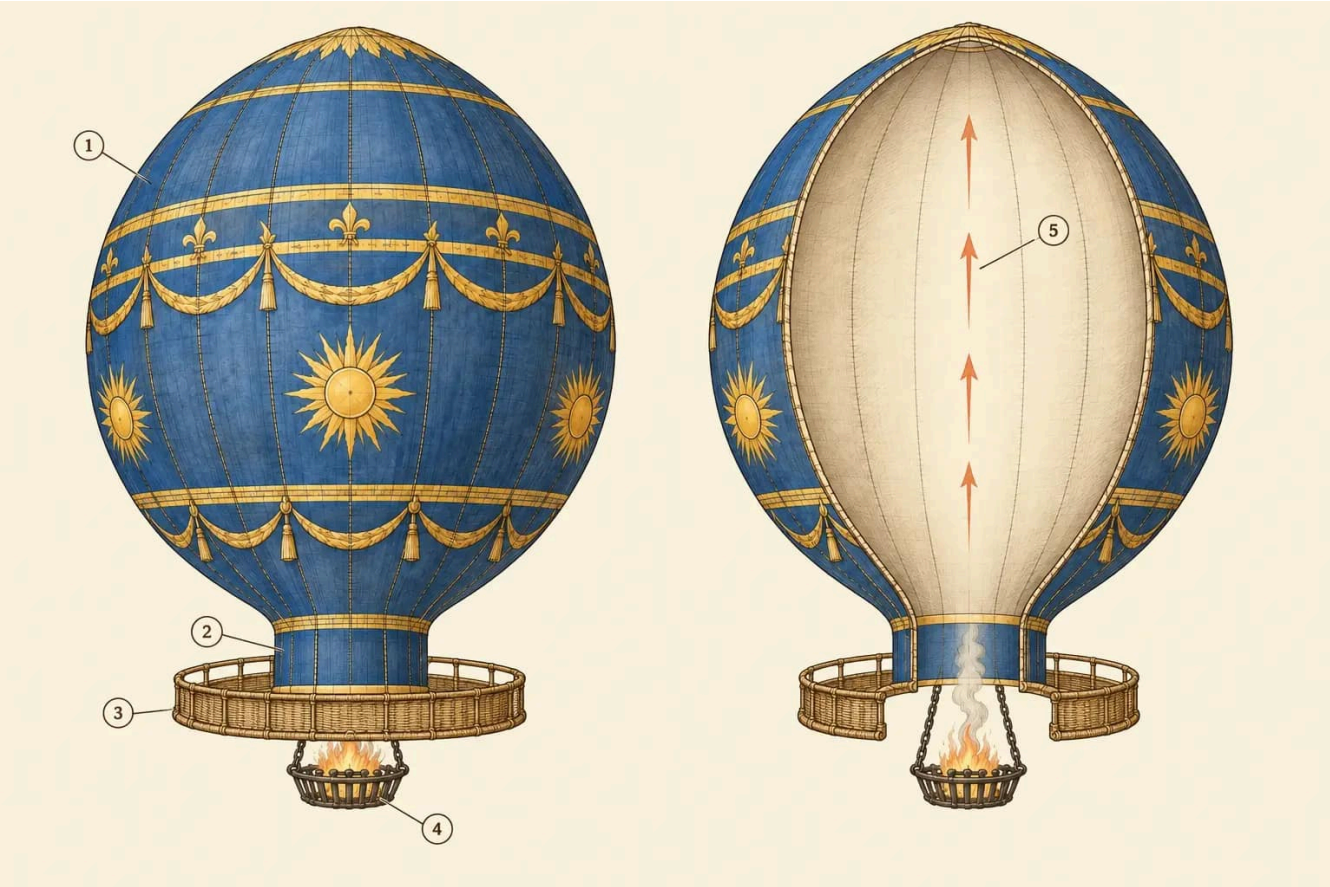
IV · AERONAUTICS

Hot-Air Balloon

Rising on warm air

1783 · Industrial age · Science & industry

Requires: Paper (p. 165), Control of Fire (p. 9), Weaving (p. 43)



1 Envelope 2 Open neck 3 Wicker gallery 4 Brazier 5 Rising warm air

A hot-air balloon rises because the heated air inside its envelope is lighter than the cooler air around it. The Montgolfier brothers, who had flown a small model indoors in 1782, first showed one in public in France in 1783, and on 21 November of that year their balloon carried two men over Paris, the first human flight in free air.

What it is

A hot-air balloon is a large, light bag, the envelope, open at the bottom and filled with heated air. Warm air is less dense than cold air, so the bag and what hangs below it weigh less than the outside air they push aside, and the whole rises. Nothing drives it: a balloon climbs when the air inside is heated, sinks as it cools, and drifts with the wind.

The balloon on the plate is the one built by Joseph and Étienne Montgolfier, paper makers from Annonay, for the first free flight with people aboard, on 21 November 1783. Accounts give it a height of a little over 20 m. It was made of cloth, described as linen or taffeta, lined with paper and coated with a varnish containing alum as

protection against fire, and painted blue and gold. A ring-shaped wicker gallery hung round the open neck for the two aeronauts, and an iron brazier burning straw hung in the middle of the opening.

How it works

At sea-level pressure, a cubic metre of air at 20 °C weighs about 1.2 kg. Heated to 100 °C, the same volume of air weighs only about 0.95 kg, because the air has expanded and part of it has spilled out of the open neck. Every cubic metre of hot air inside the envelope therefore gives about a quarter of a kilogram of lift, which must carry the envelope and its equipment before any passenger. A balloon needs a great volume to carry anything: the Montgolfiers' envelope of 1783 held more than a thousand cubic metres.

The warm air rises into the dome and pushes against the fabric. The heat slowly escapes through the cloth and the neck, so the air must be heated again and again. In 1783 the aeronauts forked straw into the brazier through openings in the gallery; to go higher they added fuel, to come down they let the fire die. The envelope caught fire several times during the first flight, and they put out the burning spots with wet sponges.

A modern balloon works the same way with better materials. The envelope is nylon or polyester, the basket wicker, and a propane burner gives short, powerful blasts of flame into the mouth of the envelope. The pilot climbs or descends to find winds blowing in different directions, which is the only way to steer.

A modern balloon: propane cylinders in a wicker basket and a burner under the open mouth of a nylon envelope.

How to build it

A model of tissue paper filled with warm air from a hair dryer shows the principle without any flame. It has to be large and light, because air from a dryer is only moderately hot.

Cut the gores. Make a card template for one gore: a long pointed leaf shape 2 m long and 40 cm across at its widest point, with the bottom end cut straight across where it is 8 cm wide. Cut eight gores from the thinnest tissue paper you can find, joining sheets with a glue stick where needed.

Glue the envelope. Glue the gores edge to edge, overlapping about 1 cm, so that their points meet at the top and their straight bottom ends form a round mouth. Close the top with a small round patch. Glue the mouth to a ring of thin wire or light card 20 cm in diameter so that it stays open.

Fill it. Indoors, in a cool room without draughts, have a helper hold the envelope upright by the top with the mouth down. Blow air from a hair dryer on its hottest setting into the mouth from about 20 cm below for two or three minutes, keeping the dryer moving and its air intake clear. Switch the dryer off and pull it away before letting go, so that only the warm air inside does the lifting. If the bag pulls upward it will rise toward the ceiling and sink as the air cools; if it does not, the air is not hot enough for its weight, and thinner paper or a bigger envelope will help.

A model of eight paper gores: warm air from a hair dryer can lift it when the paper is light enough.

> **Safety.** Never heat a paper balloon with a candle, a burner or any flame, and never release flying lanterns: they come down still burning and start fires. Keep the hair dryer at least 20 cm from the paper, never block its air intake, and stop at once if the tissue starts to brown or smell of scorching. Real hot-air balloons are flown only by licensed pilots with certified equipment.

History and evolution

Joseph Montgolfier made a small silk balloon fly indoors in November 1782 and then built larger ones with his brother Étienne. On 4 June 1783, in the market square of Annonay, they sent up an unmanned balloon of cloth and paper about 11 m across, which rose high above the town and came down more than a kilometre and a half away after about ten minutes.

On 19 September 1783, at Versailles, in front of Louis XVI and Marie-Antoinette, a balloon carried a sheep, a duck and a rooster in a basket. Two months later, on 21 November, Jean-François Pilâtre de Rozier, a teacher of science, and the Marquis d'Arlandes, an army officer, took off from the grounds of the Château de la Muette, by the Bois de Boulogne on the western edge of Paris. They flew for about 25 minutes, some 900 m up at most, and came down in open ground near today's Place d'Italie, about 9 km away. Ten days later Jacques Charles and Nicolas-Louis Robert flew a hydrogen balloon from the Tuileries. Gas balloons could stay up far longer, and hot air was little used afterwards.

The first passengers, at Versailles in September 1783: a sheep, a duck and a rooster.

The hot-air balloon came back in the late 1950s, when Ed Yost in the United States combined an envelope of synthetic fabric with a burner running on bottled propane. His flight from Bruning, Nebraska, on 22 October 1960 is counted as the first of a modern hot-air balloon, and from 1961 his company, Raven Industries, sold hot-air balloons for sport.

Key figures

First public ascent
Annonay, 4 June 1783, unmanned

First passengers
A sheep, a duck and a rooster, Versailles, 19 September 1783

First human free flight
21 November 1783, Paris: about 25 minutes, roughly 9 km

Lift of hot air
About 0.25 kg per cubic metre for air at 100 °C against 20 °C, at sea level

Modern balloon
Ed Yost, Bruning (Nebraska), 22 October 1960: propane burner

Sources

1. Model of Montgolfier balloon used in first demonstration to carry human passengers in free flight · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co29133/model-of-montgolfier-balloon-used-in-first-demonstration-to-carry-human-passengers-in-free-flight
2. Montgolfier balloon · The Museum of Flight, Seattle https://www.museumofflight.org/aircraft/montgolfier-baloon
3. Smithsonian recalls 1st manned (balloon) flight · The Christian Science Monitor https://www.csmonitor.com/1983/1205/120524.html
4. Scientist of the Day: Jacques-Alexandre Charles · Linda Hall Library https://www.lindahall.org/about/news/scientist-of-the-day/jacques-alexandre-charles
5. How the CIA's secret balloon program led Ed Yost to invent the modern hot air balloon · Seattle Ballooning https://seattleballooning.com/how-the-cia-secret-balloon-program-led-ed-yost-to-invent-the-modern-hot-air-balloon/
6. Ed Yost · Wikipedia https://en.wikipedia.org/wiki/Ed_Yost
7. 21 November 1783 · This Day in Aviation https://www.thisdayinaviation.com/?p=9465
8. Montgolfier brothers (Hall of Fame) · San Diego Air & Space Museum https://sandiegoairandspace.org/hall-of-fame/honoree/montgolfier-brothers
9. Scientist of the Day: The Montgolfier Brothers · Linda Hall Library https://www.lindahall.org/about/news/scientist-of-the-day/the-montgolfier-brothers/
10. Earth Atmosphere Model (metric units) · NASA Glenn Research Center https://www.grc.nasa.gov/www/k-12/airplane/atmosmet.html
11. Drag of a Sphere · NASA Glenn Research Center https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/drag-of-a-sphere

Fact-checked on 2026-10-12

Vaccination

Teaching the body in advance

1796 · Industrial age · Science & industry

Requires: Glass (p. 129)

Leads to: Penicillin (p. 342)

1 Dairy cow, source of cowpox 2 Milkmaid 3 Lancet in its case 4 Glass phial 5 Quill and inkwell 6 Jenner's Inquiry (1798)

Vaccination trains the immune system with a weakened, killed or partial form of a germ, so the body can fight off the real disease later. Edward Jenner showed in 1796 that cowpox protects against smallpox, and two centuries later vaccination made smallpox the first human disease to be eradicated.

What it is

Vaccination prepares the body against an infectious disease, usually before it meets the disease. The person receives a weakened, killed or partial version of the germ, or the instructions for one of its parts. The immune system responds as it would to a real infection, with far less risk than the disease itself carries, and it keeps a memory of the encounter. If the real germ arrives later, the defence starts quickly and usually stops it before it causes serious harm.

The word comes from the Latin *vacca*, cow. The first vaccine used cowpox, a mild disease of cattle that milkmaids caught on their hands, to protect against smallpox, one of the deadliest diseases in history. The plate is a

composition: the rural setting of the 1796 experiment, with objects of the period beside it, a lancet in its case, a glass phial, a quill and the book Jenner published in 1798.

How it works

The immune system learns to recognise germs by their molecular shapes, called antigens. On a first encounter it takes days to find and multiply the right cells. Some white blood cells, the B cells, make antibodies that lock onto the germ and mark it for destruction. Others, the T cells, kill infected cells and coordinate the response. That delay is why a first infection can become severe.

After the infection is over, a population of memory cells remains, sometimes for life. A second meeting with the same antigen triggers a faster and stronger reaction. A vaccine provides that first meeting at far lower risk than the disease itself.

Cowpox worked against smallpox because the two viruses are close relatives: their antigens are similar enough that immunity to one covers the other. Later vaccines were made in other ways. Some use a living germ weakened so that it rarely causes illness, an approach Louis Pasteur pioneered; such vaccines are not given to everyone, because a person with a very weak immune system can still fall ill from them. Others use a killed germ, a purified fragment, or an inactivated toxin. The newest give cells the genetic code to make one harmless protein of the germ for a short time.

For diseases that spread from person to person, a germ can no longer pass easily once enough people in a community are immune and no longer pass it on. This herd immunity also protects people who cannot receive a particular vaccine or respond poorly to it. The share of the population needed depends on how contagious the disease is, and on how well and how long the vaccine stops transmission. Tetanus, which is caught from soil and not from other people, gives no such shared protection.

Vaccines are developed and produced under strict medical regulation and are usually given by health professionals. Like any medicine they can have side effects, which are monitored after approval.

How vaccines are made

For most of the nineteenth century the only vaccine was the one against smallpox, and the main difficulty was keeping the virus alive from one patient to the next.

Arm to arm. No one could yet grow the cowpox virus in a laboratory, so it was kept going in people. About a week after vaccination a blister formed at the site. The vaccinator opened it with a lancet and used its clear fluid, called lymph, to vaccinate the next person. To send vaccine farther, lymph was dried on small ivory points, quills or threads, or sealed between glass plates, and moistened before use. The Spanish Balmis expedition, which sailed in 1803, carried the vaccine across the Atlantic in 22 orphan boys, vaccinated two at a time during the voyage. Passing lymph from person to person could also pass on other diseases, syphilis among them.

Ivory points and sealed glass plates carried dried lymph from one vaccinator to the next.

Calf lymph. In Naples, vaccinators kept the virus going in calves from early in the century. After the method was described at a medical congress in Lyon in 1864, it spread to France and then across Europe. Calves were vaccinated with shallow scratches on a shaved patch of skin, and the pulp of the blisters was collected a few days later. In 1891 the English

doctor Sydney Copeman showed that mixing this pulp with glycerine killed most of the bacteria in it over some weeks while sparing the virus. Glycerinated calf lymph, sealed in thin glass tubes, became the standard vaccine in Britain around 1900. When twentieth-century virologists examined the virus in vaccine stocks, they found it was vaccinia, a poxvirus related to cowpox but distinct from it.

Teams of the eradication programme traced every case and vaccinated the people around it.

Freeze-dried vaccine and the bifurcated needle. Liquid lymph lost its strength within a day or two in tropical heat. At the Lister Institute's laboratories in Elstree, north of London, Leslie Collier developed a freeze-dried vaccine, protected by added peptone, that kept for months without refrigeration; he worked on it there between 1948 and 1955. During the eradication campaign that began in 1967, WHO used only freeze-dried vaccine and had batches checked by reference laboratories in Canada and the Netherlands. When the campaign started, fewer than one in ten of the vaccines in use met the standard. The bifurcated needle, developed at Wyeth Laboratories in the United States in the 1960s, is a short steel rod ending in two prongs that hold a single droplet of vaccine. The vaccinator pressed it into the skin of the upper arm about fifteen times in a small area. It used a quarter of the vaccine needed before, could be sterilised and reused, and its use could be taught in minutes.

Modern vaccines. Live attenuated vaccines use a germ weakened until it rarely causes disease: the measles virus, for instance, was weakened by growing it through many generations in cell cultures, and the BCG vaccine against tuberculosis is a weakened bacterium. Inactivated vaccines start from a germ grown in culture, viruses in eggs or cell cultures, which is then killed with a chemical such as formaldehyde; Jonas Salk's polio vaccine of 1955 was made this way. Toxoids against tetanus and diphtheria are bacterial toxins inactivated in a similar way. Subunit vaccines contain only selected, purified parts of the germ: the recombinant hepatitis B vaccine, licensed in the United States in 1986, is a viral protein made by yeast cells that carry its gene. mRNA vaccines contain no part of the germ at all. The messenger RNA is copied by enzymes from a DNA template, purified, and wrapped in tiny particles of fat that carry it into cells.

Quality control. Production starts from a seed stock of virus, bacteria or cells kept frozen, so that the strain does not drift from batch to batch. Manufacturers test each lot for identity, sterility, purity and potency, and keep samples. In most countries a national regulator and its control laboratory review these results, and sometimes repeat the tests, before each lot may be released.

> **Safety.** This section describes how laboratories and factories have made vaccines. Never try to prepare a vaccine yourself: home-made material can carry dangerous germs, cause serious infection and give no protection. Use only approved vaccines from released lots, given by health workers or, for the few products approved for it, exactly as prescribed.

History and evolution

Long before vaccines there was variolation, the deliberate infection of a healthy person with material from a smallpox sore. It usually caused a milder case followed by lifelong immunity, though some people died of it. The practice was old in China, India and the Ottoman Empire. Lady Mary Wortley Montagu saw it in Constantinople and in 1721 had her daughter variolated in London, which helped spread it in Britain.

Farmers in western England had long noticed that milkmaids who caught cowpox seemed spared by smallpox. The surgeon John Fewster discussed it in 1768, and in 1774 the Dorset farmer Benjamin Jesty deliberately gave cowpox to his wife and two of their children during an epidemic.

Edward Jenner, a doctor in Berkeley, Gloucestershire, turned the folk observation into an experiment. On 14 May 1796 he took material from a cowpox sore on the hand of the milkmaid Sarah Nelmes and introduced it into the arm of James Phipps. Some weeks later he exposed the boy to smallpox matter, and Phipps did not fall ill. The Royal Society did not publish his first report, so in 1798 Jenner published the case, with others, at his own expense in a short book, the *Inquiry*. Within a few years vaccination had spread across Europe and to the Americas.

In the late 1870s Louis Pasteur found that a culture of chicken cholera bacteria left to age lost its power to cause disease but still protected birds. He developed vaccines against anthrax in sheep in 1881 and then against rabies. On 6 July 1885 a nine-year-old boy, Joseph Meister, who had been bitten by a rabid dog, began the treatment and survived. Accounts usually call him the first person vaccinated against rabies, although historians have found earlier attempts on patients in May and June 1885. The rabies virus usually takes weeks to reach the brain, so vaccination given soon after the bite, before any symptoms, could still prevent the disease; any suspected exposure needs immediate medical care. The twentieth century added vaccines against diphtheria, tetanus, whooping cough, tuberculosis, polio, measles and many other diseases.

Pasteur made vaccines by weakening the germ of the disease itself.

In 1967 the World Health Organization launched an intensified campaign to wipe out smallpox. The last natural case occurred in Somalia in 1977, and on 8 May 1980 the World Health Assembly declared the disease eradicated. In 2020 vaccines based on messenger RNA, developed over the previous decades, were deployed against COVID-19 within a year of the virus being identified.

Key figures

Jenner's first vaccination
14 May 1796, Berkeley, Gloucestershire

Joseph Meister's rabies treatment begins
6 July 1885, Paris

Bifurcated needle
1960s, Wyeth Laboratories; a quarter of the vaccine used before

Smallpox fatality rate
About 30% of cases (variola major)

Smallpox declared eradicated
8 May 1980, World Health Organization

Sources

1. Smallpox · World Health Organization https://www.who.int/health-topics/smallpox
2. Jenner, Fewster and Jesty · British Society for the History of Medicine https://bshm.org.uk/jenner-fewster-and-jesty/
3. The final years 1877–1887 · Institut Pasteur https://www.pasteur.fr/en/about-us/final-years-1877-1887
4. Edward Jenner · Wikipedia https://en.wikipedia.org/wiki/Edward_Jenner
5. Edward Jenner's ivory vaccination points, England, 1821 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co148487/edward-jenners-ivory-vaccination-points-england-1821-vaccination-point
6. Ivory vaccination points in a wooden box, Europe, 1801-1900 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co148479/ivory-vaccination-points-europe-1801-1900-vaccination-point
7. Vaccine points used by Edward Jenner · Wellcome Collection https://wellcomecollection.org/works/j36r9neu
8. The XIX century smallpox prevention in Naples and the risk of transmission of human blood-related pathogens · Journal of Translational Medicine https://pmc.ncbi.nlm.nih.gov/articles/PMC4328853/
9. Sydney Arthur Monckton Copeman · Royal College of Physicians https://history.rcp.ac.uk/inspiring-physicians/sydney-arthur-monckton-copeman
10. Collier, Professor Leslie Harold (papers) · Wellcome Collection https://wellcomecollection.org/works/egjmdv8t
11. Smallpox vaccines · World Health Organization https://www.who.int/news-room/feature-stories/detail/smallpox-vaccines
12. Donald Ainslie Henderson (1928–2016): smallpox eradication, leadership and legacy · The Journal of Infectious Diseases https://pmc.ncbi.nlm.nih.gov/articles/PMC5388283/
13. Different types of vaccines · History of Vaccines (College of Physicians of Philadelphia) https://historyofvaccines.org/vaccines-101/what-do-vaccines-do/different-types-vaccines/
14. Lot release of vaccines by NRAs/NCLs · World Health Organization https://www.who.int/teams/health-product-policy-and-standards/standards-and-specifications/norms-and-standards/vaccine-standardization/lot-release-of-vaccines
15. Smallpox and its eradication (Fenner, Henderson, Arita, Ježek, Ladnyi), chapter 7 · World Health Organization https://iris.who.int/handle/10665/39485
16. Smallpox vaccination in 2003: key information for clinicians · Clinical Infectious Diseases https://doi.org/10.1086/374792
17. Expected vaccine reactions (smallpox vaccine) · Centers for Disease Control and Prevention https://www.cdc.gov/smallpox/hcp/vaccines/expected-vaccine-reactions.html
18. Vaccination, Encyclopaedia Britannica, 9th edition, volume 24 · Wikisource https://en.wikisource.org/wiki/Page:Encyclop%C3%A6dia_Britannica,_Ninth_Edition,_v._24.djvu/40

Fact-checked on 2026-10-12

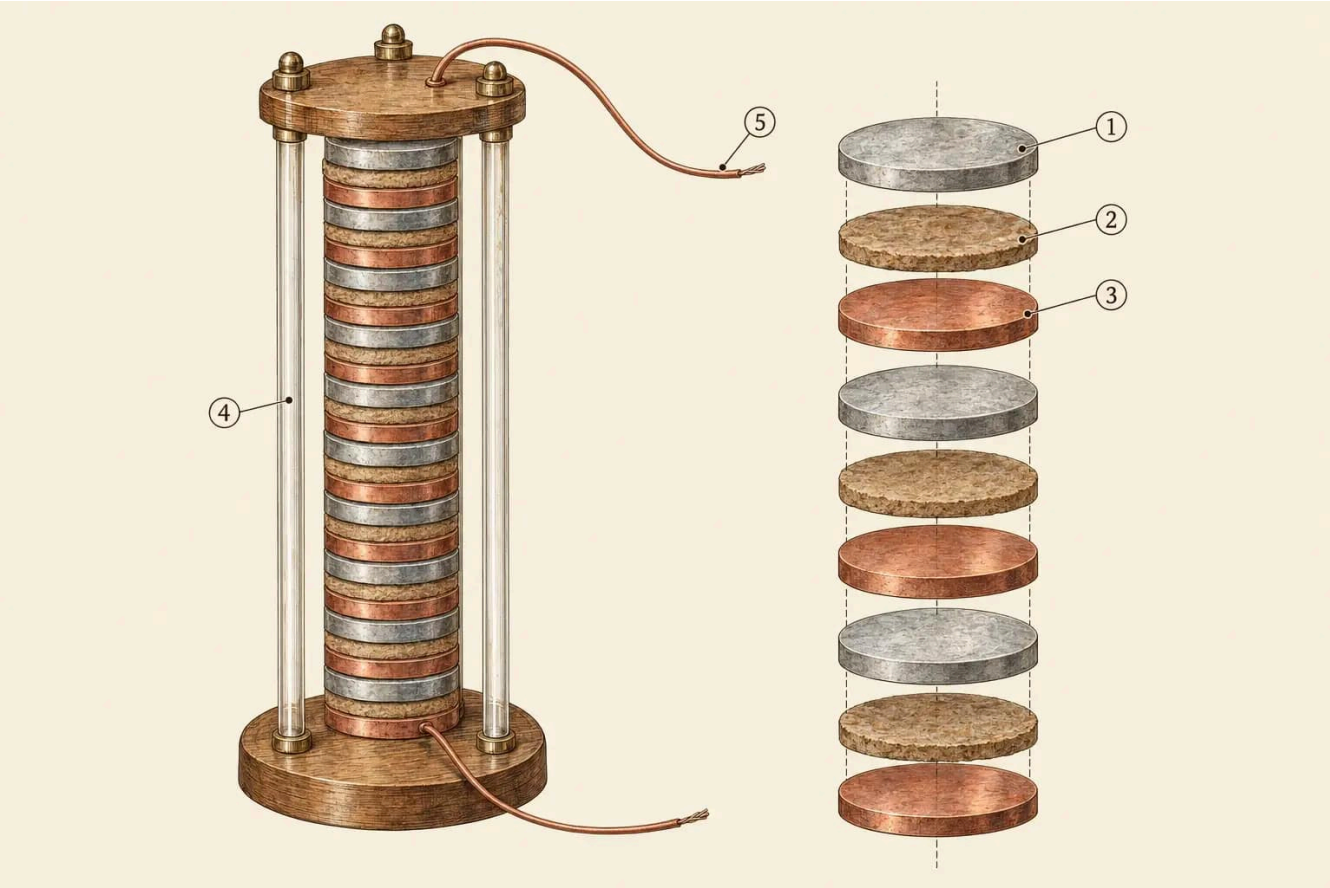
Battery

Chemistry that pushes a current

1800 · Industrial age · Science & industry

Requires: Bronze (p. 120)

Leads to: Electric Motor (p. 270), Electric Generator (p. 266), Lead-Acid Battery (p. 294), Solar cell (p. 355), Electric Telegraph (p. 278)



1 Zinc disc 2 Cardboard soaked in brine 3 Copper disc 4 Glass support rod 5 Terminal wire

A battery turns chemical reactions at two electrodes, separated by an electrolyte that conducts ions, into a steady electric current. Alessandro Volta's pile of zinc, copper and brine was the first in 1800, and every cell since, from the telegraph jar to the lithium phone battery, works on the same principle.

What it is

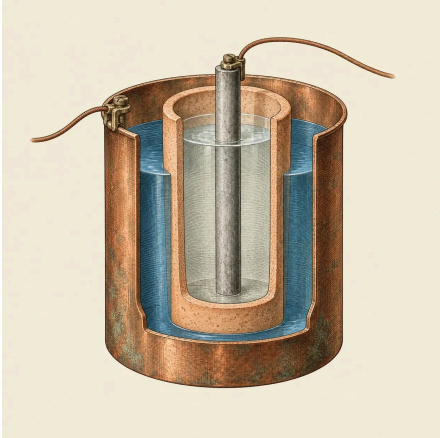
A battery stores energy as chemistry and gives it back as electric current when a circuit with a lamp or other load joins its two terminals. The basic unit is a cell. In Volta’s time a battery meant several cells joined together, like the column he stacked in 1800; today the word covers single cells too.

Before the pile, electricity came only as brief sparks; the pile gave a current that kept flowing for hours.

How it works

Each cell of the pile has a zinc disc, a copper disc, and between them a disc of cardboard or cloth soaked in salt water. Zinc gives up electrons more easily than copper. On the zinc side, metal atoms pass into the brine as ions and leave their electrons in the disc. On the copper side, a reaction takes electrons up again, using oxygen dissolved in the brine or releasing hydrogen. When an external circuit joins the two ends, electrons flow through it from zinc to copper, and ions moving through the wet layer close the circuit.

One zinc-copper pair in brine gives a little under one volt. Stack twenty pairs in series and the voltages add up, enough to feel a sharp tingle through wet fingers, which is how Volta tested his piles. The current depends on the area of the discs and on how fast the reaction can run.



In the Daniell cell, copper is deposited on the vessel instead of hydrogen, so the voltage stays steady.

As the pile works, the dissolved oxygen near the copper runs out and hydrogen bubbles begin to cover it, so the current falls. The weight of the column also squeezes brine out of the lower layers, and the zinc corrodes. In 1836 John Frederic Daniell gave each metal its own liquid: zinc in one solution, copper in copper sulfate, with a porous barrier between them. Copper is plated out instead of hydrogen, and the cell holds about 1.1 volts for a long time.

In a rechargeable cell, current pushed in the opposite direction drives the reaction backwards.

How to build it

A small pile gives a low voltage and a weak current, but it shows the principle clearly.

You need fifteen to twenty copper discs (old copper coins will do), as many zinc discs (zinc sheet or galvanised washers), blotting paper or cardboard cut slightly smaller, salt, water, two insulated wires and, ideally, a voltmeter.

Clean the metal. Rub each copper disc with fine sandpaper until it is bright.

Soak the separators. Dissolve two heaped spoonfuls of salt in a glass of water and soak the cardboard. Press each disc until it is damp but no longer dripping. Brine running down the column short-circuits the cells.

Stack in one order. Lay a copper disc, a wet separator and a zinc disc, then repeat in the same order to the top. Never reverse the order halfway, and never let the two metals of one cell touch around the edge of the separator.

Hold the column. Three wooden or glass rods set in a base keep the stack straight without pressing on it.

Connect and test. Fix one wire to the bottom copper disc and one to the top zinc disc. Expect a little under one volt per cell. A red LED needs about two volts and very little current: check that its long leg goes to the copper end and its short leg to the zinc end, and test it on four or five cells only, where it should glow faintly. Connected backwards across more cells, an LED can be damaged. When the separators dry out after a few hours, take the pile apart, then wash and dry the discs.

> **Safety.** The pile itself is low voltage, but a short circuit across a strong battery heats wires enough to burn skin and melt insulation, so never join the terminals directly. Never connect any battery to mains electricity or try to charge it from a wall socket. Do not open commercial batteries: lead-acid batteries hold sulfuric acid, which burns skin and eyes, and give off explosive hydrogen while charging; lithium cells can catch fire if punctured, crushed or shorted. Copper sulfate and zinc salts are poisonous: wear gloves and goggles, wash your hands, and keep the materials away from children.

History and evolution

Galvani's frog legs twitched whenever an arc of two metals joined nerve and muscle.

In the 1780s the Bologna anatomist Luigi Galvani saw dissected frog legs twitch when they touched two different metals at once. In 1791 he published his theory of "animal electricity". Alessandro Volta, professor of physics at Pavia, held that the metals produced the electricity and the frog only detected it, and he set out to show it with no animal at all.

He first linked cups of brine with metal strips, then built the more compact pile. On 20 March 1800 he described both in a letter, written in French, to Sir Joseph Banks, president of the Royal Society in London. The Society printed it that year with an engraving of the pile, the first published picture of a battery.

Within weeks William Nicholson and Anthony Carlisle used a pile to split water into hydrogen and oxygen. A few years later Humphry Davy used large batteries to isolate sodium and potassium. Napoleon watched Volta demonstrate the pile in Paris in 1801 and rewarded him, and the unit of electrical potential, the volt, is named after him.

Telegraph lines needed a steady current, and Daniell's cell supplied it. In 1859 Gaston Planté rolled two lead sheets into a spiral with a separator between them and immersed them in dilute sulfuric acid. Johann Ritter had shown an experimental storage pile in 1803, but Planté's was the first practical rechargeable battery. Improved by Camille Faure in 1881, the lead-acid battery still starts most cars.

Planté's spiral of lead sheets in dilute acid could be charged and discharged again and again.

In 1866 Georges Leclanché built a cell from a zinc rod, a carbon rod packed in manganese dioxide, and a solution of ammonium chloride; by 1868 twenty thousand were working on telegraph systems. Later inventors thickened the liquid into a paste, and this dry cell powered early pocket torches and the radios of the 1920s. The first commercial cylindrical alkaline cells followed in 1959, and lithium-ion cells reached the market in the early 1990s.

Key figures

Announced
20 March 1800, in a letter to the Royal Society

First practical rechargeable battery
Gaston Planté's lead-acid cell, 1859

Voltage of one zinc-copper cell
Under 1 V in brine; 1.1 V in a Daniell cell

Lithium-ion cells on sale
Early 1990s

Sources

1. Voltaic Pile (1800) · National High Magnetic Field Laboratory https://nationalmaglab.org/magnet-academy/history-of-electricity-magnetism/museum/voltaic-pile-1800/
2. Electricity and Magnetism Timeline, 1800 to 1819 · National High Magnetic Field Laboratory https://nationalmaglab.org/magnet-academy/history-of-electricity-magnetism/timeline/1800-1819/
3. Volta and the Pile · The Electrochemical Society, Electrochemistry Encyclopedia https://knowledge.electrochem.org/encycl/art-v01-volta.htm
4. Scientist of the Day: Alessandro Volta · Linda Hall Library https://www.lindahall.org/about/news/scientist-of-the-day/alessandro-volta
5. Timeline of Battery Development · LibreTexts Chemistry https://chem.libretexts.org/Bookshelves/General_Chemistry/Chem1_(Lower)/16%3A_Electrochemistry/16.07%3A_Timeline_of_Battery_Development
6. Battery History · Energizer https://oem.energizer.com/english/battery-history/

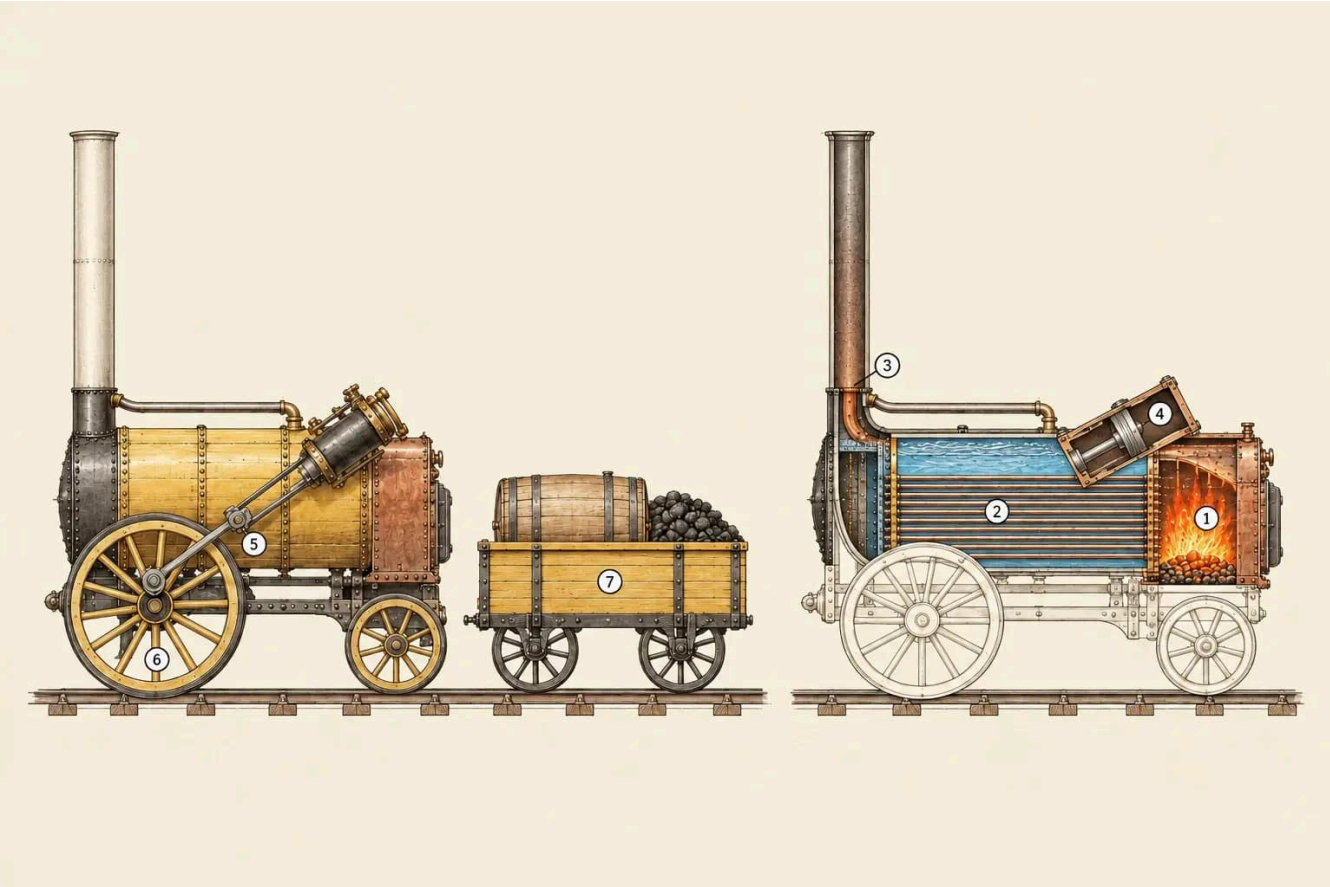
Fact-checked on 2026-10-11

Steam Locomotive

Steam power on rails

1804 · Industrial age · Science & industry

Requires: Steam Engine (p. 221), Wheel & Axle (p. 78)



1 Firebox 2 Fire tubes 3 Blast pipe and chimney 4 Cylinder 5 Connecting rod 6 Driving wheel 7 Tender

A steam locomotive is a steam engine on wheels that carries its own fuel and water and hauls trains along rails. Richard Trevithick ran the first one in Wales in 1804, and Robert Stephenson's Rocket of 1829 set the pattern that most later locomotives followed: a boiler full of fire tubes, a blast pipe under the chimney and cylinders driving the wheels directly.

What it is

A steam locomotive is a steam engine mounted on a wheeled frame, built to haul trains on a railway. It carries coal or coke and water with it, burns the fuel in a firebox, and turns the pressure of the steam into the rotation of its driving wheels through pistons and rods. The iron wheels run on iron or steel rails, which roll far more easily than wheels on a road, so one engine can pull many loaded wagons.

The plate shows Rocket, built in 1829 by Robert Stephenson and Company in Newcastle upon Tyne. It brought together in one machine a boiler crossed by many fire tubes and a blast pipe, and both features stayed standard on later steam locomotives.

How it works

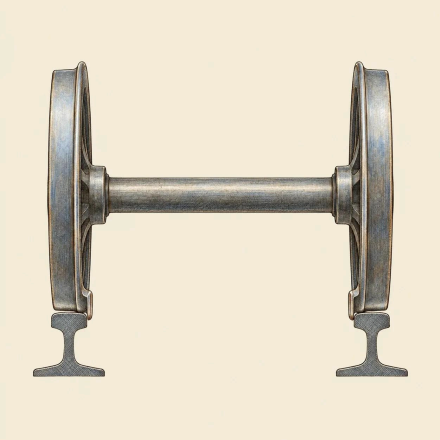
The fire burns on a grate in the firebox at the back of the engine. Its hot gases pass forward through the boiler barrel inside 25 copper tubes, each about 76 mm across, surrounded by water. Many small tubes expose far more metal to the water than one large flue would, so on Rocket the tubes provided several times the heating surface of the firebox walls (the figures given in sources vary). Steam gathers above the water at about 3.4 bar above atmospheric pressure.

From the boiler the steam goes to the two cylinders, one on each side of the engine. A sliding valve lets it in first behind the piston and then in front of it, so the piston is pushed both ways. Each piston rod drives a connecting rod, and the connecting rod turns a crank pin set in the large front wheel on its side. The weight resting on that pair of wheels, about 2.6 tonnes on Rocket, together with the grip between wheels and rails, limits how hard it can pull before the wheels slip.

Used steam leaves the cylinders through a pipe that ends in a nozzle under the chimney, and each puff drags the smoke out with it and pulls fresh air through the fire. The harder the engine works, the stronger the draught, which helps the boiler keep up with the cylinders; the fireman still has to keep the fire fed and the boiler topped up with water.

The blast pipe blows used steam up the chimney, drawing the fire harder at every stroke.

How to build it



A flange on the inner edge of each wheel keeps the wheelset between the rails.

Full-size locomotives are built in railway works. Boilermakers roll iron or steel plates, rivet them into a barrel and firebox, and fix the tubes into tube plates at each end. Before it may be steamed, the boiler is tested with water at a pressure above its working pressure, set by the applicable boiler code, and examined by an independent inspector. Founders cast the cylinders, machinists bore them and fit the pistons and valves, and the wheels get iron tyres heated and shrunk on. Heritage railways that restore locomotives today are subject to similar testing and inspection.

A model with no steam shows how the wheels are driven.

Cut the wheel. Saw a disc about 20 cm across from plywood. Glue a dowel axle firmly through its centre, and drill a second hole 5 cm from the centre for the crank pin, a short dowel glued in place. Screw two upright blocks to a baseboard and drill each to take the axle loosely, so the wheel turns freely between them.

Make the cylinder. Glue a cardboard or plastic tube about 15 cm long onto a block of wood screwed to the baseboard beside the wheel, so that the tube lies in the plane of the wheel with its axis at the height of the axle and pointing at the axle's centre. A dowel that slides freely inside it is the piston rod.

Join them. Cut a strip of thin wood about 25 cm long as the connecting rod. Drill one end to fit the crank pin and pin the other end to the outer end of the piston rod with a small nail, so it can pivot. Check that the wheel can make a full turn without the rod hitting the tube.

Run it. Push and pull the piston rod: the wheel turns once for every 10 cm forward and 10 cm back. Note the two dead points, where the crank pin, the axle and the end of the piston rod are in one straight line and pushing does nothing. Real locomotives with two cylinders set the cranks on the two sides a quarter turn apart, so that one is always away from its dead point.

> **Safety.** Never heat water in a closed container or try to make a boiler: steam under pressure can burst a vessel and scald badly. Live-steam models should only be run from commercial kits with tested boilers and working safety valves, under adult supervision. Keep fingers clear of the crank when the wheel turns.

History and evolution

Richard Trevithick, a Cornish engineer, built the first locomotive to run on rails for the Penydarren ironworks at Merthyr Tydfil. On 21 February 1804 it hauled ten tons of iron in five wagons, with seventy men riding on them, along the tramroad towards the canal at Abercynon, about 9 miles (14 km), at nearly five miles an hour by his own account. On the way back a bolt sheared and the boiler leaked, and the engine only reached home the next day. It was too heavy for the cast-iron plates of the tramroad and broke them, and it ended its working life as a stationary engine driving a forge hammer.

On the Penydarren tramroad, short cast-iron plates spiked to stone blocks guided wheels without flanges, and they cracked under the locomotive's weight.

In October 1829 the Liverpool and Manchester Railway held trials at Rainhill to choose its locomotives. Five machines entered and Rocket was the only one to finish. Its test runs averaged about 12 to 14 mph, depending on how the average is taken; running light it reached about 30 mph. It won the £500 prize and the order for the line's engines. At the opening of the railway in 1830, Rocket struck and fatally injured the politician William Huskisson. It was heavily rebuilt within eighteen months and set aside within ten years. Its remains went to the Patent Office Museum in London in 1862 and are now in the Science Museum Group collection.

Later locomotives grew much larger, with more coupled wheels to carry the weight and pull heavy trains, and higher pressures. On 3 July 1938 the London and North Eastern Railway's Mallard reached 126 mph (203 km/h) on a descent south of Grantham, still the record for steam. Mallard was withdrawn in 1963, as diesel and electric traction took over.

Key figures

First run on rails
21 February 1804, Penydarren ironworks, Merthyr Tydfil: ten tons of iron (about 10 tonnes) and 70 men

Rainhill trials, October 1829
Rocket averaged about 12 to 14 mph (19 to 23 km/h) in its test runs and reached about 30 mph (48 km/h) running light

Rocket's boiler
25 copper fire tubes, about 3.4 bar above atmospheric pressure (50 psi)

Steam speed record
Mallard, 3 July 1938: 126 mph (203 km/h)

Sources

1. Rocket locomotive (object 1862-5) · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co26704
2. Richard Trevithick’s steam locomotive · Amgueddfa Cymru – Museum Wales https://museum.wales/blog/1012
3. London & North Eastern Railway steam locomotive 'Mallard' · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co205732
4. Rocket's engineering excellence · Science and Industry Museum https://blog.scienceandindustrymuseum.org.uk/rocket-engineering-excellence/
5. Stephenson's Rocket · Wikipedia https://en.wikipedia.org/wiki/Stephenson%27s_Rocket
6. Penydarren tramplate · Amgueddfa Cymru – Museum Wales https://museum.wales/collections/online/object/11d39d27-d867-308a-b20a-9398afef1c6e
7. The Penydarren Tramroad · Industrial Railway Society, Industrial Railway Record https://shop.irsociety.co.uk/Archives/59/Penydarren.htm
8. Rocket · steamlocomotives.org https://www.steamlocomotives.org/locomotives/rocket
9. Rocket 0-2-2 Liverpool & Manchester Railway · Preserved British Steam Locomotives https://preservedbritishsteamlocomotives.com/rocket-0-2-2-liverpool-manchester-railway/

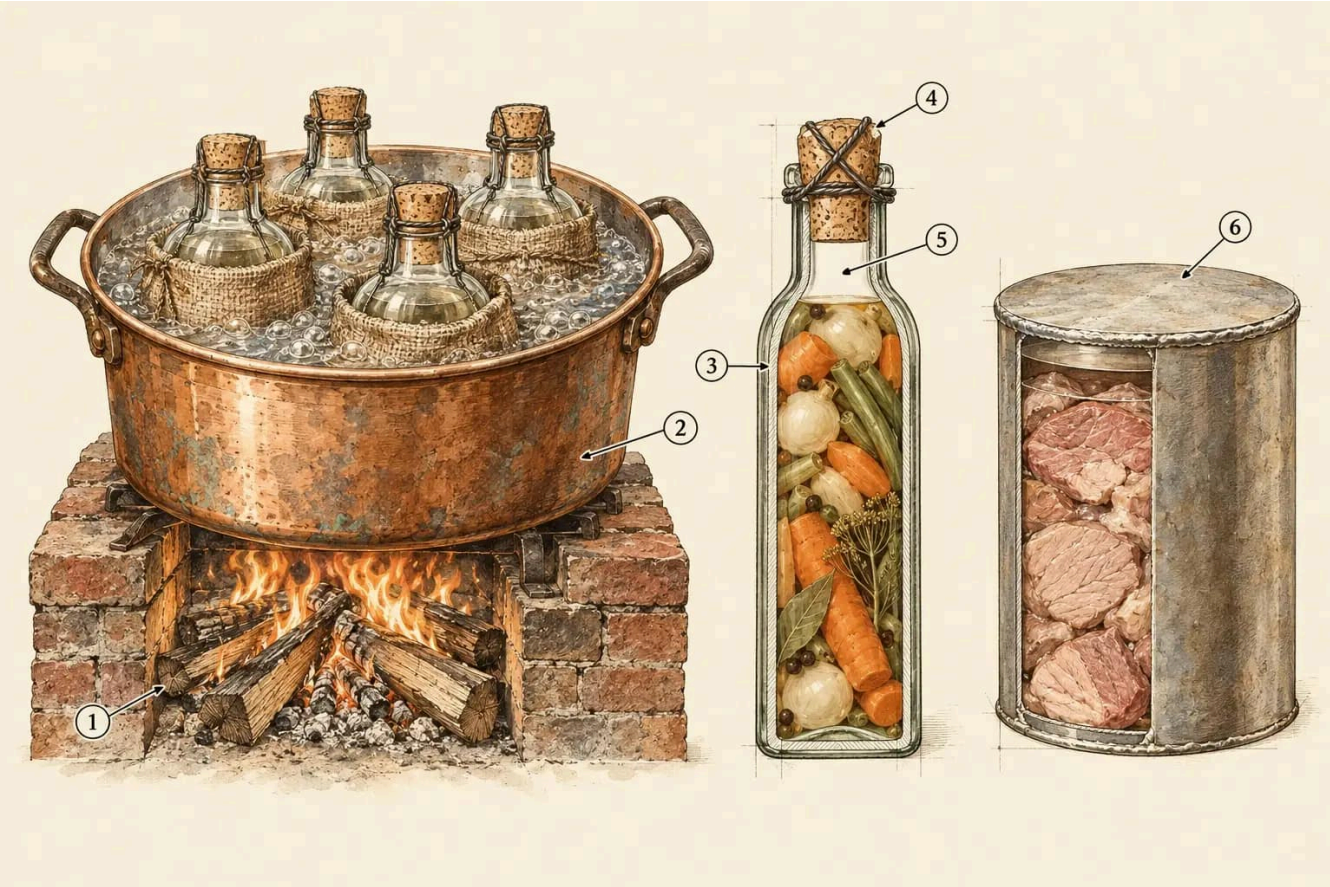
Fact-checked on 2026-10-12

Canning & Pasteurisation

Seal, heat, keep the microbes out

1810 · Industrial age · Science & industry

Requires: Glass (p. 129), Iron Smelting (p. 133), Control of Fire (p. 9)



1 Wood fire 2 Copper kettle of boiling water 3 Glass bottle packed with vegetables 4 Cork tied down with wire 5 Headspace left under the cork 6 Soldered lid of a tinplate can

Canning seals food in a jar or tin and heats it enough to kill the microbes that would spoil it; the closed lid stops new ones getting in. Nicolas Appert published the method in 1810, Louis Pasteur explained it half a century later, and his gentler heat treatment, pasteurisation, made milk, wine and beer safer to drink.

What it is

Salting and drying keep food by depriving microbes of water. Canning kills them: the food is closed in a jar or tin and heated long enough to destroy the microbes that could spoil it or make people ill. While the seal holds, no new germs get in, and the food keeps for months without cold.

The plate shows Nicolas Appert's method of 1810, corked bottles stood in boiling water, beside the soldered tinplate can adopted soon after in England. Pasteurisation, a milder relative, heats milk, wine or beer below boiling. It kills most germs that cause disease, not every microbe, so pasteurised milk still needs a refrigerator.

How it works

At 100 °C the active cells of bacteria, yeasts and moulds die within minutes. While the jar is hot, air escapes under the lid. As it cools, the contents shrink and the steam in the headspace condenses, and the vacuum pulls the lid tight onto the rim.

The hardest to deal with is Clostridium botulinum. Its spore survives boiling, and spores are on most fresh vegetables. In open air they stay dormant; in a sealed jar of moist, low-acid food at room temperature they germinate and make botulinum toxin, one of the most poisonous substances known, often without any visible sign.

The spores cannot grow at pH 4.6 or below. Most fruits, jams, pickles, and tomatoes or figs with added acid are therefore safe after a boiling-water bath, which kills the yeasts and moulds that would spoil them. Vegetables, meat and fish are less acidic. Their spores must be killed at 116–121 °C (240–250 °F), and water only gets that hot under pressure, in a pressure canner at about 0.7–1 bar above atmospheric pressure, which works like a kitchen autoclave. Each food, pack and jar size has its own tested time there; at 100 °C the same result would take hours, and no tested recipe cans these foods in a water bath.

A pressure canner holds steam under pressure, so the jars reach 116–121 °C instead of 100 °C.

Processing times are measured with thermometers at the slowest-heating point of each jar and food. At altitude water boils below 100 °C, so the tables add time or pressure.

Pasteurisation uses lower temperatures. Dairies usually heat milk to 72 °C for 15 seconds, or 63 °C for 30 minutes, then chill it. That destroys the active bacteria behind tuberculosis, salmonellosis and other milk-borne diseases. Spores and some harmless microbes survive, so the milk sours within days unless kept cold.

How to build it

Follow tested official guidance only: the USDA Complete Guide to Home Canning and the National Center for Home Food Preservation in the United States, Health Canada, or your national food safety agency. These steps cover a boiling-water bath for high-acid foods.

Pick a tested recipe. Follow it exactly: jar size, headspace, added acid (bottled lemon juice or citric acid for tomatoes), time and altitude adjustment. Adding onion or pepper to tomatoes can make them unsafe.

Gather the equipment. A deep pot with a lid and a rack, canning jars with unchipped rims, new two-piece lids (a flat lid with sealing compound, held by a screw band) and a jar lifter. Wash everything in hot soapy water. If the processing time is under 10 minutes, first sterilise the empty jars by boiling them for 10 minutes, plus one minute for every 300 m of altitude above 300 m.

Fill and close. Leave the stated headspace, free trapped bubbles, wipe the rim and screw the band on just firmly enough for air to escape.

Process. Stand the jars on the rack in hot water, covered by at least 2.5 cm (5 cm for times over 30 minutes). Start timing at a full rolling boil; if the boil stops, restart the time from zero. At the end, turn off the heat, uncover and wait five minutes.

The flat lid with its sealing ring is used once; the screw band can be used again and again.

Cool and check. Lift the jars out upright and leave them 12 to 24 hours. Remove the bands and press each lid: a sealed lid is curved down and does not flex. Refrigerate an unsealed jar and eat it within days.

Store and inspect. Keep dated jars cool, dark and dry. Before opening, look for bulging or loose lids, leaks, foam, cloudiness, mould or an odd smell.

> **Safety.** Botulism is rare but can kill. Never process vegetables, meat, fish, poultry or mixtures containing them in a water bath, an oven or an open pot, unless a tested pickling recipe has acidified them: otherwise they need a pressure canner and a tested pressure process. There is no tested home method for milk or other dairy products, so never can them. Never shorten a time or reduce the acid. Never taste a suspect jar: the toxin cannot be seen, smelled or tasted. When in doubt, throw it out. Blurred or double vision, drooping eyelids, slurred speech, trouble swallowing or spreading weakness after eating preserved food are an emergency: get medical help at once. Boiling water and hot jars scald, so use a jar lifter.

History and evolution

Appert, a Paris confectioner, began experimenting in the 1790s, when France at war needed food that kept. On 30 January 1810 the government gave him 12,000 francs on condition that he publish, and his book came out that year. He never knew why his method worked.

That same year Peter Durand took a British patent that included cans of tinplate, thin iron coated with tin. Bryan Donkin and John Hall bought it and opened a cannery in 1812, where each can was soldered by hand. By 1813 they supplied the British army and navy. In 1981 Owen Beattie's team suggested that lead from badly soldered tins had helped weaken John Franklin's lost Arctic expedition of 1845; bone studies in 2013 and 2018 found that much of the crew's lead predated the voyage, and the 2018 results did not support lead as a pivotal cause.

The first cans were opened with a hammer and chisel; can openers came decades later.

Louis Pasteur showed in the 1850s and 1860s that living microbes cause fermentation and decay, and in 1865 he patented heating wine to stop it spoiling. Pasteurising milk was proposed in 1886. Milk then carried tuberculosis, scarlet fever and infant diarrhoea, but the historian Peter Atkins found that in Britain pasteurisation spread slowly and did little before the 1920s; by 1921 about half of London's milk was heat-treated.

Canneries adopted steam retorts in the mid-nineteenth century. Machines that closed cans without solder appeared in the 1890s, open-top "sanitary" cans spread early in the twentieth century, and from about 1900 process times were set by bacteriology. From the 1980s welded side seams gradually replaced soldered ones.

Key figures

Appert's prize
12,000 francs from the French government, 30 January 1810, on condition that he publish the method

Acid limit for a boiling-water bath
pH 4.6 or lower

Low-acid foods
116–121 °C (240–250 °F), reached only in a pressure canner

Milk pasteurisation
72 °C for 15 seconds, or 63 °C for 30 minutes

Botulism
Symptoms usually 12–36 hours after eating; fatal in 5–10% of cases

Sources

1. Ensuring Safe Canned Foods · National Center for Home Food Preservation, University of Georgia https://nchfp.uga.edu/how/can/general-information/ensuring-safe-canned-foods/
2. How to Use Boiling Water and Pressure Canners · National Center for Home Food Preservation, University of Georgia https://nchfp.uga.edu/how/can/general-information/recommended-canners/
3. Recommended Jars and Lids · National Center for Home Food Preservation, University of Georgia https://nchfp.uga.edu/how/can/general-information/recommended-jars-and-lids/
4. Cooling Jars and Testing Jar Seals · National Center for Home Food Preservation, University of Georgia https://nchfp.uga.edu/how/can/general-information/cooling-jars-and-testing-jar-seals/
5. Selecting the Correct Processing Time · National Center for Home Food Preservation, University of Georgia https://nchfp.uga.edu/how/can/general-information/selecting-the-correct-processing-time/
6. Sterilization of Empty Jars · National Center for Home Food Preservation, University of Georgia https://nchfp.uga.edu/how/can/general-information/sterilization-of-empty-jars/
7. Preventing Botulism · Centers for Disease Control and Prevention https://www.cdc.gov/botulism/prevention.html
8. Home canning safety · Health Canada https://www.canada.ca/en/health-canada/services/general-food-safety-tips/home-canning-safety.html
9. Canning Controversies: No to Home Canning Dairy Products · Clemson Cooperative Extension, Home & Garden Information Center https://hgic.clemson.edu/canning-controversies/
10. Botulism (fact sheet) · World Health Organization https://www.who.int/news-room/fact-sheets/detail/botulism
11. Nicolas Appert · Grace's Guide to British Industrial History https://www.gracesguide.co.uk/Nicolas_Appert
12. Nicolas Appert · Encyclopedia.com (World of Invention; Encyclopedia of Food and Culture) https://www.encyclopedia.com/people/food-and-drink/food-and-cooking-biographies/nicolas-appert
13. 30 janvier 1810 : Nicolas Appert, inventeur de la conserve · Hérodote.net https://www.herodote.net/30_janvier_1810-evenement-18100130.php
14. Scientist of the Day: Bryan Donkin · Linda Hall Library https://www.lindahall.org/bryan-donkin/
15. Food processing: canning (Technology in Australia 1788–1988) · Australian Science and Technology Heritage Centre, University of Melbourne https://austehc.unimelb.edu.au/tia/084.html
16. Louis Pasteur : un héritage universel · Institut Pasteur https://www.pasteur.fr/fr/journal-recherche/dossiers/louis-pasteur-heritage-universel
17. White Poison? The Social Consequences of Milk Consumption, 1850–1930 (Atkins, 1992) · Social History of Medicine 5, Durham University https://pjatkins.webspace.durham.ac.uk/wp-content/uploads/sites/201/2022/07/White-Poison-1992.pdf
18. Raw Milk Misconceptions and the Danger of Raw Milk Consumption · U.S. Food and Drug Administration https://www.fda.gov/food/buy-store-serve-safe-food/raw-milk-misconceptions-and-danger-raw-milk-consumption
19. Western researchers acquit tins in expedition's fate · Western News, Western University https://news.westernu.ca/2013/04/western-researchers-acquit-tins-in-expeditions-fate/
20. Researchers provide new insights into fate of Franklin Expedition · University of Saskatchewan https://news.usask.ca/articles/research/2018/researchers-provide-new-insights-into-fate-of-franklin-expedition-.php

Fact-checked on 2026-10-14

Bicycle

Two wheels driven by the legs

1817 · Industrial age · Science & industry

Requires: Wheel & Axle (p. 78), Iron Smelting (p. 133)

1 Handlebar 2 Steering head and fork 3 Saddle 4 Crank and chainring 5 Chain 6 Rear sprocket 7 Pneumatic tyre

A bicycle is a two-wheeled machine that the rider balances by steering and drives with the legs, through pedals, a chain and a sprocket on the rear wheel. It grew from Karl Drais's wooden running machine of 1817 into the chain-driven safety bicycle of 1885, which, fitted with air-filled tyres, lets a person cover a given distance on a small fraction of the energy needed to walk it.

What it is

A bicycle carries one rider on two wheels set one behind the other. The rider sits on a saddle, keeps the machine upright by steering, and drives the rear wheel with the legs through pedals, cranks and a chain. It has no engine, and routine adjustments need only a few hand tools.

The plate shows a safety bicycle of the 1890s, the layout from which nearly every modern bicycle descends: two wheels of the same size, a frame of steel tubes forming two triangles, and tyres filled with air.

How it works

The rider balances by steering. When the bicycle begins to lean, the rider turns the front wheel slightly towards the lean, and the wheels run back underneath the rider's weight. At walking pace the corrections have to be larger, which is why a slow bicycle wobbles.

The pedals turn two cranks fixed in opposite directions to an axle that runs through the bottom of the frame. A large toothed chainring on the right-hand crank pulls a roller chain, and the chain turns a small sprocket on the rear hub. With 44 teeth at the front and 18 at the back, one turn of the pedals turns the rear wheel about 2.4 times, and a wheel 70 cm across then rolls about 5.4 metres. Earlier machines with pedals on the front hub had no such gearing: the only way to travel further at each turn of the pedals was a bigger wheel.

A clean, oiled chain passes almost all the work of the legs to the wheel, up to about 99 per cent in laboratory tests. On level ground above about 30 km/h, three quarters or more of the rider's effort goes into pushing air aside. For the same effort a rider travels about three times as fast as a walker, so a given distance costs much less energy; estimates range from about a third to a fifth of the energy needed to walk it.

A pneumatic tyre gives way around a stone instead of lifting the whole machine over it, so on rough roads it rides more smoothly and wastes less effort than the solid rubber tyres used before. Thin wire spokes, kept under tension, hold a light steel rim round and stiff.

The tyre of the 1890s: an inflated inner tube inside a cover of rubber and canvas.

How to build it

The running machine of 1817 had no pedals: the rider pushed against the ground with each foot in turn and slowed down with a cord-worked rear brake.

Drais's machine was the work of a carpenter and a wheelwright: an ash beam, two wooden wheels with iron tyres, a front fork turning on an iron pin, a padded saddle, a board for the forearms and a rear brake pulled by a cord. The safest way to try the same kind of riding today is to turn a small, sound bicycle into a running machine, so that the frame, wheels and brakes remain those it was built with.

Choose the bicycle. It must be small enough for the rider to sit on the saddle, at its lowest, with both feet flat on the ground and the knees slightly bent, and it must have two hand-operated brakes, front and rear: a back-pedal (coaster) brake stops working once the chain is removed. Check that the frame has no cracks, that the wheels turn straight and that both brakes work.

Remove the drive. Take off both pedals with a pedal spanner; the left pedal has a reversed thread and unscrews clockwise. To remove the chain, open its joining link or push out a pin with a chain tool, or ask a bicycle shop to do it. If you have a crank puller, remove the cranks and chainring too, so that nothing can catch the legs.

Set the saddle. Lower the saddle until both feet rest flat on the ground, keeping the minimum-insertion mark on the seat post hidden inside the frame, and tighten the clamp firmly.

Test the brakes. Squeeze each lever while pushing the bicycle forward: the wheel must stop. If it does not, adjust the brake or have a bicycle shop do it before anyone rides.

Learn to glide. On a flat, quiet path, walk the machine astride, then push off with alternate feet and lift both for short glides, braking to stop.

> **Safety.** Wear a helmet and ride away from traffic. Check the brakes, the wheel nuts or quick-release levers and the saddle clamp before each ride. Keep fingers away from turning spokes and from the teeth of the chainring if it is still fitted, and do not ride downhill until you can stop reliably.

History and evolution

Karl Drais, an official of the forestry service of Baden, rode his Laufmaschine out of Mannheim on 12 June 1817. Accounts of the trip give 13 to 15 km in about an hour; one timed run of 12.5 km averaged more than 12 km/h, over twice a walker's pace. The machine was sold in France as the vélocipède from 1818 and copied in Britain as the hobby horse. A surviving example weighs 23 kg; surviving machines have a rear brake worked by a cord. Roads were poor, and interest faded within a few years.

In the 1860s cranks and pedals were fixed to the front wheel in Paris. Whether the idea came from the carriage maker Pierre Lallement or from the workshop of Pierre Michaux is still argued. Lallement took it to the United States and received a patent on 20 November 1866; Michaux's machines started the first cycling craze in France at the end of the decade. Their iron-shod wooden wheels earned them the English name of boneshakers. In the 1870s wire spokes and solid rubber tyres made wheels lighter, and the front wheel grew as large as the rider's legs could reach. These high-wheelers were fast, but a rider who hit an obstacle could be thrown head first over the handlebar.

On the high-wheel bicycle of the 1870s, the pedals turned the front wheel directly, so speed depended on the size of that wheel.

The safety bicycle solved this by putting the rider low between two small wheels and driving the rear one by chain. In 1885 John Kemp Starley built the Rover in Coventry; the machine kept in London weighs 16.8 kg and still has solid tyres. In 1887 or 1888 (sources differ) John Boyd Dunlop, a veterinary surgeon in Belfast, made air-filled tyres for his son's tricycle, and patented them on 7 December 1888. The patent was later declared invalid, because Robert William Thomson had patented the same idea in the 1840s, but Dunlop's tyres went into production in Belfast at the end of 1890. Within a few years the diamond frame and the pneumatic tyre were standard, and the safety bicycle was ridden by women as well as men. Freewheels, gears and better brakes came later without changing the layout.

Key figures

First ride on a running machine
12 June 1817, from Mannheim: 13 to 15 km in about an hour (accounts differ)

Rover safety bicycle
1885, Coventry; 16.8 kg, chain drive, solid tyres

Dunlop's pneumatic tyre patent
7 December 1888 (later voided: R. W. Thomson had patented the idea in the 1840s)

Energy compared with walking
About a third to a fifth for the same distance (estimates differ)

Chain efficiency
Up to about 99% with a clean, oiled chain

Sources

1. Draisienne · Encyclopædia Universalis https://www.universalis.fr/encyclopedie/draisienne/
2. Rover 'Safety' Bicycle, 1885 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co25833/rover-safety-bicycle-1885
3. J. B. Dunlop · Grace's Guide to British Industrial History https://www.gracesguide.co.uk/J._B._Dunlop
4. Pierre Lallement and the Modern-Day Pedal Bicycle · Connecticut Humanities https://connecticuthistory.org/pierre-lallement-and-the-modern-day-pedal-bicycle-today-in-history-november-20
5. Bicycle performance · Wikipedia https://en.wikipedia.org/wiki/Bicycle_performance
6. Laufmaschine (draisine) by Karl Drais · Klassik Stiftung Weimar https://www.klassik-stiftung.de/startseite/digital/sammlungshighlights/laufmaschine/
7. Gain Ratios · Sheldon Brown https://www.sheldonbrown.com/gain.html
8. Glossary: Chain · Sheldon Brown https://www.sheldonbrown.com/gloss_ch.html
9. H. Renold · Grace's Guide to British Industrial History https://www.gracesguide.co.uk/H._Renold
10. Roller chain sprocket diameters · Engineers Edge https://www.engineersedge.com/hardware/roller_chain_sprocket_diameters_13887.htm

Fact-checked on 2026-10-12

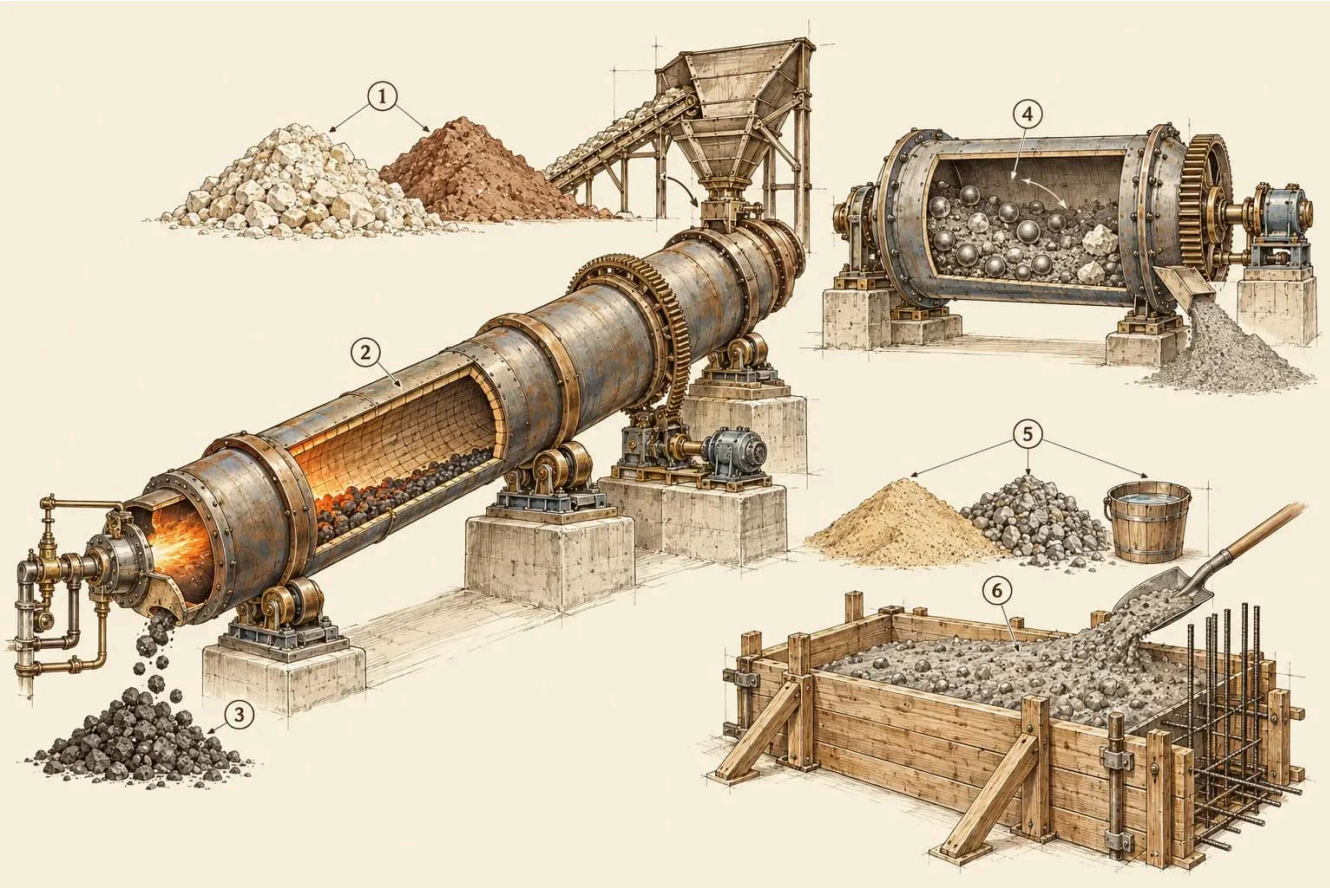
Portland Cement

The binder that hardens under water

1824 · Industrial age · Science & industry

Requires: Lime and lime mortar (p. 30), Roman Concrete (p. 161), Measures and standards (p. 124)

Leads to: Reinforced Concrete (p. 299)



1 Crushed limestone and clay 2 Rotary kiln, flame at the lower end 3 Clinker nodules 4 Mill grinding clinker with a little gypsum 5 Sand, gravel and water for the mix 6 Wooden formwork holding fresh concrete

Portland cement is limestone and clay burnt together at about 1,450 °C into hard nodules called clinker, then ground with a little gypsum. With water it hardens by a chemical reaction, even under water, and bound with sand and gravel it makes concrete, the most used building material in the world.

What it is

Portland cement is a grey powder: limestone and clay burnt until they partly melt into hard lumps, the clinker, then ground with a little gypsum. With water it forms a paste that stiffens within hours and hardens for weeks.

It hardens by reacting with water, so it sets in a wet trench or under the sea: it is a hydraulic binder. A mortar of air lime instead hardens slowly by carbonation, in contact with air. Roman concrete resisted water thanks to pozzolana, volcanic ash whose silica reacts with slaked lime. In Portland cement, lime and the silica of the clay are already combined in the kiln, so the powder needs only water, and it grows far stronger.

Mixed with sand and gravel it makes concrete, in which these grains and stones fill most of the volume and the cement glues them together.

How it works

Burning. The raw mix is typically about four-fifths limestone, with clay or shale to bring silica, alumina and iron oxide. In the kiln the limestone loses its carbon dioxide and becomes quicklime, which then combines with the clay's minerals. Near 1,450 °C part of the charge melts and the rest sinters into dark nodules. A typical clinker holds about 55% alite and 20% belite, two calcium silicates; alite forms only with hard burning above about 1,300 °C. The clinker is then cooled quickly.

Clinker from the kiln; ground with a little gypsum, it becomes cement.

Grinding. The clinker is milled very fine with about 5% gypsum, which keeps its aluminate from stiffening the paste within minutes of mixing.

Setting. In water, alite and belite form calcium silicate hydrates, a poorly crystalline gel that grows from each grain and binds the grains together, giving off calcium hydroxide and heat. Alite gives the early strength, belite the gain after the first week.

Water and strength. Surplus water leaves pores, which weaken the concrete. In 1918 Duff Abrams, at the Lewis Institute in Chicago, showed that strength depends mainly on the ratio of water to cement; most mixes sit between 0.4 and 0.6 by weight. Concrete that dries out early stops reacting, and in some tests it reached only about half the strength of concrete kept moist.

How to build

Clinker needs an industrial kiln, but bagged cement, within its use-by date, can be mixed by hand on a board for a post footing or a garden slab. Anything that carries a building or a vehicle needs an engineer's design.

Set the formwork. For a slab, dig to firm ground, compact a layer of hardcore and stake boards on edge around it, tops level and inner faces oiled. For a footing, the hole is the mould.

Water goes into a crater in the dry mix and is turned in from the edges.

Mix dry, then add little water. A common guide is one bucket of cement, two of sharp sand and three of washed gravel up to 20 mm. Turn the dry heap until it is evenly grey, then pour water into a crater and shovel the dry edges into it, a little at a time. A ratio of 0.5 means about 12.5 litres for a 25 kg bag, counting the water already in wet sand. Stop when the mix is evenly wet and soft enough to fill the form and be compacted, yet still holds its shape on the shovel: extra water makes it easier to place but the hardened concrete weaker.

Place, compact and keep damp. Fill the form in layers, rodding each and tapping the boards to drive out air; level the top with a plank. Shield the fresh concrete from sun and wind while you work. Once the surface no longer marks, keep it damp under plastic or wet hessian for at least 7 days, longer in cool weather, and protect it from frost.

Test a cube. Fill one or two oiled moulds 10 cm inside from the batch, in two layers, rodding each, and cure them under the same wet cover as the slab. A materials-testing laboratory crushes such cubes in a press at 7 and 28 days and reports their strength; that is how concrete on site is checked. Breaking a cube with a hammer tells you little and throws chips and dust.

> **Safety.** Wet cement is strongly alkaline. Trapped against the skin inside a glove or boot, it can cause serious chemical burns. Wear waterproof gloves, long sleeves, trousers over your boots and eye protection. Wash cement off the skin promptly; if it gets in the eyes, rinse with plenty of clean water for at least 15 minutes and get medical help. The powder irritates the lungs: tip bags outdoors, upwind, wearing an FFP3 mask. Cutting hardened concrete raises silica dust: use a saw with a water attachment and a fit-tested FFP3 mask. A bag weighs 25 kg: lift with bent knees, or with help.

History and evolution

In 1756 John Smeaton, rebuilding the Eddystone lighthouse off Plymouth, tested limes for a mortar that would set between tides. The best came from limestone containing clay; he laid the tower in hydraulic lime and pozzolana. In 1817–1818 the French engineer Louis Vicat showed how clay makes lime set in water, and made an artificial hydraulic lime from chalk and clay.

Smeaton's Eddystone tower, 1759: dovetailed stone in a mortar that sets in sea water.

On 21 October 1824 Joseph Aspdin, a Leeds bricklayer, patented an artificial stone "which I call Portland cement", after the pale stone of Portland in Dorset. His product was probably burnt too lightly to count as Portland cement today. In the 1840s his son William and Isaac Charles Johnson, both near London, burned the mix to clinker, which earlier makers had discarded as overburnt; each claimed the discovery. This plate keeps 1824, the year of the name.

Frederick Ransome patented a rotating kiln in 1885. His British trials failed, but an oil-fired one worked in Pennsylvania by 1890, and such kilns soon replaced static ones.

In 2018, according to Chatham House, the world made more than 4 billion tonnes of cement a year, and making it produced about 8% of global CO_2 emissions. More than half came from the limestone itself, giving up its carbon dioxide in the kiln. Replacing part of the clinker with slag, fly ash, calcined clay or limestone lowers that share.

Key figures

Kiln temperature
About 1,450 °C

Common hand mix
1 part cement, 2 of sand, 3 of gravel by volume

World production
More than 4 billion tonnes a year, about 8% of global CO_2 emissions (2018)

Gypsum
About 5%, ground in with the clinker

Water–cement ratio
Usually 0.4 to 0.6 by weight

Sources

1. About cement · Cement Kilns (D. Moore), history of the British cement industry https://www.cementkilns.co.uk/cement.html
2. Aspdin's 1824 patent · Cement Kilns (D. Moore) https://cementkilns.co.uk/cemkilndoc008.html
3. Early rotary kilns · Cement Kilns (D. Moore) https://cementkilns.co.uk/early_rotary_kilns.html
4. Hard-Headed Man (M. Rinde, 2015) · Science History Institute, Distillations https://www.sciencehistory.org/stories/magazine/hard-headed-man/
5. Aberthaw Lime and Cement Works, Rhoose (listing record 83144) · Cadw, via British Listed Buildings https://britishlistedbuildings.co.uk/300083144-aberthaw-lime-and-cement-works-rhoose
6. Louis Vicat · École polytechnique https://225.polytechnique.fr/en/225-stories/louis-vicat.html
7. Making Concrete Change: Innovation in Low-carbon Cement and Concrete (Lehne & Preston, 2018) · Chatham House https://www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf
8. Global CO2 emissions from cement production, 1928–2018 (R. M. Andrew, 2019) · Earth System Science Data https://essd.copernicus.org/articles/11/1675/2019/
9. Composition of cement · Penn State College of Engineering https://www.engr.psu.edu/ce/courses/ce584/concrete/library/construction/curing/composition%20of%20cement.htm
10. Curing concrete: normal, hot and cold weather · Penn State College of Engineering https://www.engr.psu.edu/ce/courses/ce584/concrete/library/construction/curing/curing.html
11. Water-cement ratio of concrete · Gilson Company https://www.globalgilson.com/blog/water-cement-ratio-of-concrete
12. Properties of concrete · University of Memphis, Civil Engineering https://www.ce.memphis.edu/1101/notes/concrete/section_3_properties.html
13. Cement · Health and Safety Executive https://www.hse.gov.uk/construction/healthrisks/hazardous-substances/cement.htm
14. Cutting paving blocks, kerbs and flags · Health and Safety Executive https://www.hse.gov.uk/construction/healthrisks/hazardous-substances/cutting-paving-blocks-kerbs-and-flags.htm
15. Cement hydration · MC-Bauchemie, MCpedia https://www.mc-bauchemie.com/mcpedia/cement-hydration

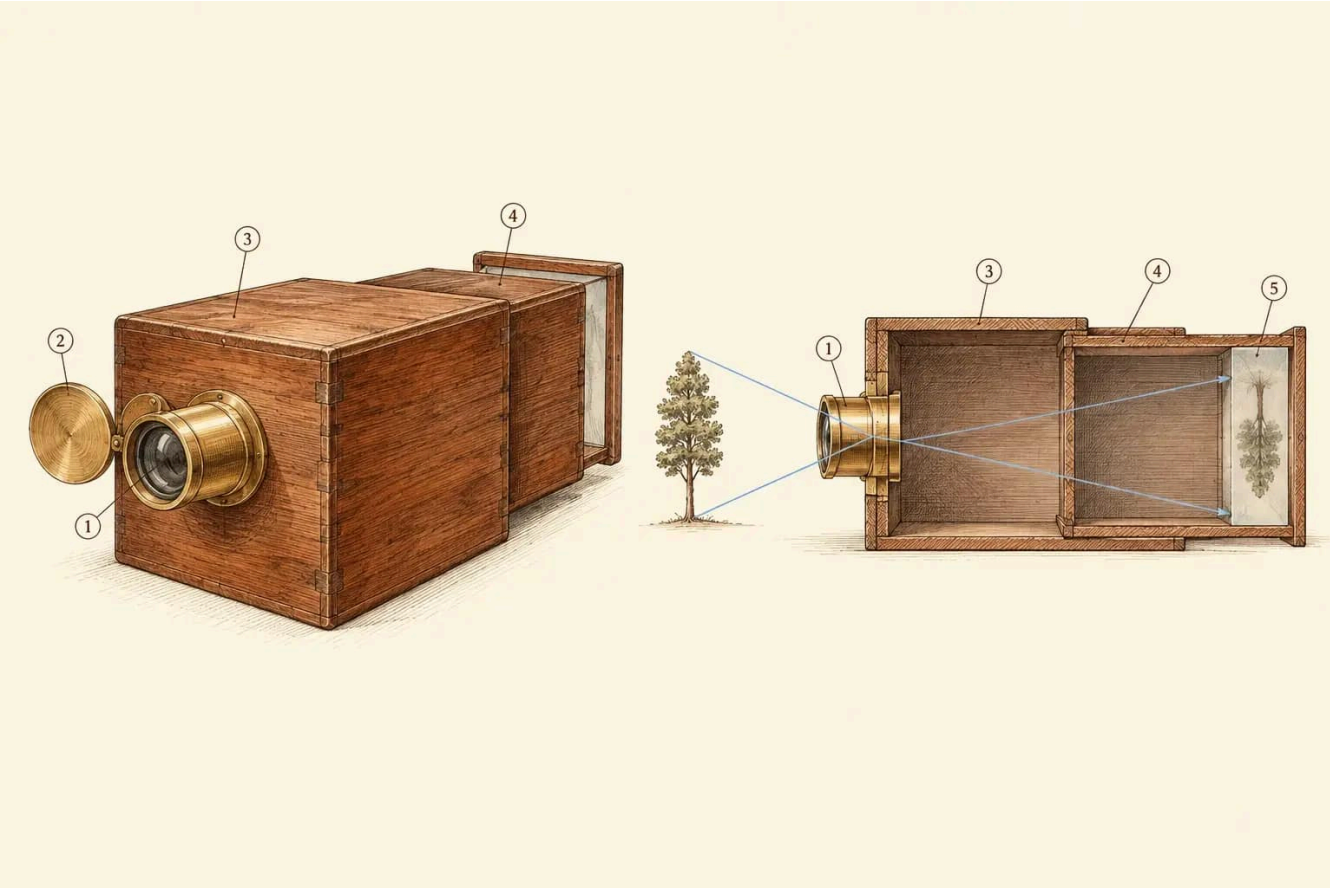
Fact-checked on 2026-10-14

Photography

Light that leaves a trace

c. 1827 · Industrial age · Science & industry

Requires: Glass (p. 129)
Leads to: X-Ray Imaging (p. 334)



1 Lens in its brass barrel 2 Pivoting brass lens cover 3 Front box 4 Sliding rear box 5 Ground-glass focusing screen

Photography fixes the image formed by a lens on a surface that light changes chemically. Nicéphore Niépce made the oldest surviving camera photograph in 1826 or 1827, and the daguerreotype, made public in Paris in 1839, was the first process sold to the public, with cameras and plates on sale within weeks.

What it is

Photography records an image made of light. A lens throws a small picture of the scene onto a surface coated with a substance that light alters; after treatment, the light and dark parts of the scene stay fixed on that surface for good. The word means “drawing with light”, and the first workers spoke of pictures that drew themselves.

The camera on the plate is the one Alphonse Giroux began selling in Paris in 1839 to the design of Louis Daguerre, the first camera made in quantity for the public. It is two wooden boxes, one sliding inside the other. The front box carries a single lens in a brass barrel, with a round brass cover that swings aside to start the exposure. At the back, a sheet of ground glass shows the image for focusing; it is then replaced by a holder carrying the sensitive plate.

How it works

Light from each point of the scene passes through the lens and is brought to a point on the back of the camera. The result is a small, sharp, upside-down copy of the scene, the same image a camera obscura had shown since the Renaissance. Moving the rear box in or out until that image looks sharp on the ground glass sets the focus.

Artists used portable camera obscuras like this long before photography; a mirror throws the image up onto a glass where it can be traced.

Photography needed a way to keep that image. Some compounds of silver darken in light, and some resins harden in it. Niépce coated a pewter plate with bitumen of Judea dissolved in oil of lavender. Where light struck, the bitumen hardened; afterwards a solvent washed away the soft, unexposed parts, leaving a picture made of bitumen on bare metal.

The daguerreotype used silver. A copper plate coated with polished silver was made sensitive over iodine vapour, exposed for several minutes in the camera, developed over heated mercury, which settled on the parts that light had touched, and fixed in salt water or “hypo”. The result was a mirror-like positive, unique, with fine detail. Talbot’s calotype worked differently: it made a paper negative, from which any number of positive prints could be made by contact, the principle of most of the photography on film that followed.

How to build it

Two simple projects show the two halves of photography at home: a pinhole camera forms the image, and cyanotype paper records light chemically. Do not attempt a daguerreotype outside a professional facility with chemical fume extraction and trained supervision: it uses heated mercury and iodine, both toxic.

Make the camera. Take a light-tight box, such as a shoebox, and paint the inside matt black. Cut a hole about 2 cm across in the centre of one end and tape over it a piece of thin aluminium foil pierced with a needle; a hole of about 0.3 mm suits a box 10 to 15 cm deep. Cover the pinhole with a flap of black card that you can lift and lower: this is the shutter.

Watch the image. Cut a window in the opposite end and tape tracing paper over it. In a bright scene, with a dark cloth over your head and the box, you will see the upside-down image on the paper, exactly as in a camera obscura.

Make a cyanotype. Ready-coated “sun print” paper, used as its maker instructs, is the simplest choice. Cyanotype, published by John Herschel in 1842, uses iron salts that turn Prussian blue in ultraviolet light. Lay a leaf or a fern on the paper in sunshine under a sheet of glass for a few minutes, then rinse the paper in water and let it dry.

Going further. Cyanotype is far too slow to take a picture through a pinhole: the exposure would run to weeks. To photograph with the box itself, replace the tracing paper with a light-tight back, seal the edges with black tape, and load black-and-white photographic paper or film in a darkroom. It is then developed and fixed with ordinary darkroom chemicals, used with gloves and good ventilation as their labels instruct.

A cyanotype photogram: where the fern blocked the light, the paper stayed white.

> **Safety.** Cyanotype chemicals and darkroom solutions irritate skin, eyes and lungs: wear gloves and eye protection, keep them away from food, children and pets, and dispose of them as the labels instruct. If you mix your own cyanotype solution, never heat potassium ferricyanide or mix it with acids. Do not look at the Sun through the pinhole or anything else. Historical processes that use mercury, cyanide or ether belong only in a professional laboratory with fume extraction.

History and evolution

The camera obscura was known long before photography, and by the eighteenth century artists carried portable boxes to trace landscapes. Chemists knew that silver salts darken in light, but nobody could stop the darkening. At his estate at Saint-Loup-de-Varennes in Burgundy, Nicéphore Niépce obtained fleeting camera pictures in 1816 and, in 1826 or 1827, the view from his workroom window that is now the oldest surviving camera photograph, kept at the Harry Ransom Center in Austin. Its exposure is usually given as several days, though some accounts say about eight hours.

Niépce went into partnership with Louis Daguerre in 1829 and died in 1833. Daguerre carried on, and on 19 August 1839 his process was explained in detail to a joint meeting of the Académie des sciences and the Académie des beaux-arts; the French state had bought it and made it free for all to use, except in England and Wales, where a patent was taken out on it. In England Henry Talbot had been making images on paper for several years and announced his first process the same year; in 1840 he devised the calotype negative and made it public in 1841.

A daguerreotype was a single silvered plate, kept under glass in a small hinged case.

From 1851 the wet collodion process of Frederick Scott Archer put negatives on glass, sharper than paper and far quicker than the daguerreotype, but the plates had to be coated, exposed and developed within minutes. By the 1880s factories sold dry plates ready to use: George Eastman began making them for sale in 1880, and in 1888 he sold the first Kodak, a box loaded with film for a hundred pictures, sent back whole to the factory for developing. Colour film spread in the twentieth century, and at its end electronic sensors began to replace the chemistry; in front of them, a lens still forms the image as it did in Giroux's box.

Key figures

Oldest surviving camera photograph
Niépce, Saint-Loup-de-Varennes, 1826 or 1827; pewter plate 16.7 × 20.3 cm

Its exposure
Probably several days in sunlight (some accounts say about 8 hours)

Daguerreotype made public
19 August 1839, Académie des sciences, Paris

Paper negative (calotype)
Devised by Henry Talbot in 1840, made public in 1841

First Kodak
1888, loaded with film for 100 pictures

Sources

1. The Niépce Heliograph · Harry Ransom Center, University of Texas at Austin https://www.hrc.utexas.edu/niepce-heliograph/
2. Daguerre introduced photography 175 years ago · George Eastman Museum https://www.eastman.org/blog/daguerre-introduced-photography-175-years-ago
3. Giroux Daguerreotype camera · Victoria and Albert Museum https://collections.vam.ac.uk/item/O1427511/giroux-daguerreotype-camera-camera-daguerre-louis/
4. Hill & Adamson: salted paper prints and the calotype · University of Glasgow Archives & Special Collections https://www.gla.ac.uk/myglasgow/archivespecialcollections/discover/specialcollectionsa-z/hilladamson/saltedpaperprints
5. Collodion glass negatives and the attendant photographic process · Bibliothèque nationale de France https://expositions.bnf.fr/les-nadar/en/the-nadars/collodion-glass-negatives.html
6. Album of cyanotypes of British and Foreign Ferns (Anna Atkins) · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co416960
7. Kodak and the Eastman company · Duke University Libraries https://library.duke.edu/rubenstein/scriptorium/eaa/kodak.html
8. Richard Beard (daguerreotype patent in England and Wales) · Science Museum Group https://collection.sciencemuseumgroup.org.uk/people/cp40983/richard-beard
9. Historique et description des procédés du daguerréotype et du diorama (Daguerre, 1839) · Internet Archive https://archive.org/details/bub_gb_Ae4TAAAAQAAJ
10. History and practice of photogenic drawing on the true principles of the Daguerréotype (McLean, 1839) · Wellcome Collection, via Internet Archive https://archive.org/details/b29310301
11. Replica of Daguerre-Giroux camera · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co8189231/replica-of-daguerre-giroux-camera
12. From Daguerreotype to Digital: the daguerreotype process · The Historic New Orleans Collection https://hnoc.org/virtual-exhibitions/from_daguerreotype_to_digital/daguerreotype-process

Fact-checked on 2026-10-12

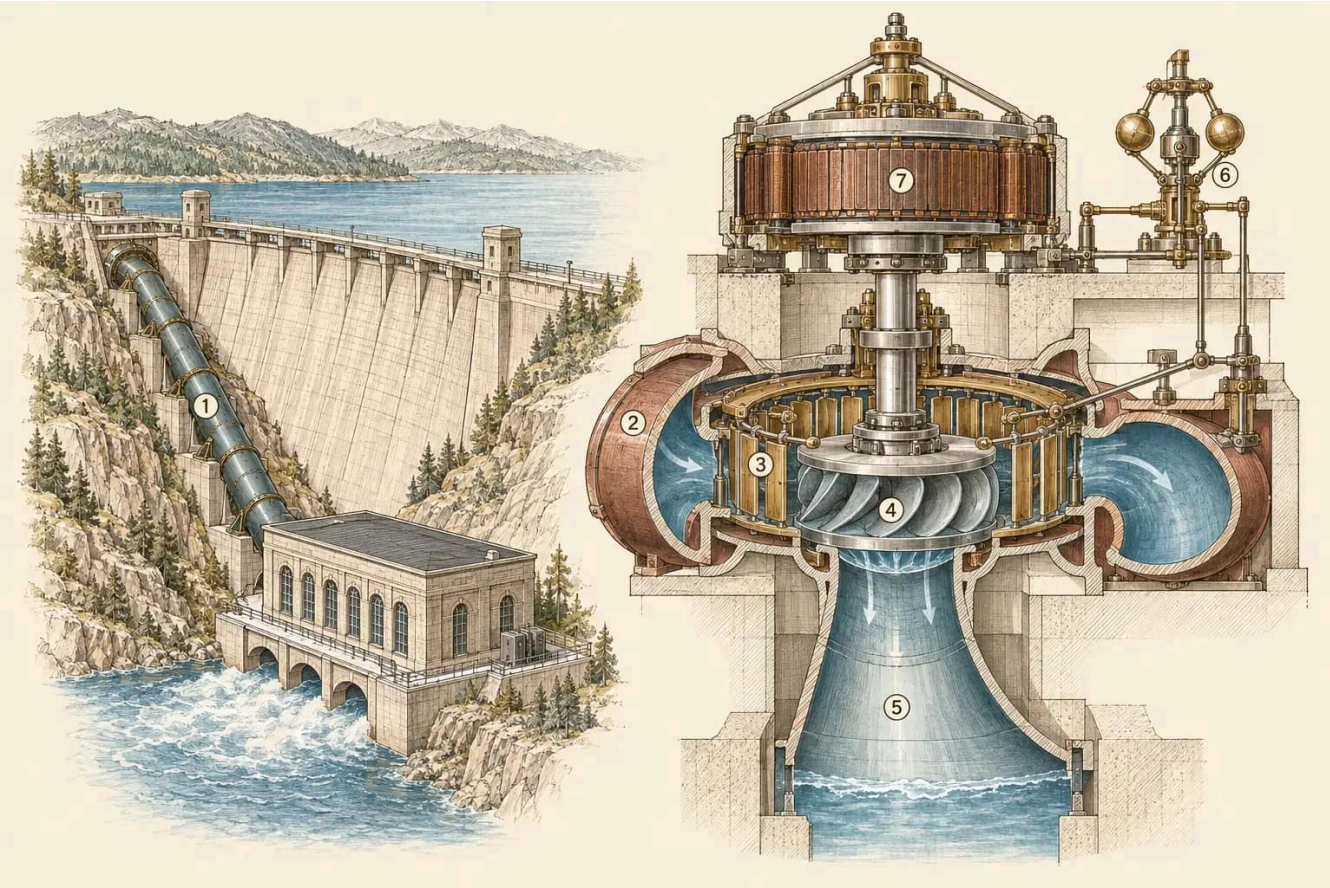
Water Turbine

Falling water turned into electricity

1827 · Industrial age · Science & industry

Requires: Water Wheel (p. 153), Steel (p. 137), Electric Generator (p. 266)

Leads to: Aluminium (p. 322)



1 Penstock 2 Spiral case 3 Guide vanes 4 Runner 5 Draft tube 6 Governor 7 Generator

A water turbine is a bladed runner that water under pressure drives at high speed, either inside a closed casing or from a jet. It takes energy from a fall of water, like the water wheel, but in a far smaller and faster machine, and since the 1880s it has driven the generators of hydroelectric plants.

What it is

A water turbine is a wheel of curved blades, the runner, driven round at high speed by water under pressure. Like the water wheel, it draws energy from water falling from a height. But an overshot wheel turns in open air under the weight of the water in its buckets, and an undershot wheel under the push of a current, at a few revolutions a minute. A turbine is fed through a pipe and turns tens or hundreds of times faster, so a much smaller machine handles the same power.

Its speed lets it drive an electric generator with little or no gearing. Almost every hydroelectric plant uses one of three designs: the Pelton wheel, the Francis turbine or the Kaplan turbine.

How it works

In an impulse turbine a nozzle turns the whole pressure into a fast jet and the runner spins in air. In a reaction turbine the runner is enclosed and full of water, and the pressure drops between its blades, which act like curved wings.

The Pelton wheel is an impulse turbine for high falls and small flows. A ridge splits each bucket, cuts the jet and turns each half almost straight back. The Francis turbine, a reaction machine and the most common type, covers the middle range, roughly 40 to 600 metres of fall. The Kaplan turbine, a propeller whose blades turn on the hub, serves low falls and large flows, below about 80 metres.

The ridge in each bucket cuts the jet in two and turns both halves back.

The plate shows a Francis unit. Water comes down the penstock (1) into the spiral case (2), which narrows as it wraps round the machine so that water enters evenly from every side. The guide vanes (3) set it swirling and control how much passes. It flows inwards through the runner (4) and leaves downwards through the draft tube (5), a flared pipe that slows it gradually and recovers part of its remaining energy.

The power available is $P = \rho \cdot g \cdot Q \cdot H \cdot \eta$: water density ρ (about 1,000 kg/m^3), gravity g (9.81 m/s^2), flow Q in m^3/s, net head H in metres and efficiency η. With 100 metres of head, 0.2 m^3/s and 85% for turbine and generator together, $P = 1{,}000 \times 9.81 \times 0.2 \times 100 \times 0.85 \approx 167$ kW. Large Francis turbines exceed 90% on their own.

The generator (7) sits on the same shaft, and its frequency follows its speed. The governor (6) holds that speed steady by closing the guide vanes when the shaft speeds up and opening them when it slows. It must act gradually: closing a long penstock suddenly causes water hammer, a pressure surge that can burst the pipe. At 100 revolutions a minute, a generator needs 60 poles to give 50 hertz.

How to build

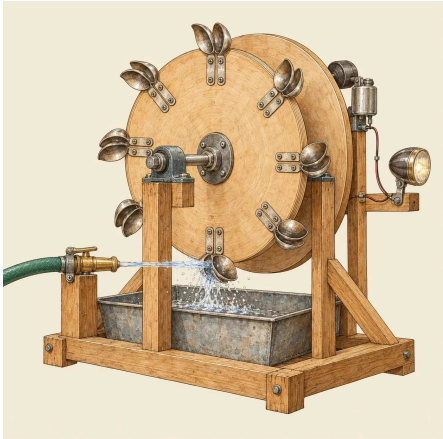
A wheel of spoons fed by a garden hose from a stream can light a bicycle lamp. Ask the landowner and the water authority first: in most countries taking water from a stream needs permission.

Measure the head. Lay a hose from the intake down to where the wheel will stand, hold its upper end under the water and let it run until no more air comes out. Then close the lower end with a pressure gauge: each bar of static pressure means about 10.2 metres of head. A builder's level and a staff, moved downhill from one marked point to the next, give a check.

Measure the flow. For a trickle under about 5 litres per second, lead it through a pipe in a small earth dam and time how long it takes to fill a bucket. For a larger stream, time a float over 10 metres, multiply the speed by about 0.85, then by the width and the mean depth.

Work out the power. With 8 metres of head and 0.3 litres per second in the hose, the water carries $P = 1{,}000 \times 9.81 \times 0.0003 \times 8 \approx 24$ W. The hose and nozzle waste part of the head, and a home-made wheel and dynamo turn only a modest share of the rest into electricity. Expect a few watts, perhaps enough for a 3-watt bicycle dynamo, and measure what you really get. Leave most of the stream to the fish.

Make the runner. Fix a plywood disc about 30 cm across on a steel axle turning in two bearings. Screw eight to ten pairs of tablespoons round the edge, side by side, their bowls standing out beyond the rim, turned to face the jet and meeting in a ridge.



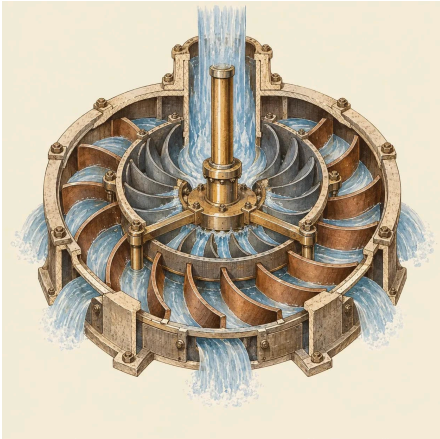
Paired spoons make a rough split bucket for the jet.

Aim the jet. Clamp a jet nozzle on the hose so the jet strikes the ridges tangentially. Without losses it would leave at 12.5 m/s; with hose friction, about 10 m/s is more likely. The spoons work best at half the jet's speed, measured on the circle where the jet strikes them: about 270 revolutions a minute if that circle is 35 cm across.

Add the dynamo. Fix a second, smooth disc about 35 cm across on the axle and press the roller of a bottle dynamo against its edge. At 270 revolutions a minute that edge moves like a bicycle tyre at about 18 km/h. Run two insulated wires to a bicycle lamp: on a bicycle the frame carries the return current, here a wire must. Lead the water back to the stream below the wheel.

> **Safety.** Never work alone by a stream, and stay out of it when it runs high: fast, cold water knocks people over and drowns them. A hose 8 metres down a slope holds almost one bar. Open and close long pipes slowly, because a sudden stop causes water hammer that splits fittings. Keep eyes and fingers out of the jet, guard the runner and stop the water before touching it. Insulate every connection and keep fingers away from the dynamo roller as well. Larger generators reach dangerous voltages: never connect one to a building's wiring.

History and evolution



In Fourneyron's turbine the water flows outwards, from fixed vanes into the moving ring.

In 1825 Claude Burdin, a professor at the Saint-Étienne mining school, built a turbine at Pontgibaud with an efficiency of 67%. His former student Benoît Fourneyron made it industrial: in April 1827, at the ironworks of Pont-sur-l'Ognon, he installed a six-horsepower turbine under a 1.40-metre fall.

At Lowell, Massachusetts, in 1849, James B. Francis built an improved inward-flow turbine and published his tests in 1855. In the California goldfields Lester Pelton built his first wheel in 1878 and patented the split bucket in 1880.

In 1878 Lord Armstrong lit his house at Cragside, in Northumberland, with arc lamps powered by water from the estate's lakes. A plant at Appleton, Wisconsin, supplied direct current from 30 September 1882. In 1895 the Adams station at Niagara Falls started Westinghouse generators of 5,000 horsepower giving alternating current on Nikola Tesla's system; from November 1896 its power reached Buffalo. Viktor Kaplan filed his patent for adjustable runner blades in 1913, and the first industrial Kaplan turbine ran at Velm, in Austria, in 1919.

The world had 1,412 GW of hydropower in 2023. China's Three Gorges Dam alone has 22.5 GW, and about 1.3 million people were moved for its reservoir. Dams block migrating fish and trap sediment: a study published in 2019 found that only 37% of the world's 246 longest rivers still flowed freely along their whole length.

Key figures

First industrial turbine
Benoît Fourneyron, April 1827, Pont-sur-l'Ognon (France): 6 hp under a 1.40 m fall

Available power
$P = \rho \cdot g \cdot Q \cdot H \cdot \eta$

Pelton's split bucket
US patent 233,692, 26 October 1880

Largest plant
Three Gorges Dam, China: 22.5 GW

World hydropower capacity
1,412 GW in 2023

Sources

1. Usine de transformation des métaux dite forges de Pont-sur-l'Ognon (IA70000081) · Ministère de la Culture, base Mérimée https://pop.culture.gouv.fr/notice/merimee/IA70000081
2. Instrument de démonstration en mécanique des fluides n° 5 : tourniquet hydraulique · Inventaire du patrimoine, Région Bourgogne-Franche-Comté https://patrimoine.bourgognefranchecomte.fr/dossier/pdf/IM21008546
3. Boyden Hydraulic Turbines (landmark brochure) · American Society of Mechanical Engineers https://www.asme.org/wwwasmeorg/media/ResourceFiles/AboutASME/Who%20We%20Are/Engineering%20History/Landmarks/5-Boyden-Hydraulic-Turbines-1871.pdf
4. #157 Pelton Waterwheel Collection · American Society of Mechanical Engineers https://www.asme.org/about-asme/engineering-history/landmarks/157-pelton-waterwheel-collection
5. US 233,692: Water-wheel (L. A. Pelton, 26 October 1880) · United States Patent Office, via Google Patents https://patents.google.com/patent/US233692A/en
6. 100 Jahre Kaplan-Turbine (H. Jaberg, WasserWirtschaft 6/2014) · Institut für Hydraulische Strömungsmaschinen, TU Graz https://www.hfm.tugraz.at/fileadmin/user_upload/pics/news/2020/201406_Helmut_Jaberg_Viktor-Kaplan-Kaplanturbine.pdf
7. History of Cragside · National Trust https://www.nationaltrust.org.uk/visit/north-east/cragside/history-of-cragside
8. Milestones: Vulcan Street Plant, 1882 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Vulcan_Street_Plant,_1882
9. Milestones: Adams Hydroelectric Generating Plant, 1895 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Adams_Hydroelectric_Generating_Plant,_1895
10. Niagara Power Houses · Edison Tech Center https://edisontechcenter.org/niagara/
11. Types of Hydropower Turbines · U.S. Department of Energy, Water Power Technologies Office https://www.energy.gov/eere/water/types-hydropower-turbines
12. Turbine types · Electrical and Mechanical Services Department, Hong Kong SAR Government https://re.emsd.gov.hk/english/other/hydroelectric/Turbine_types.html
13. Glossary of Hydropower Terms · U.S. Bureau of Reclamation https://www.usbr.gov/power/edu/Glossary%20of%20Hydropower%20Terms.pdf
14. Hydraulic head · Energy Education, University of Calgary https://energyeducation.ca/encyclopedia/Hydraulic_head
15. Water (FAO Training Series), chapter 3: Estimates of water flow · FAO https://www.fao.org/fishery/static/FAO_Training/FAO_Training/General/x6705e/x6705e03.htm
16. 2024 World Hydropower Outlook · International Hydropower Association https://www.hydropower.org/publications/2024-world-hydropower-outlook
17. Thousands being moved from China's Three Gorges, again (Reuters) · Eco-Business https://www.eco-business.com/news/thousands-being-moved-from-chinas-three-gorges-again/
18. New study: just one-third of the world's longest rivers remain free-flowing · McGill University Reporter (on Grill et al., Nature 569, 2019) https://reporter.mcgill.ca/new-study-just-one-third-of-the-worlds-longest-rivers-remain-free-flowing/
19. Fluid Machinery, lectures 26–27: Pelton wheel · NPTEL, Indian Institute of Technology Kanpur https://archive.nptel.ac.in/content/storage2/courses/112104117/chapter_7/7_5.html
20. Pelton Impulse Water Turbine Design Formulas · Engineers Edge https://www.engineersedge.com/hydraulic/pelton_impulse_water_turbine_15629.htm

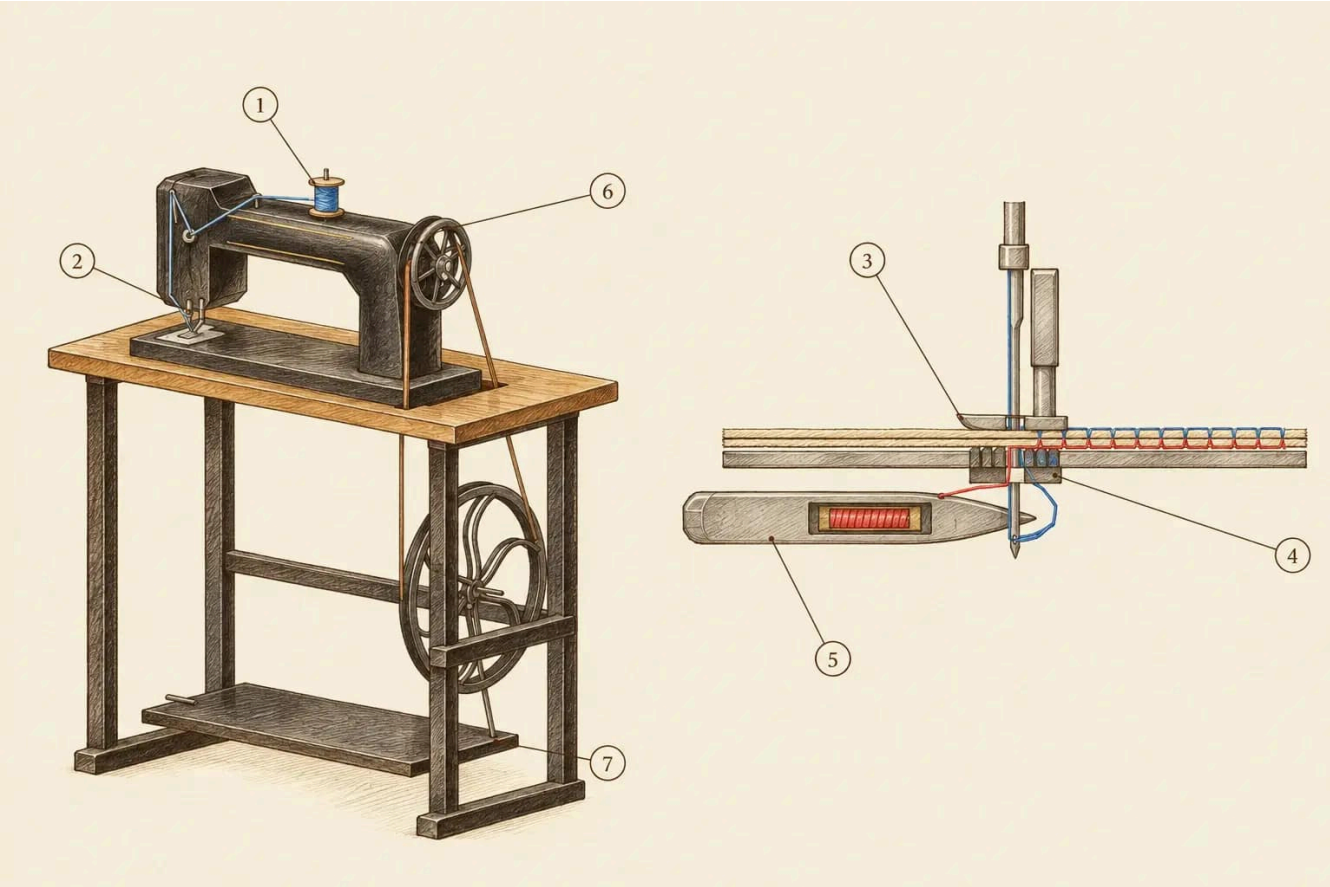
Fact-checked on 2026-10-14

Sewing Machine

A thousand stitches a minute

1830 · Industrial age · Science & industry

Requires: Gears (p. 149), Iron Smelting (p. 133), Weaving (p. 43), Steel (p. 137)



1 Spool of upper thread 2 Needle bar and needle 3 Presser foot 4 Feed dog 5 Shuttle with bobbin 6 Handwheel 7 Treadle and flywheel

A sewing machine joins cloth with stitches formed mechanically, most often by locking an upper thread, carried by a needle with its eye near the point, around a lower thread held in a shuttle or bobbin case. Barthélemy Thimonnier's chain-stitch machine of 1830 was the first put to work in a factory; Elias Howe's lockstitch patent of 1846 and Isaac Singer's machine of 1851 made it an industrial and household tool.

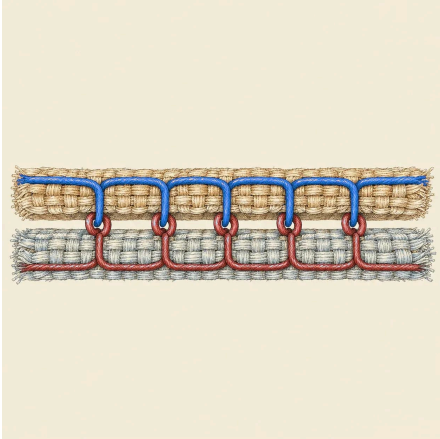
What it is

A sewing machine pushes a threaded needle through cloth again and again, and at each pass ties the thread so the stitches hold. Its mechanism repeats the same few movements: the needle goes down and up, a hook or shuttle catches the thread underneath, and the cloth moves on by one stitch.

Most machines make a lockstitch, in which two threads, one from above and one from below, are locked together in the middle of the cloth. The typical machine of the 1860s to 1880s, the type that brought machine sewing into workshops and homes, was a cast-iron head on a treadle stand, with a straight needle and a boat-shaped shuttle.

How it works

The needle of a sewing machine has its eye close to the point, the opposite of a hand needle, and it is never let go: it stays clamped in its bar while its point and eye go through the cloth. It carries the upper thread down through the fabric and the hole in the needle plate. As it starts to rise, friction holds back some thread on the underside, and a small loop opens beside the needle.



In a finished lockstitch, the upper and lower threads lock together between the layers of cloth.

The pointed shuttle swings through that loop at this moment, carrying a small bobbin of lower thread inside it. The loop slides around the shuttle and off its back, so the upper thread now encircles the lower one. A take-up lever on the front of the machine then pulls the upper thread tight, and the crossing point is drawn up into the middle of the cloth. Tension springs on both threads decide where that crossing sits: if one thread is too tight, the knot shows on one face.

The boat shuttle holds the bobbin of lower thread; the thread leaves through a hole in its side, where a small spring, not drawn here, sets its tension.

Between stitches the cloth has to move. A presser foot holds it down on a small toothed bar, the feed dog, which rises through slots in the needle plate, pushes the cloth back by one stitch length and drops away again. The same main shaft that drives the needle bar through a crank drives the shuttle and the feed from underneath, so all three stay in time. On a treadle machine the feet rock a broad iron treadle, a rod turns a heavy flywheel, and a leather belt carries the motion up to the handwheel on the arm.

The older single-thread chain stitch needs no lower thread. In Thimonnier's machine a hooked needle pulled each new loop up through the one before; later single-thread chain-stitch machines use an eyed needle and a looper underneath that holds each loop for the next stitch. Chain stitch is quick, but if the thread end at the finishing end of the seam is pulled, the whole seam can unravel.

How to build it

A working sewing machine needs hardened needles, cams and close-fitting parts cut in a machine shop. A large model on a simple frame shows how the two threads of a lockstitch interlock.

Make the frame. Stretch a piece of loose-weave hessian over a picture frame or an embroidery hoop and fix it at a comfortable height, with room to reach underneath.

Make the needle. Take a wooden dowel about 30 cm long and 8 mm thick, sharpen one end to a blunt point with a pencil sharpener, and drill a 4 mm hole about 1 cm from the point. Thread thick wool yarn of one colour through this eye, leaving a tail of about 15 cm.

Make the shuttle. Wind about two metres of wool yarn of a second colour around a clothes peg or a small wooden shuttle. Tape the end of each yarn to the back of the frame before the first stitch so that it cannot pull through.

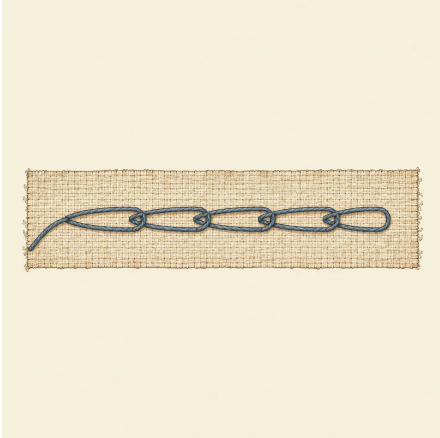
Sew. One person pushes the needle down through the hessian until the eye is well below it, then lifts it a centimetre while holding the yarn above the cloth, so that a loop opens underneath. A second person passes the

shuttle through the loop from front to back, unwinding yarn as needed. Pull the needle back up and tighten both yarns so the crossing sinks into the weave. Make the next stitch about 2 cm further along the cloth and repeat. Turn the frame over to see the two colours linked between the faces.

> **Safety.** Use a vice or clamp when drilling and keep fingers away from the bit. On a real sewing machine, keep fingers clear of the needle while it moves, never reach under the presser foot while the machine runs, and switch off and unplug an electric machine before threading it, changing the needle or cleaning out lint.

History and evolution

Several inventors patented sewing devices from the late eighteenth century onwards, but the first used in production was built by the French tailor Barthélemy Thimonnier, patented in 1830. It made a chain stitch with a barbed needle, imitating tambour embroidery. He soon had 80 machines making army clothing in a Paris workshop. A crowd of tailors who feared for their work broke in and destroyed them. Most accounts date the attack to 1831; some put it ten years later. Thimonnier died in 1857.



In a chain stitch each loop is held only by the next one. Nothing holds the last loop, so pulling the thread at that end undoes the seam loop after loop.

In the United States, Elias Howe received patent 4,750 on 10 September 1846 for a lockstitch machine. It used a curved needle with the eye near the point and a shuttle carrying the second thread, and he claimed it could sew 250 stitches a minute. In 1851 Isaac Merritt Singer patented a machine whose straight needle moved up and down over a flat table, the arrangement still used today. Their patents overlapped, and the makers sued one another until 1856, when Howe, Singer, Wheeler and Wilson, and Grover and Baker pooled their patents in the Sewing Machine Combination, and Howe received a royalty on each machine sold.

Singer’s partner Edward Clark sold machines by instalments and through agents who went from door to door. In 1875 about 250,000 Singer machines were licensed, against about 104,000 for its nearest rival, Wheeler and Wilson. Rotary hooks took the place of the shuttle on faster machines, electric motors were fitted from the end of the nineteenth century, and clothing factories came to depend on rows of powered machines sewing at several thousand stitches a minute.

Key figures

Thimonnier's machine
Patented in France in 1830; 80 machines sewing army clothing in Paris before tailors wrecked them

Singer's patent
12 August 1851: straight needle moving vertically over a flat table

Singer machines licensed in 1875
About 250,000 machines licensed, more than twice its nearest rival

Howe's lockstitch patent
US patent 4,750, 10 September 1846; claimed 250 stitches a minute

Sewing Machine Combination
1856, the first patent pool in American industry

Sources

1. Copy of Thimonnier's chain-stitch sewing machine, 1830 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co44718/copy-of-thimonniers-chain-stitch-sewing-machine-1830-sewing-machines
2. Sewing Machine (Designs for Democracy) · U.S. National Archives https://www.archives.gov/exhibits/designs_for_democracy/symbols_and_substance/articles/sewing_machine_1.html
3. Isaac M. Singer (Scientist of the Day) · Linda Hall Library https://www.lindahall.org/about/news/scientist-of-the-day/isaac-m-singer/
4. 'New Family' sewing machine (model 12/12k) · Victoria and Albert Museum https://collections.vam.ac.uk/item/O1351206
5. The Invention of the Sewing Machine (Grace Rogers Cooper, Smithsonian Institution, 1968) · Project Gutenberg https://www.gutenberg.org/files/32677/32677-h/32677-h.htm
6. Singer New Family sewing machine, 1865 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co44768/singer-new-family-sewing-machine-1865-1
7. Instructions for using and adjusting the Singer 12K sewing machine · ISMACS International (Needlebar archive) https://ismacs.net/needlebar/main/manuals/singer12k/
8. Howe Machine Company instruction book · ISMACS International (Needlebar archive) https://ismacs.net/needlebar/main/manuals/howe/index4.html
9. Singer oscillating shuttle machines: retiming · Singer Sewing Info https://www.singersewinginfo.co.uk/28timing
10. Needles for domestic Singer sewing machines · Singer Sewing Info https://www.singersewinginfo.co.uk/needles

Fact-checked on 2026-10-12

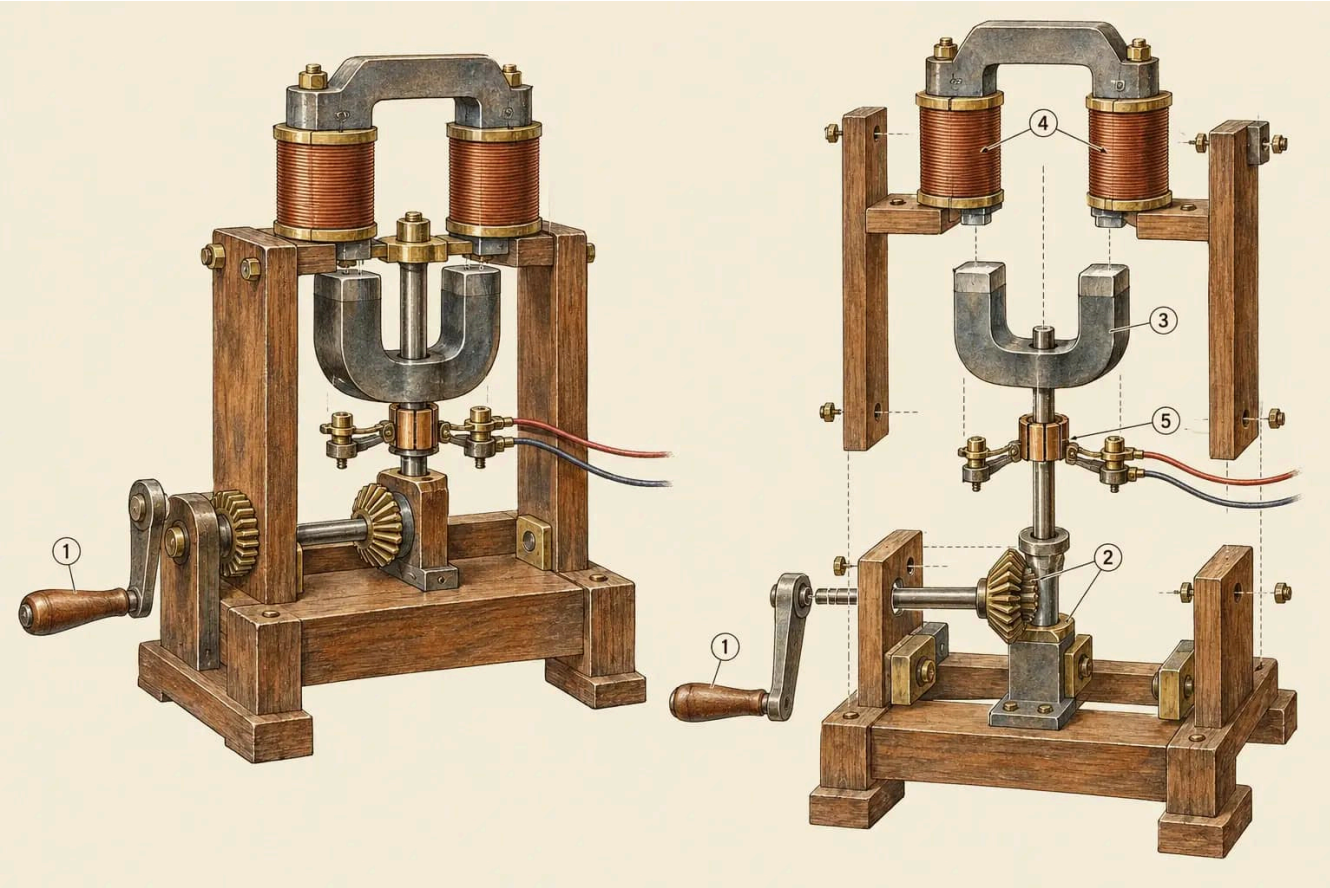
Electric Generator

Motion turned into current

1831 · Industrial age · Science & industry

Requires: Battery (p. 234), Iron Smelting (p. 133)

Leads to: Aluminium (p. 322), Lead-Acid Battery (p. 294), Incandescent Light Bulb (p. 310), Radio (p. 330), Steam Turbine (p. 314), Transformer (p. 318), Water Turbine (p. 258), Wind Turbine (p. 326), X-Ray Imaging (p. 334)



1 Hand crank 2 Bevel gears 3 Horseshoe magnet 4 Coils on iron cores 5 Commutator and brushes

An electric generator turns mechanical motion into electric current by moving a magnet and a coil of wire past each other. Michael Faraday found the principle in 1831, and almost all the electricity used today still comes from machines built on it.

What it is

A generator converts mechanical work, from a hand crank, a water wheel, a steam engine or a turbine, into electric current. It needs a magnet, a coil of copper wire, and some way to move one past the other.

Batteries are costly and run down; generators made electricity in bulk from coal or falling water. Power stations, car alternators, bicycle dynamos and wind turbines all work this way.

How it works

The principle is electromagnetic induction. When the magnetic flux through a coil (the amount of field passing through it) changes, a voltage appears across the ends of the coil. If the flux stays constant, there is no voltage. The faster the flux changes and the more turns the coil has, the higher the voltage.

Faraday's induction ring: the needle jumped only at the moment the battery was connected or disconnected.

In the machine on the plate, built by Hippolyte Pixii in 1832, a crank turns a vertical shaft through a pair of bevel gears. The shaft carries a horseshoe permanent magnet whose poles sweep just under two fixed coils wound on iron cores. As a north pole comes under a coil, the flux through it grows and current flows one way. As the pole moves away, the flux shrinks and the current reverses. The south pole then repeats the cycle with the field the other way round, so the bare machine makes alternating current.

Pixii added a commutator, suggested by André-Marie Ampère: a switch on the shaft that swaps the two output connections every half turn, just as the current reverses. The output becomes a pulsing direct current that can charge batteries or split water.

Faraday's disc of 1831 gave a small, continuous direct current.

As soon as current flows, the coils become magnets themselves and push back against the motion, so the crank gets heavier when a lamp is connected. The electrical energy that comes out is the work put in by the hand or the engine, minus losses to friction and heat.

Nineteenth-century permanent magnets were weak, so large machines used electromagnets. In a self-excited dynamo, part of the machine's own output feeds them. The faint magnetism left in the iron starts a small current, which strengthens the field, which raises the current, until the voltage settles at a level set by the speed and by the saturation of the iron. A modern power-station generator spins an electromagnet inside fixed windings; with two poles it turns at 3,000 revolutions per minute for 50 hertz, or 3,600 for 60 hertz.

How to build it

A small hand-cranked alternator can light an LED or a torch bulb.

Make the rotor. Cut a disc of plywood or hardwood about 15 cm across. Glue eight flat disc magnets (ferrite or neodymium) on one face, evenly spaced near the rim, so that the faces turned outward alternate north, south, north, south. Bind them with cord, because a loose magnet flies off at speed.

Wind the coils. Wind eight flat coils of enamelled copper wire 0.3 to 0.5 mm thick, a few hundred turns each, all in the same direction, on a former about the size of a magnet.

Mount the stator. Fix the coils on a board parallel to the rotor, one facing each magnet, with a gap of a few millimetres. Neighbouring coils always face opposite poles, so connect them in series with every second coil reversed; then their voltages add.

Gear it up. A belt from a large pulley on the crank to a small one on the rotor shaft multiplies the speed four or five times.

Rectify and test. The output is alternating current. Four diodes in a bridge turn it into pulsing direct current. Light an LED from the bridge through a one-kilohm, half-watt resistor, which keeps the current under about 20 milliamperes as long as the output stays below about 20 volts; check the voltage with a meter before cranking hard. Charging a battery needs a proper charge controller suited to its type, not diodes alone.

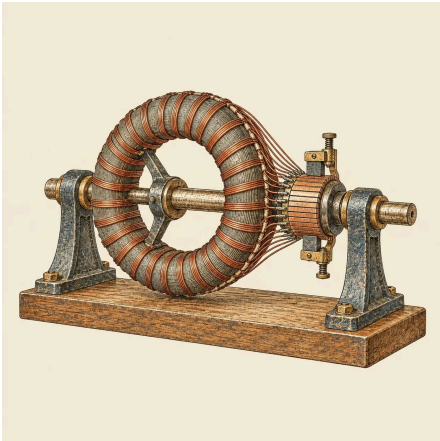
Without bought magnets, steel bars can be magnetised inside a coil fed for a few seconds by a battery, with a car bulb in series to limit the current. A self-excited dynamo, once started from residual magnetism, needs no permanent magnet at all.

> **Safety.** Rotating parts catch fingers, hair and loose clothing: guard the belt and rotor. Neodymium magnets snap together hard enough to pinch skin and shatter; keep them away from pacemakers. Voltage rises with speed, and larger machines reach dangerous levels. Never connect a home-made or portable generator to a building's wiring or to the mains: current fed back into the network can kill line workers, and only an electrician fitting a proper transfer switch should make such a connection.

History and evolution

In 1820 Hans Christian Ørsted showed that an electric current deflects a compass needle. Michael Faraday reasoned that magnetism should, in turn, be able to produce electricity. On 29 August 1831, at the Royal Institution in London, he wound two coils on an iron ring and saw a galvanometer needle jump each time he connected or disconnected a battery on the other coil. That autumn he spun a copper disc between the poles of a magnet and drew a continuous current from it. He presented the results to the Royal Society on 24 November 1831.

Within a year Pixii, a Paris instrument maker, built the hand-cranked machine on the plate. In 1866 and 1867 Samuel Alfred Varley, Werner Siemens and Charles Wheatstone each announced the self-excited dynamo, and Siemens named the dynamo-electric principle. Around 1870 Zénobe Gramme built a ring armature that gave a smooth current.



The Gramme ring spread the winding all around the armature, so the current hardly pulsed.

On 4 September 1882 Thomas Edison's Pearl Street Station in New York began supplying direct current at 110 volts from six steam-driven "Jumbo" dynamos. Alternating current later won for long distances because transformers can raise its voltage; in 1891 a three-phase line carried power 175 km from Lauffen am Neckar to Frankfurt. Charles Parsons coupled a dynamo to a steam turbine in 1884, and turbine-driven generators have powered most large stations since. In 1975 the first of three 600 MW units started at the Grand Coulee Dam, with a stator 22 metres across.

Key figures

Induction discovered
29 August 1831, by Michael Faraday

Pixii's magneto-electric machine
Paris, 1832

Self-excited dynamo
1866 to 1867 (Varley, Siemens, Wheatstone)

Pearl Street Station, 1882
Six dynamos of about 100 kW each, 110 V direct current

Sources

1. Michael Faraday · The Institution of Engineering and Technology (IET) Archives https://www.theiet.org/membership/library-archives/the-iet-archives/biographies/michael-faraday/
2. Magnetoelectric machine by Pixii · Museo Galileo, Florence https://catalogue.museogalileo.it/object/MagnetoelectricMachineByPixii.html
3. Chronik: Generatoren · VDE Verband der Elektrotechnik https://www.vde.com/de/geschichte/chronik/generatoren
4. Milestones: Pearl Street Station, 1882 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Pearl_Street_Station

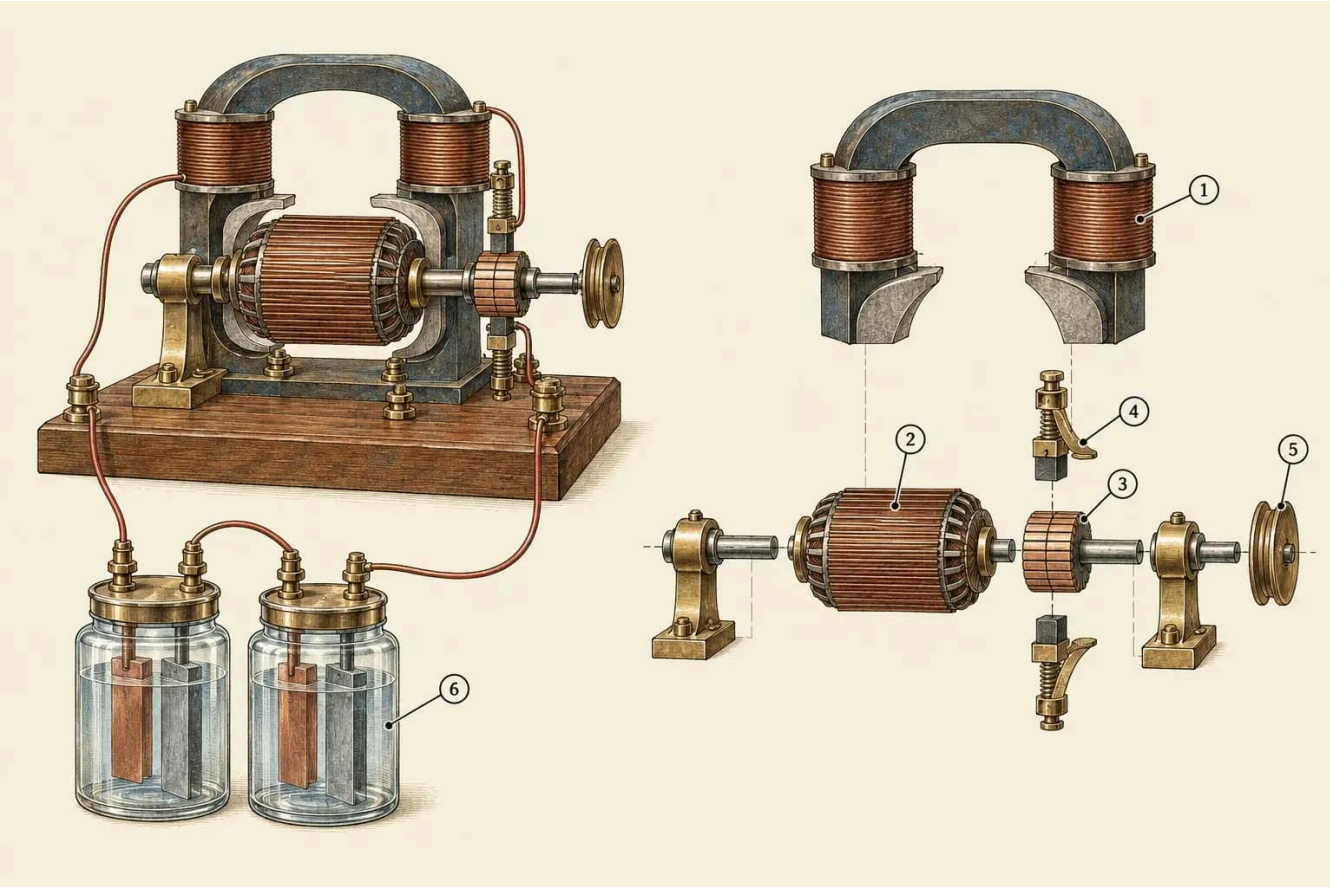
Fact-checked on 2026-10-11

Electric Motor

Current turned into rotation

1834 · Industrial age · Science & industry

Requires: Battery (p. 234), Iron Smelting (p. 133)



1 Field magnet 2 Armature winding 3 Commutator 4 Brush 5 Shaft and pulley 6 Battery

An electric motor turns current into rotation: a coil carrying current between magnet poles is pushed sideways, and a commutator or a rotating field keeps that push acting in one direction. Moritz Jacobi's motor of 1834 delivered far more power than any before it, and motor-driven systems now use about half the world's electricity.

What it is

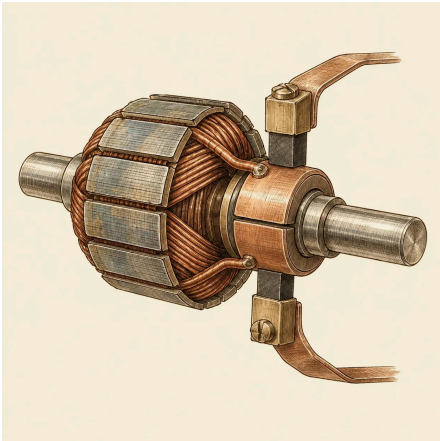
An electric motor turns electric current into rotation. It drives fans, pumps, lifts, trams and machine tools. The Electric Motor Systems Platform of the IEA's 4E programme estimates that motor-driven systems used about 53% of the world's electricity in 2023.

The plate shows a battery-fed direct-current motor of the late nineteenth century.

How it works

A wire carrying current inside a magnetic field is pushed sideways, at right angles to both the current and the field. In a coil set between two poles, the two long sides carry current in opposite directions, so one side is pushed up and the other down, and the coil turns.

Left alone, the coil would swing until its plane stood square to the field, rock a few times and stop there. The commutator prevents this. It is a ring on the shaft cut into insulated segments, each wired to the coil, and two fixed brushes rub on it to bring in the current. In the simplest, two-segment form, every half turn the brushes pass to the other segment, the current in the coil reverses, and the torque keeps pointing the same way.



A two-part commutator: the brushes swap halves every half turn.

Working armatures carry many coils spread around an iron drum, each joined to its own segments, so the torque stays even. The iron is stacked from thin insulated sheets, because a solid core would carry eddy currents that waste power as heat. The field comes from permanent magnets in many small motors and from electromagnets in most machines of the nineteenth century, like the one on the plate.

A spinning armature also works as a generator. Its coils produce a voltage that opposes the supply, called back-EMF, which grows with speed. At start-up there is none, so the current can be many times its running value. As the motor speeds up, the back-EMF rises and the current falls until the torque matches the load. Turned by hand, with its field magnetised and a load connected, the same machine sends current out: a motor and a generator are one device used in opposite directions.

Induction motors, fed with alternating current, have no commutator. Fixed windings carrying currents out of step create a rotating magnetic field. It induces currents in the copper or aluminium bars of the rotor, which turns a little slower than the field.

How to build

The classroom motor needs one 1.5 V cell (size D or AA), about a metre of enamelled copper wire 0.5 to 0.8 mm thick, two large paper clips, a ceramic or neodymium disc magnet, a strong rubber band and fine sandpaper.

Wind the coil. Wrap the wire 10 to 20 times around a marker pen, leaving 4 to 5 cm straight at each end. Loop each free end twice round the bundle to hold it. The two ends must leave the coil on opposite sides, in one straight line through its centre: they are the axle.

Make the commutator. On one end, sand off all the enamel. On the other, hold the coil upright as it will stand and remove the enamel from the top half of the wire only. That end conducts for half a turn and is insulated for the other half, so the coil is never pushed backwards; it coasts through the dead half on its momentum.

Mount the supports. Bend each paper clip into an upright with a flat foot at the bottom and a small loop at the top. Stretch the rubber band lengthwise round the cell, over both feet, so that it presses each clip firmly against one terminal. Set the magnet on the side of the cell under the loops, where it clings to the steel casing. Lay the coil in the loops a few millimetres above the magnet.

Start it. Give the coil a light flick. If it only rocks, turn it end for end or sand the bare side again.

The paper-clip commutator: bare copper on top, enamel left underneath, so current flows only during the half turn when the bare side rests on the clip.

Scale up. A stronger magnet gives more torque; more turns help too, as long as the longer wire does not cut the current too much. A workshop motor uses several coils on a laminated iron core, with a commutator of many segments and spring brushes, as on the plate.

> **Safety.** Use one or two ordinary 1.5 V cells and nothing else: never the mains, a car battery or a lithium-ion pack. The coil is close to a short circuit, and those sources can push enough current to burn skin, melt the wire or start a fire. Even a small cell heats up, running or not: keep each run short and supervised, and disconnect the cell when it or the wire feels warm, before adjusting or sanding, and after use. Neodymium magnets snap together hard enough to pinch skin and can shatter. Keep them away from pacemakers and other medical implants, and out of reach of small children: two swallowed magnets can pull together through the wall of the gut.

History and evolution

In 1820 Hans Christian Ørsted saw a compass needle swing beside a wire carrying current. On 3 September 1821 Michael Faraday made a wire dipping into mercury circle a magnet, and in 1822 Peter Barlow spun a star-shaped wheel between magnet poles. Both were demonstrations with little usable power. Strong fields came with the electromagnet, which William Sturgeon made in the mid-1820s, and around 1832 William Ritchie and Sturgeon built rotating machines with a commutator.

Faraday's rotation (1821): the free end of the wire circles the magnet.

In May 1834, in Königsberg, Moritz Hermann Jacobi finished a motor with eight horseshoe electromagnets that developed about 15 watts. This plate takes 1834 as its date: Faraday showed the principle and Sturgeon's small engine already turned a roasting spit, but Jacobi's machine was far more powerful, and no other builder matched it before about 1839. Thomas Davenport's American patent came in 1837.

Batteries made these motors costly to run until the generator brought cheap current. In 1873 a Gramme dynamo was found to run as a motor when fed by another one. Galileo Ferraris in Turin worked out the rotating field from 1885 and published in March 1888; Nikola Tesla, working separately in New York, was granted his induction-motor patent on 1 May 1888. Today permanent-magnet motors switched by electronics drive drones and electric cars.

Key figures

Jacobi's motor, May 1834

About 15 W at 60–130 rpm, fed by zinc and copper cells

First US motor patent

Thomas Davenport, patent no. 132, February 1837

Rotating magnetic field

Galileo Ferraris, published March 1888; Nikola Tesla's patent, 1 May 1888

Share of world electricity

About 53% used by motor-driven systems in 2023

Sources

1. The invention of the electric motor 1800–1854 · Elektrotechnisches Institut, Karlsruhe Institute of Technology https://www.eti.kit.edu/english/1376.php
2. Jacobi's Motor · Elektrotechnisches Institut, Karlsruhe Institute of Technology https://www.eti.kit.edu/english/1382.php
3. 200 Years Ago, Faraday Invented the Electric Motor · IEEE Spectrum https://spectrum.ieee.org/200-years-ago-faraday-invented-the-electric-motor
4. Barlow's Wheel – 1822 · National High Magnetic Field Laboratory https://nationalmaglab.org/magnet-academy/history-of-electricity-magnetism/museum/barlow-s-wheel-1822/
5. Replica of William Sturgeon's rotary electromagnetic engine · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co36713/replica-of-william-sturgeons-rotary-electromagnetic-engine
6. Zenobe Gramme · Grace's Guide to British Industrial History https://www.gracesguide.co.uk/Zenobe_Gramme
7. Milestones: Rotating Fields and Early Induction Motors, 1885–1888 · IEEE, Engineering and Technology History Wiki https://ethw.org/Milestones:Rotating_Fields_and_Early_Induction_Motors,_1885-1888
8. Tesla's Electro-magnetic motor · Engineering and Technology History Wiki https://ethw.org/Tesla's_Electro-magnetic_motor
9. AC Motors · HyperPhysics, Georgia State University https://hyperphysics.gsu.edu/hbase/magnetic/motorac.html
10. Simple DC Motor (demonstration 5K40.18) · Oberlin College Physics Department https://www2.oberlin.edu/physics/catalog/demonstrations/em/simpledcmotor.html
11. Policy Brief: Electric Motor Systems, why are they important? · IEA 4E Electric Motor Systems Platform (EMSA) https://www.iea-4e.org/emsa/publications/policy-brief-electric-motor-systems-why-are-they-important/
12. College Physics 2e, 22.8 Torque on a Current Loop: Motors and Meters · OpenStax, via LibreTexts https://phys.libretexts.org/Bookshelves/College_Physics/Book%3A_College_Physics_(OpenStax)/22%3A_Magnetism/22.08%3A_Torque_on_a_Current_Loop_-_Motors_and_Meters
13. College Physics 2e, 23.6 Back Emf · OpenStax, Rice University https://openstax.org/books/college-physics-2e/pages/23-6-back-emf
14. RE-280RA/SA metal-brush motor datasheet · Mabuchi Motor Co. (copy hosted by the University of North Carolina at Charlotte) https://webpages.charlotte.edu/~jmconrad/ECGR4161-2009-01/labs/re_280rasa.pdf

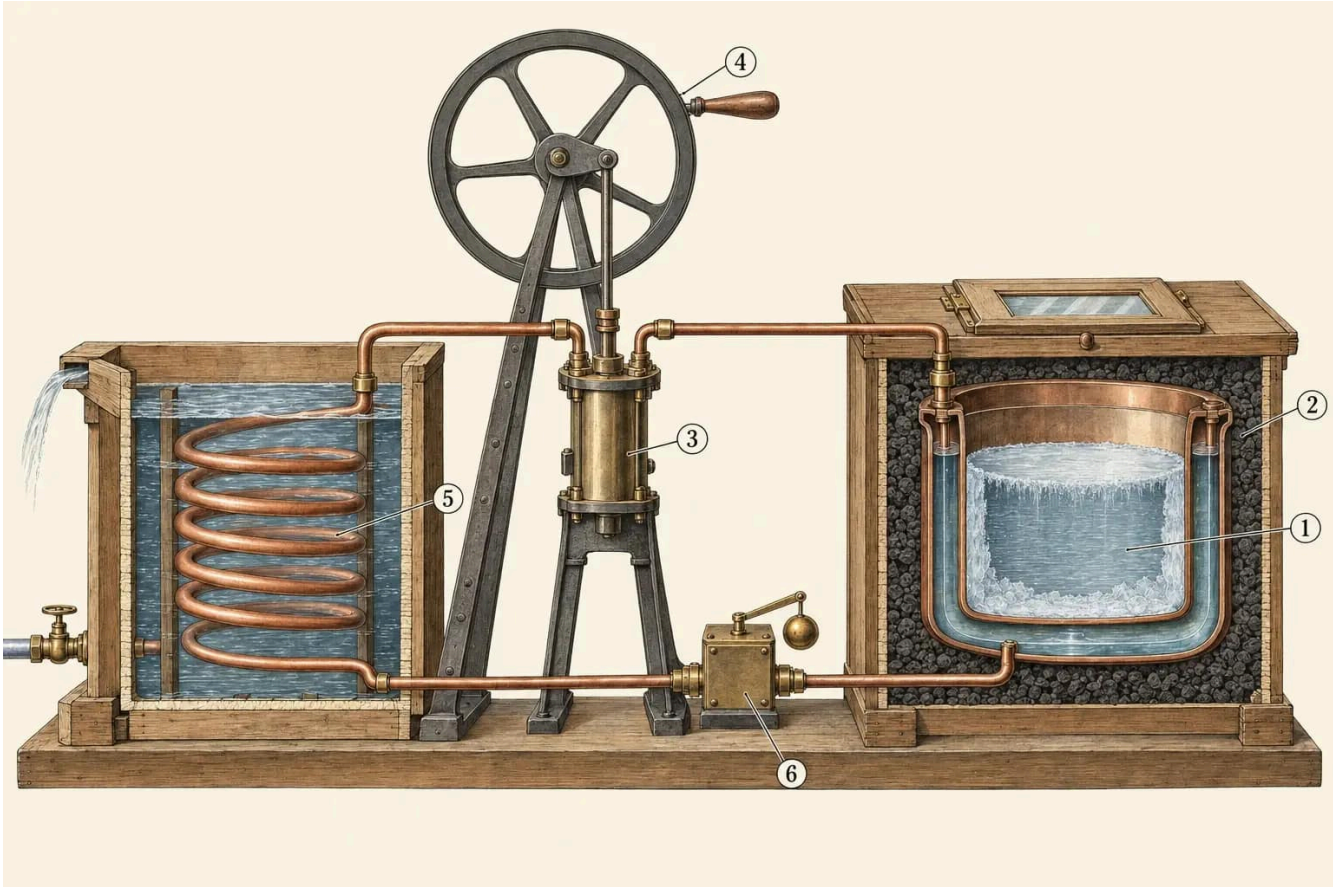
Fact-checked on 2026-10-14

Refrigeration

Pumping heat out of a box

1834 · Industrial age · Science & industry

Requires: Steam Engine (p. 221), Piston Pump (p. 157), Thermometer and barometer (p. 217), Distillation (p. 169)



1 Jacketed pan with the water to be frozen 2 Box packed with charcoal 3 Pump 4 Flywheel and handle 5 Worm in its cooling-water tub 6 Weighted valve box

Refrigeration keeps a space colder than its surroundings by making a liquid boil inside it, so that it soaks up heat, then carrying the vapour outside, compressing it and turning it back into liquid. Jacob Perkins patented the first closed vapour-compression machine in London in 1834; ammonia machines ran breweries and ships by the 1870s, and electric home refrigerators spread from the late 1920s.

What it is

A refrigerator moves heat out of a closed space and dumps it outside, from cold to warm, the opposite of the way heat flows on its own. Food keeps longer because the bacteria and moulds that spoil it grow slowly in the cold. The same machines make ice, cool beer during brewing, carry frozen meat across oceans and air-condition buildings.

Nearly all of them work on the vapour-compression cycle. The plate shows its first working form: an ether machine that the engineer John Hague built in London to Jacob Perkins's patent of 1834. The pump was worked by hand.

How it works

A liquid that evaporates takes heat from whatever it touches. Sweat cools skin in the same way. The lower the pressure, the lower the temperature at which a liquid boils: ether boils at about 35 °C in open air, but in a vessel where a pump keeps the pressure low it boils well below the freezing point of water.

A clay pot-in-pot cooler uses the same effect: water evaporating from the damp sand draws heat from the inner pot.

On Hague's machine the jacketed copper pan holds the water to be frozen in its inner bowl, and ether fills the space between its two walls. The pump draws ether vapour from the top of the jacket, so the liquid ether keeps boiling and pulls heat out of the water until it freezes. Powdered charcoal packed around the pan slows the heat coming in from the room.

The same pump then pushes the vapour into a copper coil, the worm, standing in a tub of running water. A valve loaded to about 15 pounds per square inch, a little over one bar, holds the vapour in the worm under pressure. Compressed and cooled by the water, the vapour turns back into liquid and gives up the heat it took from the pan, together with the work put in at the pump. The liquid passes the valve, its pressure falls, and it runs back into the jacket to boil again. The same charge of ether goes round and round without being used up.

A modern refrigerator does the same with an electric compressor, a grid of tubes at the back that warms the kitchen, a narrow tube or valve where the pressure drops, and an evaporator inside the cabinet. Absorption refrigerators replace the pump with a liquid that soaks up the refrigerant vapour and a burner or heater that drives it out again.

How to build it

A real refrigerating circuit holds a volatile fluid under pressure. Ether is highly flammable and its vapour can explode; ammonia is toxic; modern refrigerants are stored as liquids under several bars and some are flammable. Machines are built and charged in factories; leave any opening, filling or emptying of a circuit to qualified refrigeration technicians, following local rules. Do not make a compressor or a pressure vessel, and never cut or drill the pipes of an old refrigerator.

The effect behind it can be shown safely with a pot-in-pot evaporative cooler.

Choose the pots. Take two new, clean unglazed terracotta pots, one about 5 cm wider than the other all round; the inner one, which touches the food, should be sold for food use, never an old garden pot. Plug the drainage holes with clay or a cork.

Fill the gap. Put a layer of sand in the bottom of the large pot, stand the small pot on it, and fill the gap between them with sand up to the rim.

Wet it. Pour clean water into the sand until it is soaked but not flooded. Cover the inner pot with a damp cotton cloth.

Place it. Stand the cooler in shade where dry air can move around it. Water seeping through the outer wall evaporates and draws heat from the sand and the inner pot. In hot, dry air the inside can stay several degrees cooler than the surroundings; in humid air the effect is small. Add water once or twice a day.

> **Safety.** An evaporative cooler only slows spoilage: it does not reach the 5 °C or below needed for meat, fish or dairy, so keep it for whole, uncut vegetables and fruit that keep at room temperature, never for cut fruit, salads or cooked food, and check its temperature with a thermometer. Keep the sand and cloth clean and dry the pots out regularly to stop mould. Never open, puncture or heat the circuit of a refrigerator or air conditioner.

History and evolution

Before machines reached the kitchen, a zinc-lined icebox was cooled by a block of ice.

People stored winter ice in pits and ice houses, and cooled water in porous jars, long before any machine. In Scotland, William Cullen showed that a liquid evaporating quickly under reduced pressure, ether in his best-known demonstration, can cool the water around it until it freezes; accounts date the work between 1748 and 1756. It remained a laboratory demonstration. In 1805 Oliver Evans described a closed vapour-compression cycle in the United States but never built it.

Jacob Perkins, an American inventor living in London, patented a closed machine on 14 August 1834. Hague built it, and it made a small amount of ice, but it found no buyers. The idea became a business in the 1850s, when James Harrison in Australia and Alexander Twining in the United States built the first ice machines sold commercially. In 1859 Ferdinand Carré in France patented an absorption machine that used ammonia dissolved in water. In the 1870s Carl von Linde in Munich designed ammonia compression machines; one of the first, sold in 1876, went to a brewery in Trieste. The same year the French ship Frigorifique, fitted out by Charles Tellier, carried the first cargo of refrigerated meat by sea between Rouen and Buenos Aires.

Small electric motors made home refrigerators possible. General Electric's Monitor Top of 1927, with its compressor in a drum on the cabinet, cost about 525 dollars at launch and fell to about 200 within a few years. Chlorofluorocarbons such as Freon, developed in 1928 and made commercially from the early 1930s, then replaced the toxic or flammable refrigerants used in early household machines, such as sulphur dioxide, methyl chloride and ammonia. They were later found to destroy the ozone layer, and the Montreal Protocol of 1987 phased them out; in 2016 the Kigali amendment added their replacements, the HFCs, which are strong greenhouse gases. In 2024 the International Institute of Refrigeration estimated that refrigeration and air conditioning use about a fifth of the world's electricity.

The Monitor Top of 1927: the compressor sits in the drum, and the copper coil around it gives off the heat taken from the cabinet.

Key figures

Perkins's patent
British patent 6662, 14 August 1834, ether as the working fluid

Carré's ammonia absorption machine
1859, France

Share of world electricity used for cooling
About 20% (International Institute of Refrigeration)

Weighted valve on Hague's machine
Loaded to about 15 pounds per square inch (about 1 bar)

Montreal Protocol on ozone-depleting gases
Signed 1987, in force 1989; HFCs added at Kigali in 2016

Sources

1. #274 Perkins Vapor-Compression Cycle for Refrigeration (landmark brochure) · American Society of Mechanical Engineers https://www.asme.org/getmedia/cb9bea09-6d23-425e-bfe5-5f6d786919fb/274-Perkins-Vapor-Comp-Refrig.pdf
2. Froid · Encyclopédie Larousse https://www.larousse.fr/encyclopedie/divers/froid/53766
3. Historical beginnings: using natural refrigeration · Chillventa / NürnbergMesse https://www.chillventa.de/en/expert-insights/refrigeration/beginnings-of-refrigeration
4. Cornerstones of compression: making cold · COMPRESSORtech2 https://www.compressortech2.com/news/cornerstones-of-compression-making-cold/8054876.article
5. GE Monitor-Top Refrigerator · Albany Institute of History & Art https://albanyinstitute.org/online-exhibition/50-objects/section/ge-monitor-top-refrigerator
6. The Montreal Protocol · UNEP Ozone Secretariat https://ozone.unep.org/treaties/montreal-protocol
7. New IIR figures highlight the role of the refrigeration sector · International Institute of Refrigeration https://iifiir.org/en/news/de-nouveaux-chiffres-de-l-iif-mettent-en-lumiere-la-place-du-secteur-du-froid
8. Got a question about Monitor Top refrigerators? (model history) · cool386.com https://www.cool386.com/ge/ge1.html
9. Diethyl ether: phase change data (vapour pressure, enthalpy of vaporization) · NIST Chemistry WebBook https://webbook.nist.gov/cgi/cbook.cgi?ID=C60297&Mask=4
10. Diethyl ether (compound summary, vapor pressure) · PubChem, National Library of Medicine https://pubchem.ncbi.nlm.nih.gov/compound/3283

Fact-checked on 2026-10-12

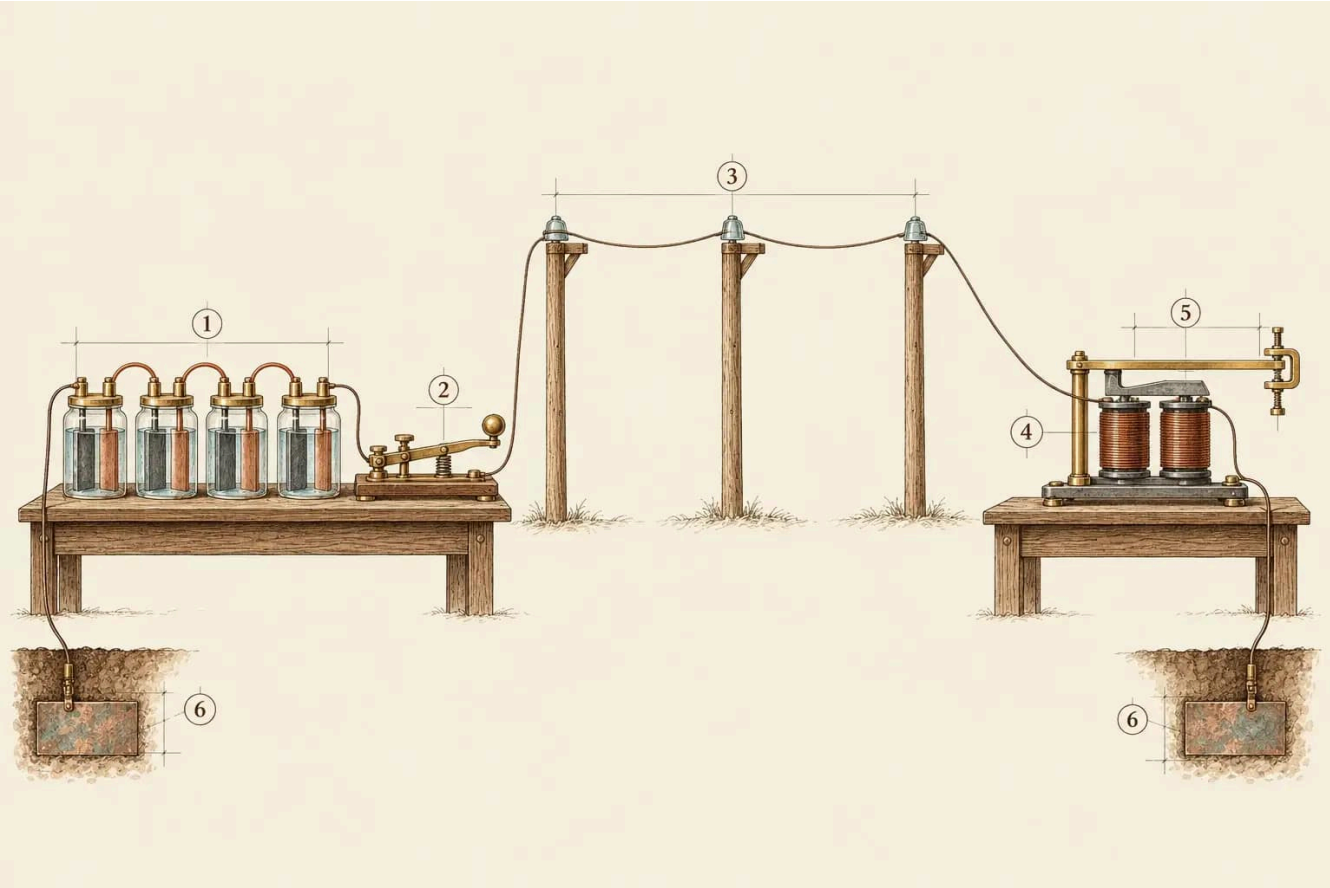
Electric Telegraph

Written messages sent along a wire

1837 · Industrial age · Science & industry

Requires: Battery (p. 234), Writing (p. 82)

Leads to: Radio (p. 330), Telephone (p. 306)



1 Battery 2 Key 3 Line wire on insulators 4 Electromagnet of the sounder 5 Armature lever 6 Earth plate

The electric telegraph sends messages along a wire as pulses of current from a battery, switched on and off with a key and read at the far end by an electromagnet. William Cooke and Charles Wheatstone patented a needle telegraph in Britain in 1837, Samuel Morse and Alfred Vail demonstrated their recording telegraph in 1838, and within thirty years cables linked continents.

What it is

An electric telegraph sends written messages as electrical signals along a wire. At one end an operator opens and closes a circuit; at the other end an instrument moves each time the current flows. Letters are spelt out with a code. In Cooke and Wheatstone's first five-needle instruments, needles pointed to letters on a board; later needle instruments used a code of left and right swings.

The plate shows the simplest form, the single-wire line used with Morse code: a battery, a key, a line of poles and, at the receiving station, a sounder. The ground itself carries the current back.

How it works

The battery is a row of cells, each a pair of zinc and copper plates in a liquid, joined in series so their voltages add up. One end of the battery goes to the earth through a buried metal plate, the other to the key. The key is a sprung brass lever: pressing it closes a contact and connects the battery to the line.

Current runs along the line wire, carried on glass insulators so it does not leak into the wet wood of the poles, and through the coils of an electromagnet at the far station. From there it goes down into the ground at a second earth plate and returns through the soil to the battery. Using the earth as the return path halves the amount of wire.

A Morse key: pressing the knob closes the contact under the lever.

While current flows, the coils become a magnet and pull down an iron armature fixed to a pivoted lever, which strikes a stop with a click. When the key is released, a spring lifts the lever against a second stop with a different click. A short press gives a dot and a longer one a dash, and groups of them stand for letters and figures. Morse's first instruments embossed or inked the dots and dashes on a moving paper strip, but operators soon found they could read the clicks by ear.

How to build it

A working key and sounder can be built on a table and run from a small battery, which makes the principle easy to see.

Wind the electromagnet. Wind about 30 metres of enamelled copper wire 0.2 mm in diameter in neat layers around a large iron nail or bolt about 10 cm long, leaving both ends free. Scrape the enamel off the last centimetre of each end. This coil has a resistance of about 16 ohms, so a 4.5-volt battery of three AA cells drives less than 0.3 amperes through it.

Make the sounder. Drill a hole in a wooden board and glue the nail into it upright, head up, without squeezing the winding. Cut a strip about 1 cm wide and 8 cm long from the tinplate of a food can, file its edges smooth, and screw one end to a block of wood so the free end sits a few millimetres above the head of the nail. Bend it so it springs back when pushed, and fix a screw in a small wooden bracket just above the free end, so the strip clicks against the nail when it is pulled down and against the screw when it springs back. Adjust the gap to 2 or 3 mm, bending the strip until it is pulled down firmly and still springs back.

Make the key. Screw a strip of springy brass or a folded piece of tin to another board so that one end rises a little. Put a drawing pin or screw under the free end as a contact.

Wire the circuit. Connect one coil end to one terminal of a holder with three AA cells. Connect the other battery terminal to the fixed contact of the key, and the key strip back to the other coil end. Use ordinary bell wire, up to about 10 metres, between the two boards: longer or thinner wire adds resistance and the strip may no longer pull down.

Send. Press the key: the strip snaps down onto the nail with a click and springs up when released. Agree on a code with a partner and send short words.

> **Safety.** Use only a small battery of a few volts and never connect anything to mains electricity. Do not leave the key pressed for long, because the coil and the cells warm up, and disconnect the battery when you stop. Never join the battery terminals directly. Cut tin edges are sharp, so file them and wear gloves.

History and evolution

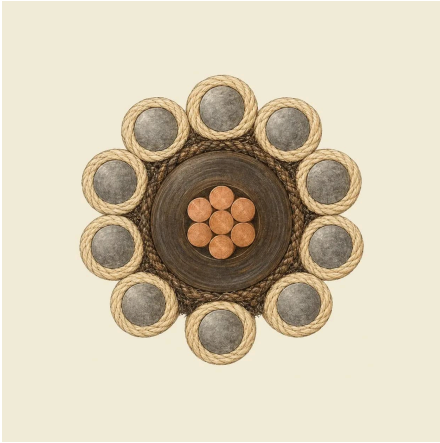
Before electricity, Chappe's optical telegraph passed signals from tower to tower; a message could go from Paris to Lille in about half an hour.

The word telegraph first named the optical system of Claude Chappe and his brothers, demonstrated in 1791. Its first line, from Paris to Lille, opened in 1794 and covered about 230 km. Operators in towers moved wooden arms into set positions and read the next tower through a telescope. At its height the French network ran to nearly 5,000 km.

Electric telegraphs became practical once batteries could supply a steady current and electromagnets could detect it. In Britain, William Fothergill Cooke and Charles Wheatstone patented a needle telegraph in June 1837, described with five needles, and tried a needle instrument between Euston and Camden Town stations in London the same year. In 1839 the Great Western Railway installed one of their telegraphs on about 21 km of line from Paddington. Later British instruments needed only one or two needles.

In the United States, Samuel Morse, a painter and professor in New York, worked with Alfred Vail, who built the instruments. They demonstrated their telegraph at the Vail family's iron works near Morristown on 6 January 1838, over about two miles of wire. In 1843 Congress paid $30,000 for a line from Washington to Baltimore, and on 24 May 1844 Morse sent the words "What hath God wrought" over it. By 1850 lines reached every important town east of the Mississippi, and one reached California in 1861.

A submarine cable linked Dover and Calais in 1851. The first Atlantic cable, laid in August 1858, failed after a few weeks; a lasting one was landed in July 1866. Engineers learnt to send several messages over one wire, first one in each direction at the same time, with the duplex perfected by Joseph Stearns in 1868, then two in each direction with Thomas Edison's quadruplex. British telegraph traffic peaked around 1900 at about 90 million messages a year. The telephone then took most of the work, and by 1980 satellites and new cables had made submarine telegraphy obsolete.



The deep-sea Atlantic cable of 1865–66 in section: seven copper wires in gutta-percha, a layer of tarred jute, and ten iron wires each wrapped in hemp.

Key figures

Cooke and Wheatstone patent
June 1837, five needles and six wires

Morse and Vail's first demonstration
6 January 1838, Speedwell Iron Works, New Jersey, over about 3 km of wire

Washington to Baltimore line
$30,000 voted by Congress in 1843; first message 24 May 1844

Lasting transatlantic cable
July 1866, after a cable of 1858 failed within weeks

Chappe optical network at its height
Nearly 5,000 km of semaphore towers, replaced by electric lines in the 1850s

Sources

1. Telegraph · Engineering and Technology History Wiki (IEEE) https://ethw.org/Telegraph
2. Milestones: Demonstration of Practical Telegraphy, 1838 · Engineering and Technology History Wiki (IEEE) https://ethw.org/Milestones:Demonstration_of_Practical_Telegraphy,_1838
3. Cooke and Wheatstone · Grace's Guide to British Industrial History https://www.gracesguide.co.uk/Cooke_and_Wheatstone
4. Submarine cable section (Atlantic cable, 1865) · Royal Museums Greenwich https://rmg.co.uk/collections/objects/rmgc-object-6204
5. Sample of the 1865/66 Transatlantic Telegraph Cable · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co34219/sample-of-the-1865-66-transatlantic-telegraph-cab-cable
6. Modern Practice of the Electric Telegraph (appendix and notes) · Frank L. Pope, 1869 (insulators.info) https://www.insulators.info/books/mpet/chap10.htm
7. Insulator Tests, The Journal of the Telegraph, 16 December 1872 · Western Union (insulators.info) https://reference.insulators.info/publications/view/?id=11419
8. Resistivity and temperature coefficient at 20 C · HyperPhysics, Georgia State University https://hyperphysics.gsu.edu/hbase/Tables/rstiv.html
9. Copper Wire Tables (Handbook 100) · National Bureau of Standards https://nvlpubs.nist.gov/nistpubs/Legacy/hb/nbshandbook100.pdf
10. Electromagnet · Wikipedia https://en.wikipedia.org/wiki/Electromagnet

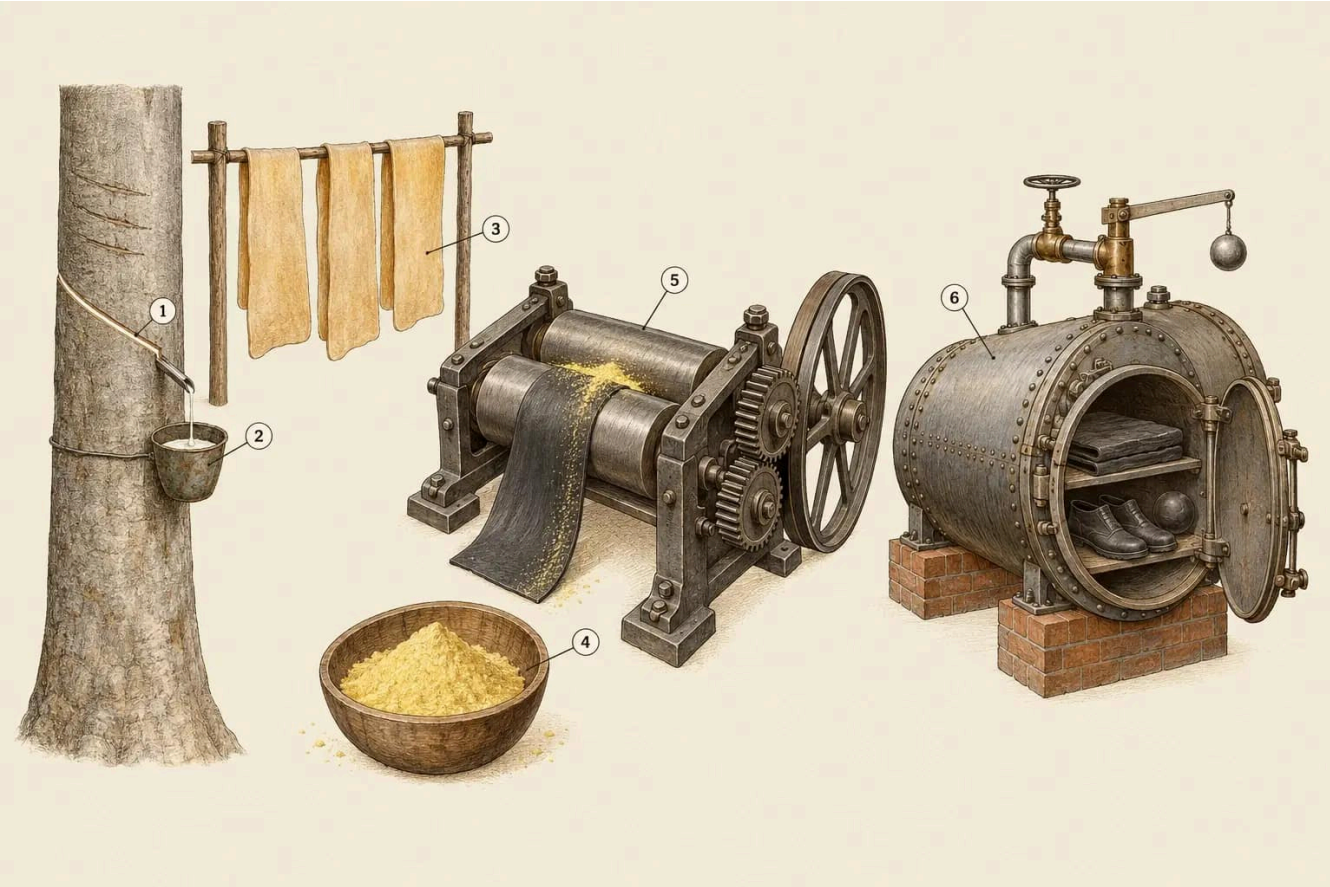
Fact-checked on 2026-10-12

Vulcanised Rubber

Sap made tough with sulphur

1839 · Industrial age · Science & industry

Requires: Control of Fire (p. 9)



1 Tapping cut 2 Latex cup 3 Sheets of raw rubber 4 Sulphur 5 Two-roll mill 6 Vulcaniser

Vulcanised rubber is rubber whose long molecules have been tied together, first by heating natural rubber with sulphur, so that it stays elastic in heat and cold instead of turning sticky or brittle. Charles Goodyear in the United States and Thomas Hancock in Britain worked out the process in the early 1840s, and it made rubber usable for tyres, hoses, seals and footwear.

What it is

Natural rubber comes from latex, a milky fluid that flows from cuts in the bark of certain tropical trees, today mostly the Pará rubber tree, Hevea brasiliensis. Dried and pressed, it is waterproof and stretchy, but raw rubber goes soft and tacky on a hot day, stiff and cracked in frost, and it slowly stretches out of shape under load.

Vulcanisation fixes these faults. The rubber is mixed with a small amount of sulphur and heated. The result is the material of tyres, hoses, conveyor belts, gaskets, boots and rubber bands, which springs back to its shape over a wide range of temperatures.

How it works

Rubber is made of very long chain molecules, each a string of thousands of small units. In raw rubber the chains lie tangled like cooked spaghetti. Pulled, they straighten out; let go, they curl up again, which is why rubber is elastic. They are not tied to one another, though, so under a steady pull or in warmth they slide past each other, and the material flows and sticks.

Mesoamerican rubber was made by mixing latex from Castilla elastica with the juice of a morning-glory vine.

Sulphur atoms, at the temperature of vulcanisation, attach to sites along the chains and form bridges between neighbouring chains, of one or several sulphur atoms each. A few bridges along each chain turn the tangle into a single loose network. It can still stretch a long way, because the chain segments between bridges can uncoil, but it cannot flow, and it returns to its shape when released.

The number of bridges sets the hardness. Soft rubber needs only a small proportion of sulphur. With much more, the network becomes so dense that the product, ebonite or hard rubber, is rigid and brittle. Heated with sulphur alone, rubber cures slowly; since the early twentieth century, accelerators, with zinc oxide and stearic acid as activators, have made it faster and more even.

How it is made

Goodyear said he found the effect when a mixture of rubber and sulphur touched a hot stove and charred without melting.

Rubber goods are made in factories, with heated presses, ventilated mixing rooms and fume extraction. Hot sulphur catches fire easily and burns to toxic sulphur dioxide, curing compounds give off irritating fumes, and modern accelerators irritate skin and lungs, so vulcanising is not a home process. The usual steps are these.

Tapping. A thin sliver of bark is shaved off in a sloping cut every second day or so, deep enough to open the latex vessels without reaching the cambium, the thin growing layer under the bark. The latex runs along the cut into a cup.

Coagulating. The latex is diluted and set with a weak acid such as formic or acetic acid; the rubber separates as a soft curd. It is pressed into sheets and dried, often in smoke, which also keeps mould away.

Mixing. The raw rubber is worked between heavy rolls until it softens, and the sulphur, fillers and accelerators are kneaded in.

Shaping and curing. The compound is moulded, extruded or spread on cloth, then heated in a press or a steam vessel until the bridges form.

A simple, qualitative comparison shows the change. Cut a rubber band open into a strip, and cut a strip of the same width, thickness and length from raw, unvulcanised crepe rubber sold for craft work (some crepe soles are vulcanised, so check the label). Hang the same small weight on each overnight, take it off and wait ten minutes: the band usually returns close to its length, while the raw strip tends to stay longer. Then leave both in a freezer for an hour, warm them in water at about 40 °C, and compare how stiff and how sticky they feel. Different products contain different fillers, so treat the result as a tendency.

> **Safety.** Do not heat sulphur or try to vulcanise rubber at home: the fumes are poisonous, and molten sulphur burns and can catch fire. In factories, mixing rolls can crush and drag in hands, and presses and steam vulcanisers are hot and under pressure, so they need guarded machines and trained operators. Natural rubber and latex cause allergies in some people: anyone with a latex allergy should not handle the samples, and others should wear nitrile gloves. Test the water temperature before putting your hands in it.

History and evolution

People in Mesoamerica were processing rubber by about 1600 BC. They mixed latex from Castilla elastica with juice pressed from a morning-glory vine, which made it more elastic, and made balls weighing up to 7 kg for a ritual ball game, as well as sandal soles and bindings. Spanish observers described rubber in the sixteenth century. In Europe and North America its use grew in the early nineteenth century, but goods made of raw rubber went soft in summer and cracked in winter.

In 1837 Thomas Hancock patented a machine to knead raw rubber, and in the 1830s several people found that sulphur made it less sticky. Charles Goodyear, a hardware merchant beset by debts, whose backing collapsed again in the panic of 1837, spent years trying treatments. In 1839, by his own account, a lump of rubber mixed with sulphur touched a hot stove and charred at the edge without melting. It took him about five years to make the process reliable. In Britain, Hancock was shown samples of the American sulphur-treated rubber in 1842 and worked out a process of his own. He filed a patent for vulcanising on 21 November 1843; Goodyear's US patent 3,633 followed on 15 June 1844. The name comes from Vulcan, the Roman god of fire, and was suggested by Hancock's friend William Brockedon. Goodyear spent years in patent lawsuits and died in 1860 without having profited from his discovery.

Demand for tyres, belts and insulation drove a rush for wild rubber in the Amazon basin. In 1876 Henry Wickham shipped about 70,000 Hevea seeds from Brazil to the Royal Botanic Gardens at Kew in London, and seedlings were sent on to British colonies in Asia. In 1900 Asian plantations produced about 4 tonnes, against about 27,000 tonnes gathered in the Amazon; by 1916 they supplied most of the world's rubber. Many synthetic rubbers made later from oil are vulcanised with sulphur in much the same way; others, such as neoprene, are cured with metal oxides.

Fruit, seeds and leaf of the Pará rubber tree: each capsule holds three seeds, like those Wickham shipped to Kew in 1876.

Key figures

Processed rubber in Mesoamerica
By about 1600 BC; balls for the ritual game weighed up to 7 kg

Rubber content of fresh latex
About 30 to 40%, the rest mostly water

Hancock's British patent
Filed 21 November 1843

Goodyear's US patent
No. 3,633, 15 June 1844

Hevea seeds shipped by Wickham
About 70,000, from Brazil to Kew in 1876

Sources

1. Charles Goodyear (Scientist of the Day) · Linda Hall Library https://www.lindahall.org/about/news/scientist-of-the-day/charles-goodyear/
2. Rubber processed in ancient Mesoamerica, MIT researchers find · MIT News https://news.mit.edu/1999/rubber-0714
3. Natural rubber · Transport Information Service (GDV) https://www.tis-gdv.de/tis_e/ware/kautschuk/naturkautschuk/naturkautschuk.htm
4. The seeds of discord · Revista Pesquisa FAPESP https://revistapesquisa.fapesp.br/en/the-seeds-of-discord/
5. Sulfur vulcanization · Wikipedia https://en.wikipedia.org/wiki/Sulfur_vulcanization
6. Thomas Hancock (inventor) · Wikipedia https://en.wikipedia.org/wiki/Thomas_Hancock_(inventor)
7. Hevea brasiliensis (rubber tree) fact sheet · EAFRINET, National Museums of Kenya and Lucidcentral https://keys.lucidcentral.org/keys/v3/eafrinet/weeds/key/weeds/Media/Html/Hevea_brasiliensis_%28Rubbertree%29.htm

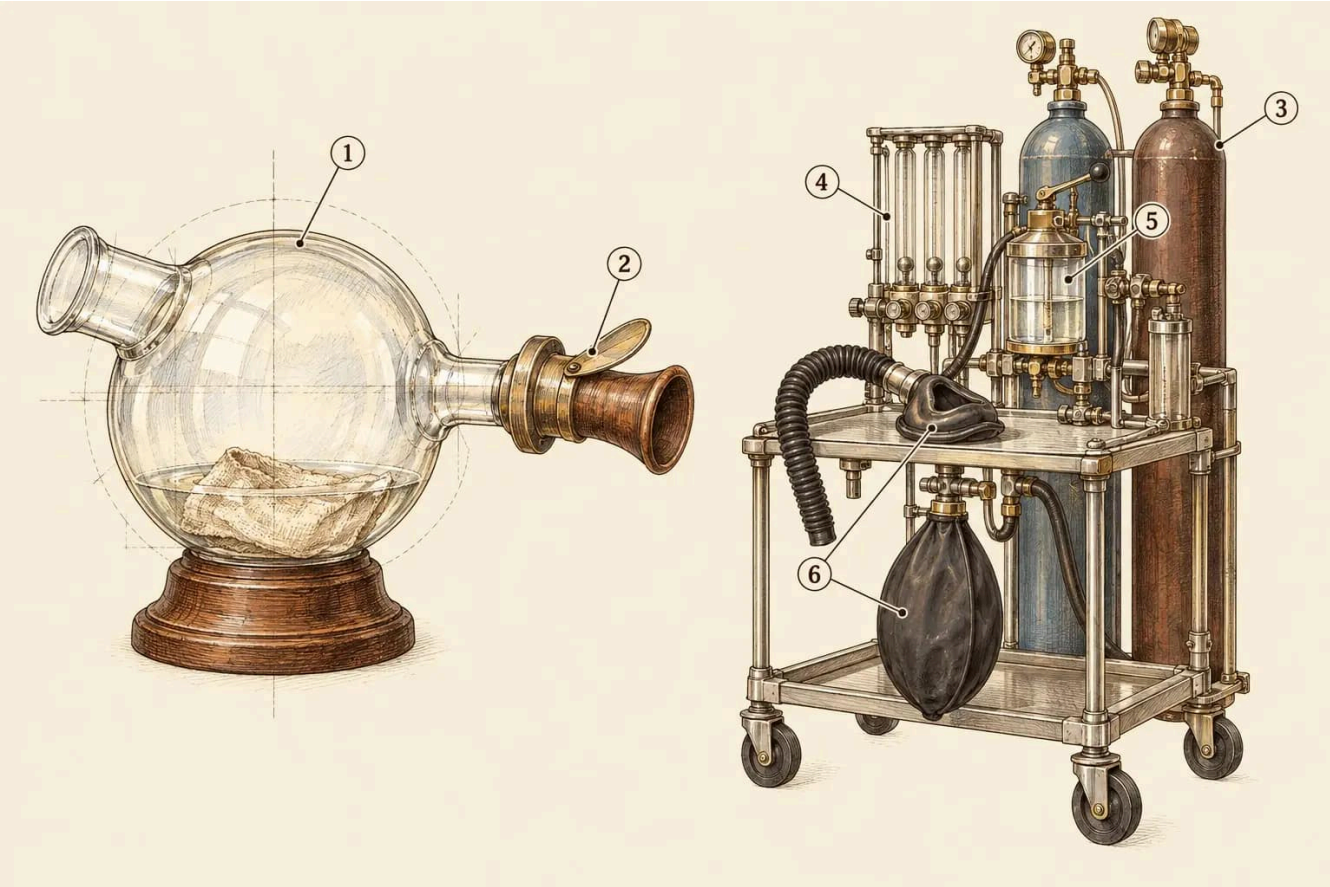
Fact-checked on 2026-10-12

Anaesthesia

Surgery without pain or awareness

1846 · Industrial age · Science & industry

Requires: Hygiene & Antisepsis (p. 290), Glass (p. 129)



1 Glass globe of Morton's ether inhaler 2 Mouthpiece and valve 3 Gas cylinders 4 Glass flowmeters 5 Vaporiser bottle 6 Reservoir bag and face mask

Anaesthesia is the medical practice of taking away pain, and often awareness, so that an operation can be done. Since a public demonstration with ether in Boston in 1846, trained anaesthetists, monitoring and oxygen have made it routine, and together with antisepsis it turned surgery from a last resort into ordinary care.

What it is

Anaesthesia removes pain, and in its general form awareness as well, so that a surgeon can operate. General anaesthesia is a controlled, reversible unconsciousness. Regional anaesthesia numbs a large part of the body, such as a limb or everything below the waist, while the patient stays awake. Local anaesthesia numbs a small area, enough to stitch a cut or treat a tooth.

The plate sets two machines side by side. On the left is the glass inhaler with which William Morton gave ether in Boston in 1846. On the right is an anaesthetic machine of the early twentieth century: cylinders of compressed gas,

glass flowmeters, a bottle where the gas picks up the vapour of a volatile agent, and a bag and mask through which the patient breathes.

How it works

General anaesthetics reach the brain through the blood, breathed in through the lungs or injected into a vein. Many of them strengthen the effect of GABA, the brain's main braking signal, so that nerve cells fire less. Consciousness fades and no memories are laid down. The details are still debated.

Depending on the drug and the patient, the depression also reaches the centres that keep the body running. Breathing can become shallow or stop. The throat muscles relax, so the tongue can fall back and block the airway. Coughing and swallowing reflexes weaken, and stomach contents can rise into the lungs. Blood pressure often drops. The anaesthetist therefore keeps the airway open, gives oxygen, often breathes for the patient through a tube or mask, and adjusts the drugs minute by minute.

Local anaesthetics act on the nerves themselves. A nerve signal is a wave of electrical change running along a fibre, carried by sodium ions rushing in through tiny channels in its membrane. The drug blocks these channels, so the wave dies where the drug lies and the brain hears nothing from beyond it. Placed around a nerve, it numbs whatever that nerve supplies; in the fluid around the spinal nerve roots, it numbs the lower half of the body. Heart and brain cells use the same kind of channel, so too much local anaesthetic in the blood can cause fits or stop the heart.

A nerve is a cable of thousands of fibres; a local anaesthetic silences each one it reaches.

How it is made safe

This section describes how hospitals organise anaesthesia, not a procedure to follow outside them.

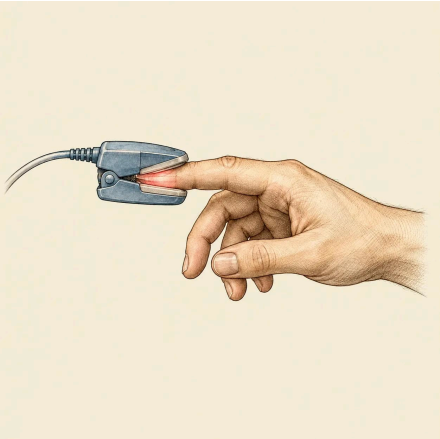
A trained team. Depending on the country, the anaesthetic is given by a doctor trained in it for years or by specialist nurses. They stay with the patient from the first drug until breathing and consciousness are safely back.

Assessment beforehand. The team asks about illnesses, medicines, allergies and earlier anaesthetics, examines the mouth, neck, heart and lungs, and chooses with the patient between general, regional and local anaesthesia.

An empty stomach. Before a planned operation, patients stop eating some hours ahead, often about six after a light meal, which lowers the risk of stomach contents reaching the lungs. The hospital sets the exact times for each patient.

Equipment checked before each case. Oxygen with a reserve cylinder, suction, devices to hold the airway open, a way to ventilate by hand if the machine fails, and resuscitation drugs. A field hospital uses simpler equipment, but cannot leave any of these out.

Monitoring throughout. A pulse oximeter shows the oxygen saturation of the blood. Other instruments track heart rhythm, blood pressure and the carbon dioxide in each breath out, which shows that air is really reaching the lungs. None of them replaces an anaesthetist watching the patient.



The probe shines red and infrared light through the finger and estimates what share of the haemoglobin is carrying oxygen.

The checklist. In 2008 the World Health Organization introduced a surgical safety checklist. The team pauses before the anaesthetic, to confirm the patient, the operation, allergies, a difficult airway and a working pulse oximeter, then again before the incision and before the patient leaves the theatre. In a study of eight hospitals, deaths after major surgery fell from 1.5% to 0.8%.

Recovery. Patients wake in a recovery room where nurses watch breathing, oxygen, pain and nausea. After a general anaesthetic, someone must take them home, and they should not drive for at least a day.

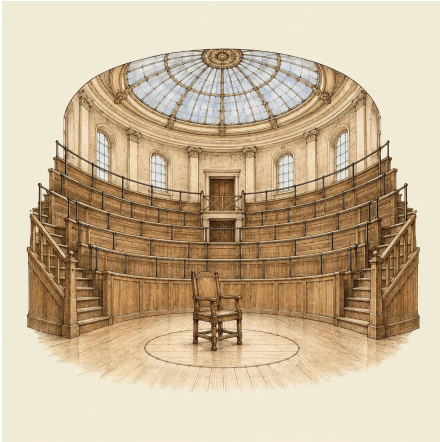
> **Safety.** Anaesthetic gases and drugs must never be used outside trained medical care. With many of these drugs, the dose that removes awareness is not far from one that stops breathing or abolishes the protective reflexes, and the gap varies between people and from minute to minute. Without someone trained to keep the airway open and give oxygen, and without monitoring and resuscitation equipment, an unconscious person can die within minutes. Breathing gases or solvents for their effect has killed many people, and ether is highly flammable. A person in severe pain or needing an operation should be taken to a hospital.

History and evolution

Before anaesthesia, surgeons relied on alcohol, opium and speed. On 13 October 1804, in Japan, Hanaoka Seishū removed a breast tumour from a woman who had swallowed his herbal mixture, but Japan was closed to the world and his work stayed unknown abroad.

In 1800 Humphry Davy suggested that nitrous oxide might be used in surgery. In December 1844 the dentist Horace Wells had a tooth pulled under the gas, but his demonstration in Boston in January 1845 failed when the patient cried out. In Georgia, Crawford Long had operated under ether on 30 March 1842, but published only in 1849.

The plate takes 16 October 1846 as its date. At Massachusetts General Hospital, Morton gave ether to Gilbert Abbott while the surgeon John Collins Warren removed a tumour from his neck. The news spread fast, and within months ether was in use in Europe. In Edinburgh, James Young Simpson tried chloroform on 4 November 1847; it acted faster and did not burn, but the margin between enough and too much was narrow. John Snow studied its doses and in 1853 gave it to Queen Victoria for the birth of Prince Leopold. Anaesthesia allowed longer operations, but wounds still festered until antisepsis arrived in the late 1860s.



Surgery was taught in steep amphitheatres like the one in Boston now called the Ether Dome.

In 1884 Carl Koller showed that cocaine numbed the eye, and in 1898 August Bier gave the first spinal anaesthetic in Kiel. Cocaine was toxic and addictive, so safer synthetic drugs followed: procaine in 1905, lidocaine in the 1940s. In the twentieth century intravenous drugs and muscle relaxants arrived and breathing tubes came into routine use, and pulse oximetry, described by Takuo Aoyagi in 1974, spread through operating theatres in the 1980s.

Key figures

Ether Day
16 October 1846, Massachusetts General Hospital, Boston

Hanaoka's operation
13 October 1804, Japan, under an anaesthetic taken by mouth

Cocaine on the eye
Koller's paper read at Heidelberg on 15 September 1884

Pulse oximetry
Principle described by Takuo Aoyagi in 1974

WHO surgical safety checklist
19 items; in eight trial hospitals deaths fell from 1.5% to 0.8% (2009)

Sources

1. Ether & Ether Dome History · Massachusetts General Hospital, Treadwell Virtual Library https://libguides.massgeneral.org/mghhistory/ether
2. Crawford Long (Scientist of the Day) · Linda Hall Library https://www.lindahall.org/about/news/scientist-of-the-day/crawford-long
3. The surprising and long story of the first use of ether in surgery · The Conversation https://theconversation.com/the-surprising-and-long-story-of-the-first-use-of-ether-in-surgery-113340
4. Horace Wells (1815–1848) and William TG Morton (1819–1868): pioneers in anaesthesiology · South African Dental Journal, vol. 75 no. 2 (2020) https://scielo.org.za/pdf/sadj/v75n2/11.pdf
5. Davy, Researches, chemical and philosophical, chiefly concerning nitrous oxide (1800) · Heirs of Hippocrates, University of Iowa Libraries https://heirs.lib.uiowa.edu/record.php?id=1338.5
6. History of the Japanese Society of Anesthesiologists · Japanese Society of Anesthesiologists https://anesth.or.jp/users/english/about_jsa/history
7. A great leap forward: James Young Simpson · Royal College of Surgeons of Edinburgh https://archiveandlibrary.rcsed.ac.uk/special-collections/the-battle-for-midwifery/a-great-leap-forward-james-young-simpson
8. John Snow: anesthesia · UCLA Fielding School of Public Health https://epi-snow.ph.ucla.edu/Stream4_Snowlife_d.html
9. Cocaine: what is the crack? A brief history of the use of cocaine as an anesthetic · PubMed Central https://pmc.ncbi.nlm.nih.gov/articles/PMC4335732/
10. Cocaine and self-experimentation · Association of Anaesthetists, Heritage Centre https://anaesthetists.org/Home/Heritage-centre/Learning/Heritage-Centre-blog-celebrating-75-years-of-Anaesthesia/Cocaine-and-Self-experimentation-a-blog-post-from-the-Heritage-Centre
11. Sodium channels and local anesthetics: old friends with new perspectives (Körner et al., 2022) · Frontiers in Pharmacology https://www.frontiersin.org/articles/10.3389/fphar.2022.837088/full
12. How general anesthetics work (Hibbs lab, Nature 2020) · UT Southwestern Medical Center https://www.utsouthwestern.edu/ctplus/stories/2020/general-anesthetics-benzos.html
13. General anaesthesia · NHS https://www.nhs.uk/conditions/general-anaesthesia/
14. Local anaesthesia · NHS https://www.nhs.uk/conditions/local-anaesthesia/
15. Pulse oximetry, Takuo Aoyagi memorial issue (Journal of Anesthesia, 2021) · PubMed Central https://pmc.ncbi.nlm.nih.gov/articles/PMC8327306/
16. Safe surgery: tools and resources · World Health Organization https://www.who.int/teams/integrated-health-services/patient-safety/research/safe-surgery/tool-and-resources
17. RCSI endorses the World Health Organisation's second Global Patient Safety Challenge (June 2008) · RCSI University of Medicine and Health Sciences https://www.rcsi.com/dublin/news-and-events/news/news-article/2008/06/rcsi-endorses-the-world-health-organisations-second-global-patient-safety-challenge
18. Implementation manual: WHO surgical safety checklist 2009 · World Health Organization https://www.who.int/publications/i/item/9789241598590
19. Simple surgical checklist cuts deaths 40 percent · Harvard Medical School https://hms.harvard.edu/news/simple-surgical-checklist-cuts-deaths-40-percent

Fact-checked on 2026-10-14

Hygiene & Antisepsis

Stopping the spread of germs

1847 · Industrial age · Science & industry

Requires: Soap (p. 90), Microscope (p. 209), Drinking Water (p. 34), Distillation (p. 169)

Leads to: Anaesthesia (p. 286), Penicillin (p. 342)

1 Washbasin and jug 2 Boiler of the carbolic spray 3 Nozzle and carbolic mist 4 Bolted lid, gauge and safety valve 5 Basket of instruments in the steam 6 Burner under the autoclave

Hygiene and antisepsis cut the routes that germs take from one person to the next: hands, instruments, dressings and water. Washing with soap, keeping water apart from sewage, chemicals that kill germs on wounds and heat that sterilises tools made childbirth and surgery far safer in the second half of the nineteenth century.

What it is

Germs pass between people along routes nobody sees: a hand that touched a sick patient and then a wound, a knife wiped on an apron, water drawn downstream of a latrine. Hygiene and antisepsis are the habits and tools that cut these routes. Soap and water remove germs. Heat and certain chemicals kill them. Asepsis, in the surgeon's sense, keeps them away from a wound from the start.

The plate shows three stages of this idea: the washbasin set at the door of a Vienna maternity ward in 1847, the carbolic acid spray Joseph Lister used in the 1870s, and the steam autoclave that, from the 1880s, sterilised

instruments and dressings by heat instead of chemicals.

How it works

Bacteria are single cells a few thousandths of a millimetre long; viruses are far smaller and multiply only inside living cells. Both ride on skin, droplets, dust, food, water or tools, and faeces carry them in vast numbers. An infection needs a source, a carrier and a way in, such as the mouth or a break in the skin. Washing hands between one patient and the next takes away the carrier, and the germ goes no further.

Soap works mostly by carrying microbes away. One end of each soap molecule holds on to water and the other to grease, so it lifts the oily film of the skin, with the microbes caught in it, into the rinse. It also breaks open viruses wrapped in a fatty envelope, such as the flu virus.

Rubbing with the fingers interlaced reaches the skin between them, one of the places most often missed.

Heat kills by unfolding a microbe's proteins for good, the way it sets egg white. A rolling boil kills ordinary bacteria, viruses and parasites. Some bacteria, among them the agents of tetanus and botulism, can shut down into spores whose tough coats survive boiling. Steam under pressure in an autoclave, held at 121 °C or more for long enough and reaching every surface of the load, kills these too: that is sterilisation in the strict sense.

Antiseptics are chemicals used on living tissue; disinfectants are used on objects. Alcohol unfolds proteins, which is why hand rubs contain at least 60% of it. Chlorine compounds, like the chlorinated lime used in Vienna or household bleach, oxidise whatever part of the cell they touch. Lister's carbolic acid killed germs but also damaged patients' tissue and surgeons' hands, and was dropped. Dirt and blood shield germs from all these chemicals, so cleaning comes first.

How to build

These are everyday habits recommended by public-health bodies, not medical procedures.

Wash your hands properly. Wet them with clean running or poured water and lather with soap. Rub palm to palm, each palm over the back of the other hand with fingers interlaced, palm to palm again with fingers interlaced, the backs of the fingers, each thumb turned inside the other palm, and the fingertips into the palm. The WHO sequence takes 40 to 60 seconds; the CDC asks for at least 20 seconds of scrubbing. Rinse and dry on a clean towel or in the air.

Know when to wash. After the toilet or a nappy change, before cooking and eating, before and after tending a sick person or a wound, and after touching animals or rubbish.

Keep water and waste apart. Dig latrines downhill of any well or spring and at least 30 m from it, further in gravel or fissured rock, with the bottom of the pit at least 1.5 m above the highest water table of the rainy season. These distances are a starting point: ask the local health or water service to check the ground and the way the groundwater flows.

Boil tools and cloths. Wash scissors, tweezers and cloths with soap first, since heat penetrates dried blood and grease badly. Cover them with water in a lidded pot, bring it to a full boil and count 20 minutes from then without adding anything. Let it cool, lift the items out with tongs boiled at the same time and put them straight into a

Count the twenty minutes from the moment the water boils hard, and add nothing after that.

boiled container with a lid. They will do for removing a splinter or cutting a dressing. Boiling disinfects but does not sterilise: needles and anything that enters the body must come sterile and sealed from a pharmacy or clinic.

Clean a small cut. Wash your hands, then rinse the cut under clean tap water or cooled boiled water until no dirt remains, and wash the skin around it with soap. Pat it dry and cover it with a sterile dressing or plaster from a pharmacy.

> **Safety.** Do not make antiseptics or disinfectants at home, and never mix cleaning products: bleach with acids or ammonia releases toxic gas. Nothing here is to be swallowed or injected. Boiling water and steam scald, so keep children away from the pot. Call emergency services for bleeding that will not stop or a very deep cut. Get medical care quickly for a gaping or long cut, a burn, any bite from an animal or a person, or a wound with soil in it, and if a wound becomes red, swollen or more painful, oozes pus or comes with fever. A tetanus injection may be needed.

History and evolution

At the Vienna maternity hospital, the clinic where medical students trained lost about one mother in ten to childbed fever, the midwives' clinic about one in thirty. In March 1847 Jakob Kolletschka, a colleague of the young doctor Ignaz Semmelweis, died of a cut received during an autopsy, with the same signs as the women. Semmelweis concluded that students carried "cadaveric particles" from the autopsy room to the labour ward. From May 1847, the date this plate takes as its start, he had them wash in chlorinated lime solution, and in 1848 deaths in his clinic fell to 1.27%. Many colleagues rejected his explanation.

In 1854 John Snow tied a London cholera outbreak to one street pump. At the Scutari army hospital, where Florence Nightingale nursed, deaths among admitted soldiers reached 42% in February 1855, then fell once the sewers were repaired and the wards aired.

In the early 1860s Louis Pasteur showed that boiled broth in a flask with a long bent neck stayed clear, while broth open to falling dust spoiled: living germs caused decay. In Glasgow, Joseph Lister reasoned that germs also made wounds fester. In August 1865 he dressed a boy's open leg fracture with carbolic acid, and it healed cleanly; he published the method in 1867. Among his amputations, deaths fell from 16 in 35 to 6 in 40, numbers he admitted were small.

Pasteur's swan-neck flask: dust caught in the bend never reached the broth, which stayed clear.

Charles Chamberland, Pasteur's assistant, designed a steam steriliser in 1879, and in 1886 Ernst von Bergmann in Berlin switched to steam-sterilised dressings. Surgeons now kept germs out of the wound with sterilised instruments, gowns and, from the 1890s, rubber gloves. The WHO's 2009 hand hygiene guidelines name five moments when a carer must clean their hands.

Key figures

Handwashing in Vienna

From May 1847; deaths in the doctors' clinic fell from about 10% (1840–1846) to 1.27% in 1848

Lister's amputations

16 deaths in 35 cases before antisepsis, 6 in 40 after

Hand hygiene (WHO)

40–60 s with soap and water, 20–30 s with an alcohol hand rub

Steam sterilisation (CDC)

Wrapped items: 121 °C for at least 30 min in a gravity-displacement steriliser, or 132 °C for 4 min in a pre-vacuum one

Boiling tools

20 min at a full boil disinfects them but does not reliably kill bacterial spores

Sources

1. Ignaz Phillip Semmelweis' studies of death in childbirth (I. Loudon, Journal of the Royal Society of Medicine, 2013) · PubMed Central https://pmc.ncbi.nlm.nih.gov/articles/PMC3807776
2. Pioneering Hand Hygiene: Ignaz Semmelweis and the Fight Against Puerperal Fever (Cureus, 2024) · PubMed Central https://pmc.ncbi.nlm.nih.gov/articles/PMC11568873/
3. Joseph Lister (1827-1912): A Pioneer of Antiseptic Surgery (Cureus, 2022) · PubMed Central https://pmc.ncbi.nlm.nih.gov/articles/PMC9854334/
4. Statistics and the British controversy about the effects of Joseph Lister's system of antisepsis for surgery, 1867-1890 (U. Tröhler) · James Lind Library https://www.jameslindlibrary.org/articles/statistics-and-the-british-controversy-about-the-effects-of-joseph-listers-system-of-antisepsis-for-surgery-1867-1890/
5. Charles Chamberland, l'inventeur d'outils de stérilisation · Institut Pasteur https://www.pasteur.fr/fr/institut-pasteur/notre-histoire/charles-chamberland-inventeur-outils-sterilisation
6. Bergmann, Ernst von · Deutsche Biographie https://www.deutsche-biographie.de/pnd118656104.html
7. Florence Nightingale: the Lady with the Lamp · National Army Museum https://www.nam.ac.uk/explore/florence-nightingale-lady-lamp
8. John Snow, cholera and the Broad Street pump · London Museum https://www.londonmuseum.org.uk/collections/london-stories/john-snow-cholera-broad-street-pump/
9. Hand Hygiene: Why, How & When? · World Health Organization https://www.afro.who.int/sites/default/files/2017-06/Hand_Hygiene_Why_How_and_When_Brochure.pdf
10. About handwashing · Centers for Disease Control and Prevention https://www.cdc.gov/clean-hands/about/index.html
11. Handwashing facts · Centers for Disease Control and Prevention https://www.cdc.gov/clean-hands/data-research/facts-stats
12. Steam sterilization · Centers for Disease Control and Prevention https://www.cdc.gov/infection-control/hcp/disinfection-sterilization/steam-sterilization.html
13. Clostridium botulinum · AGES, Austrian Agency for Health and Food Safety https://www.ages.at/en/human/disease/pathogens-from-a-to-z/clostridium-botulinum
14. A Community Guide to Environmental Health: Disinfecting with heat · Hesperian Health Guides https://en.hesperian.org/hhg/A_Community_Guide_to_Environmental_Health:Disinfecting_with_Heat
15. Excreta, pit for stools and vomit · Médecins Sans Frontières https://medicalguidelines.msf.org/en/viewport/CHOL/english/appendix-14-excreta-pit-stools-and-vomit-32409860.html
16. Cuts and grazes · NHS https://www.nhs.uk/conditions/cuts-and-grazes/

Fact-checked on 2026-10-14

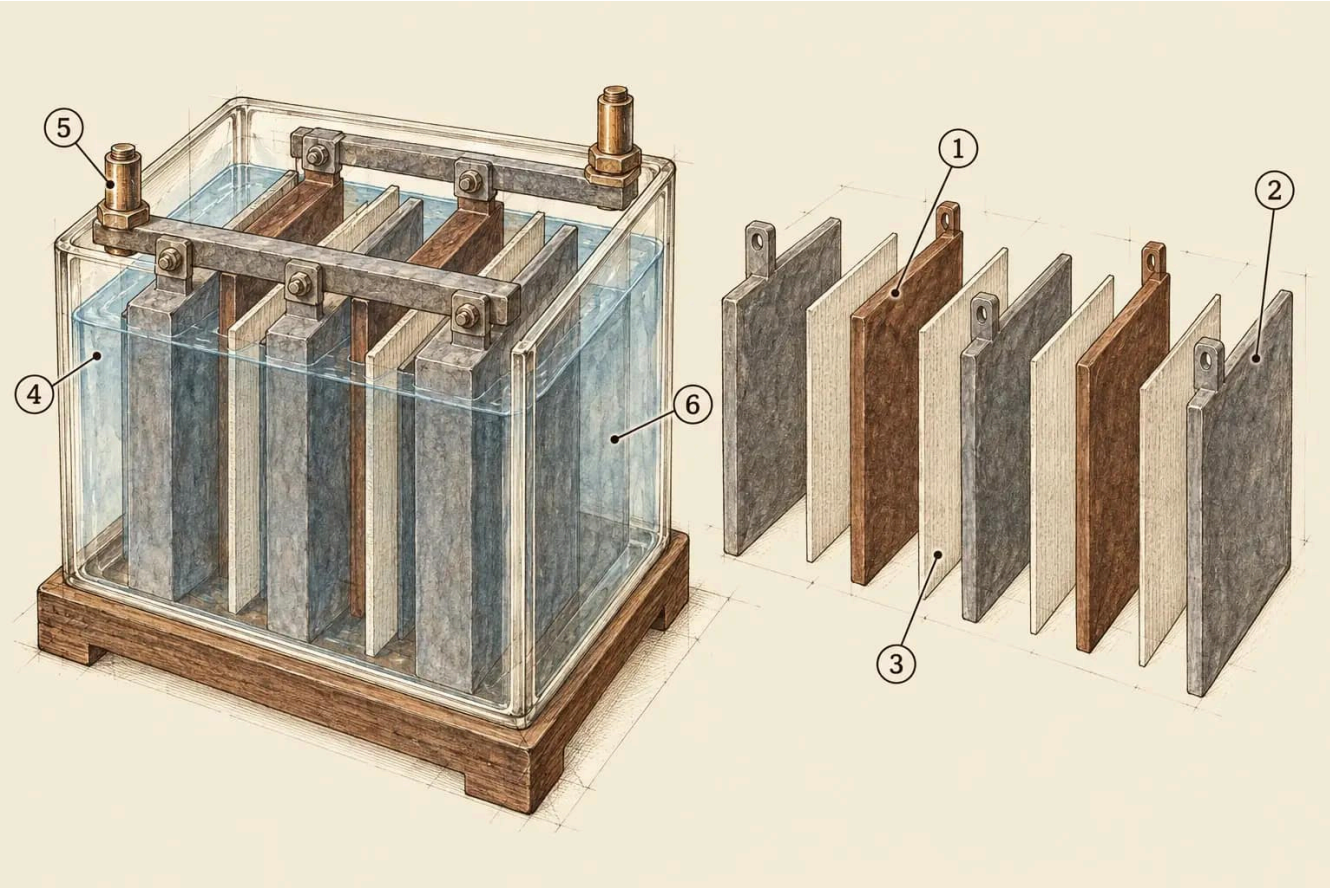
Lead-Acid Battery

Electricity kept in lead and acid

1859 · Industrial age · Science & industry

Requires: Battery (p. 234), Electric Generator (p. 266)

Leads to: Wind Turbine (p. 326)



1 Positive plate (lead dioxide) 2 Negative plate (spongy lead) 3 Separator 4 Electrolyte (dilute sulfuric acid) 5 Lead strap and terminal post 6 Glass jar

A lead-acid battery stores electricity in plates of lead and lead dioxide standing in dilute sulfuric acid, gives it back as current, and can be recharged hundreds of times. Gaston Planté built the first cell in 1859; with Camille Faure's pasted plates of 1881 it became an industrial product, and it still starts most of the world's cars.

What it is

A lead-acid battery stores electricity as chemistry and gives it back as current, hundreds of times over. Each cell holds lead plates in dilute sulfuric acid and gives about two volts. A car battery is six cells in one case, connected in series for twelve volts.

The French physicist Gaston Planté built the first rechargeable cell in 1859: it could be charged again by sending current back through it. In 1881 Camille Faure changed the way the plates were prepared, coating them with lead oxide, so that cells were ready sooner and could be made in factories. The reaction inside is the one Planté used.

How it works

The positive plates (1) carry lead dioxide, a dark brown powder. The negative plates (2) carry spongy grey lead, full of pores so the acid reaches as much metal as possible. Separators (3) keep them apart, and the electrolyte (4), sulfuric acid diluted in water, fills every gap.

A pasted plate: lead oxide paste pressed into a cast lead grid, which holds it in place.

During discharge the lead and lead dioxide on the plates react with the acid and turn into lead sulfate, while the lead grids carry the current. Electrons leave the negative plate and reach the positive one through the outside circuit, running the lamp or motor on the way. The reaction consumes acid and makes water, so the electrolyte thins as the cell empties: in a starter battery its specific gravity (density relative to water) falls from about 1.265 to about 1.12.

Charging runs the reaction backwards. Current from a generator, a solar panel or a mains charger turns the sulfate back into lead and lead dioxide, and the acid returns to the liquid. Near the end, little sulfate is left and part of the current splits water instead: hydrogen bubbles off the negative plates, oxygen off the positive ones. This gassing is why flooded cells lose water and charging rooms need fresh air.

Capacity is counted in ampere-hours (Ah): a 60 Ah battery supplies 3 A for about 20 hours, the usual rating period, and less if drained faster. Sulfate left on a discharged plate for weeks can grow into hard crystals that ordinary charging may not reverse, and deep discharges wear out the active material. In one Battery University comparison, a starter battery fully emptied each time lasted 12 to 15 cycles, against 130 to 150 when only 30% of its charge was used.

How to build

Making cells means handling molten lead and strong acid, so this section covers choosing, charging and looking after a bought battery.

Size it for the load. A cabin runs three 5 W LED lamps for five hours and a 10 W radio for three hours each day: 75 + 30 = 105 watt-hours, about 9 Ah at 12 V. Allow two days without charging (18 Ah) and use no more than half the capacity: you need at least 36 Ah. Choose a 40 to 50 Ah deep-cycle battery: cold also cuts capacity.

Charge at the right voltage. Use a charger made for that battery's voltage and type (flooded, AGM or gel) and follow the maker's charging profile. At about 25 °C a 12 V flooded battery is typically charged up to between 13.8 and 14.7 V, depending on the model, then held at about 13.5 V; good chargers adjust the charging voltage to the battery's temperature. With a solar panel, put a charge controller between panel and battery. Whatever the charging source, fit a fuse sized for the cable close to the battery's positive terminal, and protect each circuit that feeds a load. Recharge soon after use; never charge a frozen battery.

Check the state of charge. Let the disconnected battery rest at least four hours, ideally a day, then measure across the terminals. As an example, one starter battery at 26 °C after a day's rest reads about 12.65 V when full and about 11.9 V when flat; every model differs, so use the maker's table. With flooded cells, a hydrometer reads each cell: on that same battery, about 1.265 when full and about 1.12 when flat.

Top up with distilled water only. Add distilled water to the mark after charging, once the battery has cooled; if the plates are uncovered before charging, add just enough to cover them first. Never add acid. Sealed AGM and gel batteries need no water.

Squeeze the bulb, draw acid from a cell and see how high the float rides: the denser the acid, the fuller the cell.

Clean, store, recycle. Brush terminal crust off with baking soda in water, keeping it out of the cells, then dry and grease the posts. Store a battery charged, cool and dry; check its voltage every month or so and recharge it before it falls below about 12.3 V, or the maker's threshold, and at least every six months. Take a dead one back to a dealer or a collection point.

> **Safety.** Battery acid burns skin and eyes: wear goggles and acid-resistant gloves, and after a splash rinse with running water for at least 30 minutes and get medical help. Charging releases hydrogen, which a spark or flame can ignite: charge in a ventilated place, never smoke nearby, and switch the charger off before fitting or removing its clips. In a car, disconnect the cable bolted to the bodywork first (on almost every car the negative) and reconnect it last. A short circuit drives hundreds of amperes and can melt a spanner: use insulated tools and take off rings and watches. A car battery can weigh 15 kg or more: keep it upright and lift with your legs. Lead is toxic: wash your hands after handling, never burn a battery or break its case open (on a flooded battery, remove only the filler caps), and keep batteries away from children.

History and evolution

Planté showed his cells to the French Academy of Sciences in 1860: lead sheets separated by rubber strips in dilute acid, formed by reversing the current again and again until their surfaces turned porous.

While charging meant using up primary cells, the batteries stayed in laboratories; dynamos changed that in the 1870s. Faure's paste replaced months of forming with one charge of about sixty hours. Power stations of the 1880s and 1890s kept banks of cells across their mains to take the evening peak. From about 1893 telephone exchanges fed subscribers' lines from a central battery.

Racks of glass cells kept lighting stations and telephone exchanges going through peaks and breakdowns.

Around 1900 electric cars, most on lead-acid batteries, made up about a third of the vehicles on American roads. Charles Kettering's electric starter, fitted to the 1912 Cadillac, did away with the hand crank; as it spread to other makes, the starting battery became standard equipment. In the United States about 99% of lead batteries are recycled, and new ones contain more than 80% recycled material.

Key figures

Voltage of one cell

About 2.1 V at rest when fully charged; six cells in series make a 12 V battery

Charging voltage

2.30–2.45 V per cell, then about 2.25 V per cell to hold it full

Acid specific gravity

About 1.265 when charged, about 1.12 when discharged (starter battery, after a 24-hour rest)

Recycling

99% of lead batteries recycled in the United States (industry study, data to 2018)

Sources

1. Accumulator (1911 Encyclopædia Britannica) · Encyclopædia Britannica, 11th edition, via Wikisource https://en.wikisource.org/wiki/1911_Encyclop%C3%A6dia_Britannica/Accumulator
2. One of the First Rechargeable Batteries, about 1860 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co36401/one-of-the-first-rechargeable-batteries-about-1860-lead-acid-rechargeable-batteries
3. Planté Battery – 1859 · National High Magnetic Field Laboratory https://nationalmaglab.org/magnet-academy/history-of-electricity-magnetism/museum/plante-battery-1859/
4. BU-201: How does the Lead Acid Battery Work? · Battery University (Cadex Electronics) https://batteryuniversity.com/article/bu-201-how-does-the-lead-acid-battery-work
5. BU-403: Charging Lead Acid · Battery University (Cadex Electronics) https://batteryuniversity.com/article/bu-403-charging-lead-acid
6. BU-903: How to Measure State-of-charge · Battery University (Cadex Electronics) https://batteryuniversity.com/article/bu-903-how-to-measure-state-of-charge
7. BU-804b: Sulfation and How to Prevent it · Battery University (Cadex Electronics) https://batteryuniversity.com/article/bu-804b-sulfation-and-how-to-prevent-it
8. Battery Charging – Industrial Lead-Acid Batteries · Canadian Centre for Occupational Health and Safety https://ccohs.ca/oshanswers/safety_haz/battery-charging.html
9. Charging safely · Safety+Health, National Safety Council (NIOSH advice) https://www.safetyandhealthmagazine.com/articles/charging-safely-2
10. Lead Battery Industry Issues New National Recycling Rate Study · Battery Council International https://batterycouncil.org/news/lead-battery-industry-issues-new-national-recycling-rate-study/
11. The History of the Electric Car · U.S. Department of Energy https://www.energy.gov/articles/history-electric-car
12. Switches, PBXs and Central Offices, chapter 12: power plants · TelephoneTribute.com https://www.telephonetribute.com/switches_survey_chapter_12.html
13. Lead poisoning and health · World Health Organization https://www.who.int/news-room/fact-sheets/detail/lead-poisoning-and-health
14. Lead–acid battery · Wikipedia https://en.wikipedia.org/wiki/Lead%E2%80%93acid_battery

Fact-checked on 2026-10-14

V

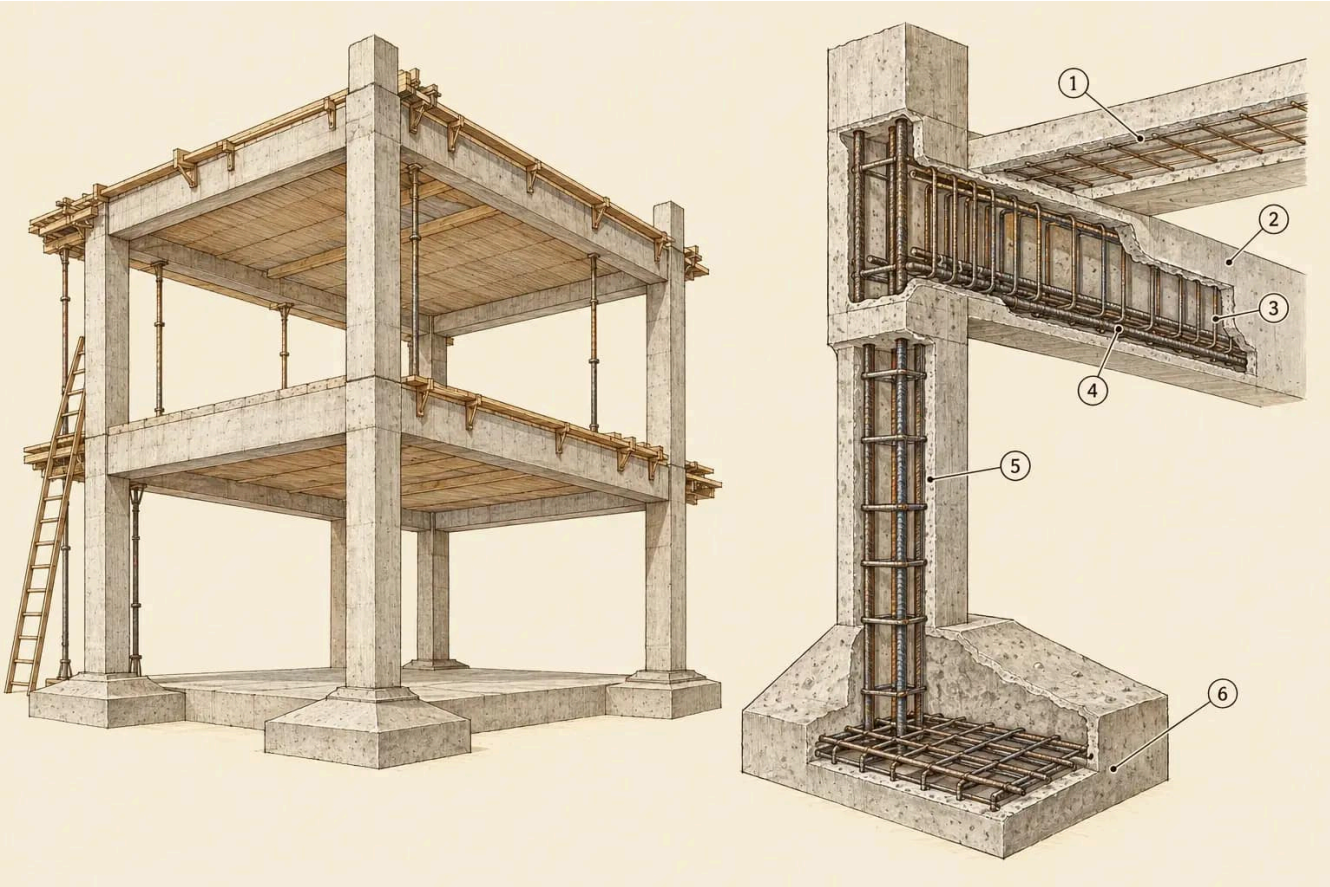
Electric age

Reinforced Concrete

Steel for tension, concrete for compression

c. 1848 · Industrial age · Electric age

Requires: Portland Cement (p. 250), Steel (p. 137)



1 Floor slab 2 Beam 3 Stirrups 4 Main bars along the stretched face 5 Column with ties 6 Footing

Reinforced concrete is concrete with steel bars cast inside it, placed where the member will be stretched. The concrete takes the squeezing and the steel the pulling, so a flat beam or slab can span an opening where plain concrete or stone would crack.

What it is

Concrete resists crushing well and pulling badly: its tensile strength is about a tenth of its compressive strength. A plain concrete beam, like a stone lintel, cracks along its stretched underside under a modest load. That is why Roman builders spanned with arches, vaults and domes, shapes that work almost entirely in compression.

Reinforced concrete puts steel where the stretching happens. Bars near the bottom of a beam take the tension and the concrete above them the compression. It is cast as slabs, beams, columns, footings, walls, tanks and bridges.

How it works

A loaded beam sags: its top shortens, its underside lengthens and opens in hairline cracks, and from then on the bottom bars carry the pull. Over the inner supports of a continuous beam, and in a cantilever, the stretched face is

on top, so the main bars go on top there. A slab resting on all four sides bends both ways and gets a mesh; one spanning a single way still gets lighter bars across, against shrinkage cracks. Near the supports a beam also tends to crack on a slant; closed loops of thinner bar, the stirrups, cross those cracks and are set closer together there. Columns are mostly squeezed, and ties around their vertical bars stop them from bulging outward.

The pairing works for three reasons. Steel and concrete expand with heat by almost the same amount, about 10 to 12 millionths per degree Celsius. The ribs rolled onto modern bars lock into the concrete and pass the force from one to the other. And the water in concrete's pores is strongly alkaline, around pH 12.5 to 13, which covers the steel with a thin oxide film that stops rust.

That protection lasts as long as the cover, the concrete outside the bars. Carbon dioxide from the air slowly neutralises it by carbonation, and sea salt or de-icing salt brings in chlorides. Once enough of either reaches the steel, with moisture and oxygen present, the bar rusts. Rust takes up several times the volume of the steel it replaces, so it cracks the cover and pushes it off in flakes. This spalling starts where the cover is thin or porous. The American code ACI 318 asks for about 38 mm of cover over small bars outdoors and 75 mm where concrete is cast against soil.

Rust swells as it forms and pushes off the thin concrete over the bar.

Prestressed concrete goes further: stretched high-strength wires, anchored to the concrete, squeeze the member in advance, so under load its bottom sees little or no tension and longer, thinner beams become possible.

How to build

This is a small precast lintel for an opening of up to 0.9 m in a low garden wall, under no more than a few courses of blocks and no floor or roof. Anything that carries people or part of a building, a house lintel included, or any lintel whose fall could hurt someone, must be designed by an engineer under local codes, or bought as a certified product.

Make the mould. On level ground, screw boards into an open box 1.2 m long with an inside section of 150 × 150 mm, so that the lintel bears 150 mm at each end. Oil the inner faces and stake the sides so wet concrete cannot push them out.

The bars sit on spacers, so concrete flows under them and covers them.

Place the steel. Cut two 10 mm ribbed bars to 1.1 m, leaving 50 mm of concrete at each end. Stand them on 40 mm plastic spacers, or chairs, 40 mm in from the sides, and wire them down so they cannot shift. Use whole bars. In larger work, bars are joined by overlapping them over a length the design sets, at least 500 mm in Australian house slabs.

Fill, compact and cure. Mix concrete as for Portland cement, with gravel no larger than 10 mm. Fill in two layers, rod each one around the steel and tap the boards to drive out air. Scratch an arrow on the top face: laid upside down, the lintel would have its steel in the squeezed face. Keep it damp under plastic for at least 7 days, longer in cool weather.

Set it in place. The lintel weighs about 65 kg: move it with two people at ground level, or with a lifting aid above waist height, and lay it on a bed of mortar, steel side down. Build on it only after about 28 days, when concrete is close to its design strength.

See the tension at work. Cast three mortar bars 50 × 50 × 500 mm, one plain and two with a 4 mm wire 15 mm above one face. After a week, lay each across two bricks 400 mm apart on the ground, set a short board across its middle and stack bricks on the board one at a time. The plain bar snaps suddenly; the one with its wire at the bottom cracks, sags and holds much more; tested wire side up, the third breaks almost like the plain one.

> **Safety.** Wet cement is strongly alkaline and burns skin it is trapped against: wear waterproof gloves, long sleeves and eye protection, and wash off splashes. Cut steel with bolt cutters or an angle grinder only with eye protection and gloves, away from anything that can burn. Brace every mould; formwork that holds concrete overhead is work for professionals, because it can collapse under the pour. During the load test, wear eye protection, stand to the side and keep your feet clear of the load.

History and evolution

In 1848 Joseph-Louis Lambot floated a boat of cement over iron mesh on the pond of his estate in the Var. He patented it in 1855 and showed a second boat in Paris that year; the first is kept at the museum in Brignoles. This plate keeps 1848, the date of this boat, an early surviving example of iron and cement working together. In 1854 William Boutland Wilkinson of Newcastle patented iron-reinforced floors.

Lambot's boat: a thin shell of cement over a grid of iron rods.

Joseph Monier, a Paris gardener, patented reinforced tubs and tanks on 16 July 1867, then bridges in 1873 and beams in 1878. In Germany, Gustav Adolf Wayss bought his patents and built more than 300 arched bridges between 1887 and 1891. In 1892 François Hennebique patented a complete frame of columns, beams and slabs, built by licensed contractors. In the United States Ernest Ransome patented a twisted bar in 1884, and the Ingalls Building in Cincinnati rose 16 storeys in 1903.

Robert Maillart's Salginatobel bridge (1930) crosses a Swiss gorge with a hollow arch of 90 m, only 20 cm thick at the crown. Eugène Freyssinet patented prestressing in 1928, and in 1934 used it to save the sinking maritime station at Le Havre.

A 2018 Chatham House report puts world cement production at more than 4 billion tonnes a year, most of it for concrete, and its share of global CO_2 emissions at about 8%.

Key figures

Concrete in tension
About 10% of its compressive strength

Pore water around the bars
pH 12.5 to 13, which keeps steel from rusting

Early landmarks
Lambot's boat, 1848; Monier's first patent, 16 July 1867

Thermal expansion
About 10 millionths per °C for concrete, 11 to 12 for steel

Minimum cover (ACI 318)
About 38 mm on small bars outdoors, 75 mm against soil

Sources

1. Joseph Monier et l'invention du béton armé (B. Lemoine, 2023) · Association française de génie civil (AFGC) https://www.afgc.asso.fr/app/uploads/2026/03/JosephMONIER_InventionBeton.pdf
2. The Construction Industry enters the 20th Century (R. Day, 1980) · Bristol Industrial Archaeological Society Journal 13 https://b-i-a-s.org.uk/wp-content/uploads/2021/01/BIAS_Journal_13_FERRO_CONCRETE.pdf
3. The Invention of Reinforced Concrete (1848–1906) (Moussard, Garibaldi & Curbach, 2018) · TU Dresden, in High Tech Concrete (Springer) https://fis.tu-dresden.de/portal/en/publications/the-invention-of-reinforced-concrete-1848--1906(8f5281e9-99eb-4cdd-9eff-3687b595367f).html
4. Maison de Joseph Lambot à Montfort-sur-Argens · Office de tourisme Provence Verte & Verdon https://www.la-provence-verte.net/ot_campslasource/patrimoine-montfort-sur-argens-maison-de-joseph-lambot_1679.html
5. Musée des Comtes de Provence, Brignoles · Office de tourisme Provence Verte & Verdon https://www.la-provence-verte.net/activites/patrimoine-brignoles-musee-des-comtes-de-provence_435.html
6. Why is reinforced concrete used? · American Concrete Institute https://www.concrete.org/frequentlyaskedquestions.aspx?faqid=666
7. Concrete cover for members cast against earth (ACI 318-19) · American Concrete Institute https://www.concrete.org/frequentlyaskedquestions.aspx?faqid=903
8. Beam reinforcement detailing per ACI 318-19 (cover table) · ideCAD documentation https://help.idecad.com/ideCAD/beam-reinforcement-detailing
9. What stops the reinforcing steel in damp, porous concrete from corroding (usually)? (J. Broomfield) · Institute of Corrosion https://www.icorr.org/?p=22054
10. Thermal expansion and contraction of concrete · Penn State College of Engineering https://www.engr.psu.edu/ce/courses/ce584/concrete/library/cracking/thermalexpansioncontraction/example.htm
11. Principles of reinforced concrete: objective of the steel-concrete combination (W. Pauchet, 2021) · Techniques de l'Ingénieur https://www.techniques-ingenieur.fr/en/resources/article/ti264/principles-of-reinforced-concrete-tba1024/objective-of-the-steel-concrete-combination-2
12. Properties of concrete · University of Memphis, Civil Engineering https://www.ce.memphis.edu/1101/notes/concrete/section_3_properties.html
13. Concrete slab reinforcement: lapping · RMIT University Learning Lab https://learninglab.rmit.edu.au/Toolbox/buildright/content/bcgbc4010a/10_floor_systems/03_concrete_slab_reinforcement/page_006.htm
14. Ingalls Building · American Society of Civil Engineers https://asce.org/about-civil-engineering/history-and-heritage/historic-landmarks/ingalls-building
15. Alvord Lake Bridge · American Society of Civil Engineers https://www.asce.org/about-civil-engineering/history-and-heritage/historic-landmarks/alvord-lake-bridge
16. Salginatobel Bridge · American Society of Civil Engineers https://www.asce.org/about-civil-engineering/history-and-heritage/historic-landmarks/salginatobel-bridge
17. World Monument Salginatobel Bridge, technical profile · Schiers Tourism https://www.salginatobelbridge.com/s/English_Flyer.pdf
18. The Story of Eugène Freyssinet (K. Shushkewich, 2010) · ASPIRE, The Concrete Bridge Magazine https://www.aspirebridge.com/magazine/2010Fall/Perspective_Fall10.pdf
19. Making Concrete Change: Innovation in Low-carbon Cement and Concrete (Lehne & Preston, 2018) · Chatham House https://www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf
20. Cement · Health and Safety Executive https://www.hse.gov.uk/construction/healthrisks/hazardous-substances/cement.htm

Fact-checked on 2026-10-14

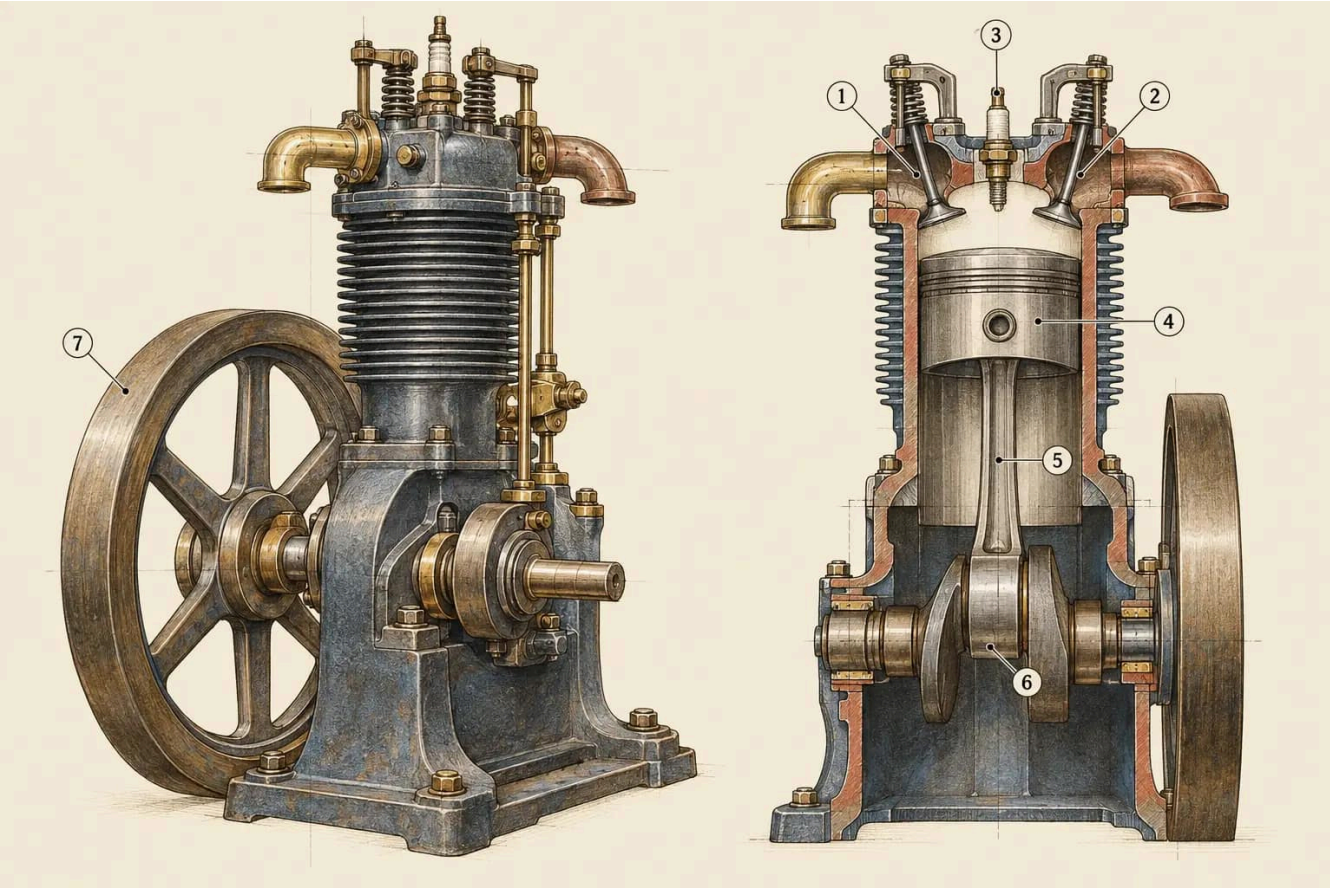
Internal Combustion Engine

Small explosions, steady power

1876 · Electric age · Electric age

Requires: Steam Engine (p. 221), Iron Smelting (p. 133), Steel (p. 137), Distillation (p. 169)

Leads to: Aeroplane (p. 338)



1 Intake valve 2 Exhaust valve 3 Spark plug 4 Piston 5 Connecting rod 6 Crankshaft 7 Flywheel

An internal combustion engine burns fuel inside a closed cylinder and lets the hot gas push a piston, which turns a crankshaft. Nicolaus Otto's four-stroke gas engine of 1876 set the pattern still used in most car, boat and generator engines.

What it is

An internal combustion engine makes heat inside the machine itself. A steam engine burns its fuel under a separate boiler and sends steam to the cylinder. Here a small charge of fuel and air burns in the cylinder, and the gas it produces pushes directly on a piston.

The engine on this plate is a single upright cylinder of the kind built in the 1880s and 1890s: a cast-iron cylinder with cooling fins, a piston sliding inside it, a crankshaft below and a heavy flywheel to carry the shaft round between firings. Modern car engines have several cylinders and lighter alloys, but they still turn the push on a piston into rotation through a connecting rod and a crankshaft.

How it works

The piston is a close-fitting plug that slides up and down in the cylinder. A connecting rod joins it to a crank on the crankshaft, so the back-and-forth motion of the piston becomes rotation, the same way a cyclist's knees turn the pedals.

Most engines follow the four-stroke cycle that Otto made practical. In a spark-ignition engine like the one drawn here, it runs as follows. In the first stroke the piston moves down with the intake valve open and draws in a mixture of air and fuel. In the second, both valves are shut and the piston rises, squeezing the mixture into a small space at the top. Near the top a spark (or, in early engines, a flame or a glowing tube) ignites it. The gas heats up very quickly and drives the piston down: this third stroke is the only one that delivers work. In the fourth the exhaust valve opens and the rising piston pushes out the burnt gas.

Springy rings in grooves round the piston seal it against the cylinder wall.

The crankshaft turns twice for each power stroke, and the flywheel stores enough energy to carry it through the other three strokes. A camshaft geared to turn at half the crankshaft's speed opens each valve at the right moment.

Compression is what made Otto's engine better than its rivals. A charge squeezed before it burns releases its heat at a higher pressure, so more of that heat turns into work. Rudolf Diesel pushed the idea further in the 1890s: he compressed air alone until it was hot enough to ignite fuel sprayed into it, with no spark at all.

How to build it

A working engine is precision work. It needs a foundry, a lathe and a boring machine, measuring tools that read to a hundredth of a millimetre, and a reliable fuel. What follows describes how the parts were made historically. It is not a plan for building one.

Cast the cylinder and frame. Early makers cast the cylinder and base in grey iron, which machines well and resists wear. The cylinder was then bored perfectly round and straight. The water jacket or cooling fins were cast in the same piece.

Make the piston and rings. The piston was cast iron, later aluminium, turned slightly smaller than the bore. Split rings of springy iron sit in grooves round it and press outwards against the wall, so the gas cannot leak past.

Forge the crankshaft and rod. These carry the hardest loads and were forged in steel, then turned and fitted with bearings of bronze or white metal.

Time the valves and ignition. The cams, and later the magneto or coil that makes the spark, have to act at the right point in the cycle. A fault here makes the engine run badly or kick back.

Feed it fuel and cool it. Otto's engines ran on town gas. Petrol engines needed a carburettor to mix fuel and air in the right proportion. Every engine needs cooling by water or air, and oil to keep the moving parts from seizing.

> **Safety.** Fuel and its vapour catch fire easily and can explode in a closed space. Exhaust contains carbon monoxide, which kills without smell or warning: never run an engine indoors or in a partly enclosed space, even with doors and windows open. The flywheel, belts and starting handle can break bones, and a kickback during hand starting can cause serious injury. Hot parts and cooling water under pressure cause burns.

History and evolution

Stationary gas engines like this one drove workshop machinery before motor vehicles became common.

People had tried for two centuries to drive a piston with an explosion. Christiaan Huygens experimented with gunpowder in the 1670s, and in 1807 the Swiss inventor François Isaac de Rivaz patented a hydrogen engine, which he later fitted to a small cart. The first engine sold in numbers was Étienne Lenoir's gas engine of 1860. It looked like a double-acting steam engine, but it burned the mixture without compressing it and wasted most of its fuel.

Nicolaus Otto, a travelling salesman from Cologne, had a local mechanic, Michael Zons, build him an engine on Lenoir's pattern in 1861 so that he could study it. With the engineer Eugen Langen he built an "atmospheric" engine that won a gold medal at the Paris Exhibition of 1867. Several thousand were built. In 1876 Otto built his four-stroke engine with compression. The Frenchman Alphonse Beau de Rochas had described the same cycle in an 1862 pamphlet, and in 1886 Otto's German patent was annulled on that ground, leaving other firms free to build the design.

Gottlieb Daimler and Wilhelm Maybach, who had both worked for Otto's company, built a small fast engine in 1885 that turned several hundred times a minute. That made engines light enough for vehicles. The same year Carl Benz completed his three-wheeled motor car and filed the patent for it in January 1886.

Diesel's engine reached 26.2% efficiency in a test at Augsburg in 1897, more than twice what the steam engines of the time managed. In the twentieth century internal combustion engines took over road transport, farming, shipping and the first aircraft. Electric motors are replacing them in many cars, yet most combustion engines built today still use the four-stroke sequence Otto put to work in 1876.

Benz's car used a single-cylinder four-stroke engine of under one litre.

Key figures

Otto's first four-stroke
1876, about 3 hp at 180 rpm

Diesel's test engine
26.2% efficiency, 17 February 1897

Power strokes (four-stroke engine)
One per cylinder for every two turns of the crankshaft

Sources

1. Replica Otto four-stroke engine · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co8405692/replica-otto-four-stroke-engine-internal-combustion-engine
2. Nikolaus August Otto · EBSCO Research Starters https://www.ebsco.com/research-starters/history/nikolaus-august-otto
3. Early history of the diesel engine · DieselNet https://www.dieselnet.com/tech/diesel_history.php
4. Otto engine · Wikipedia https://en.wikipedia.org/wiki/Otto_engine

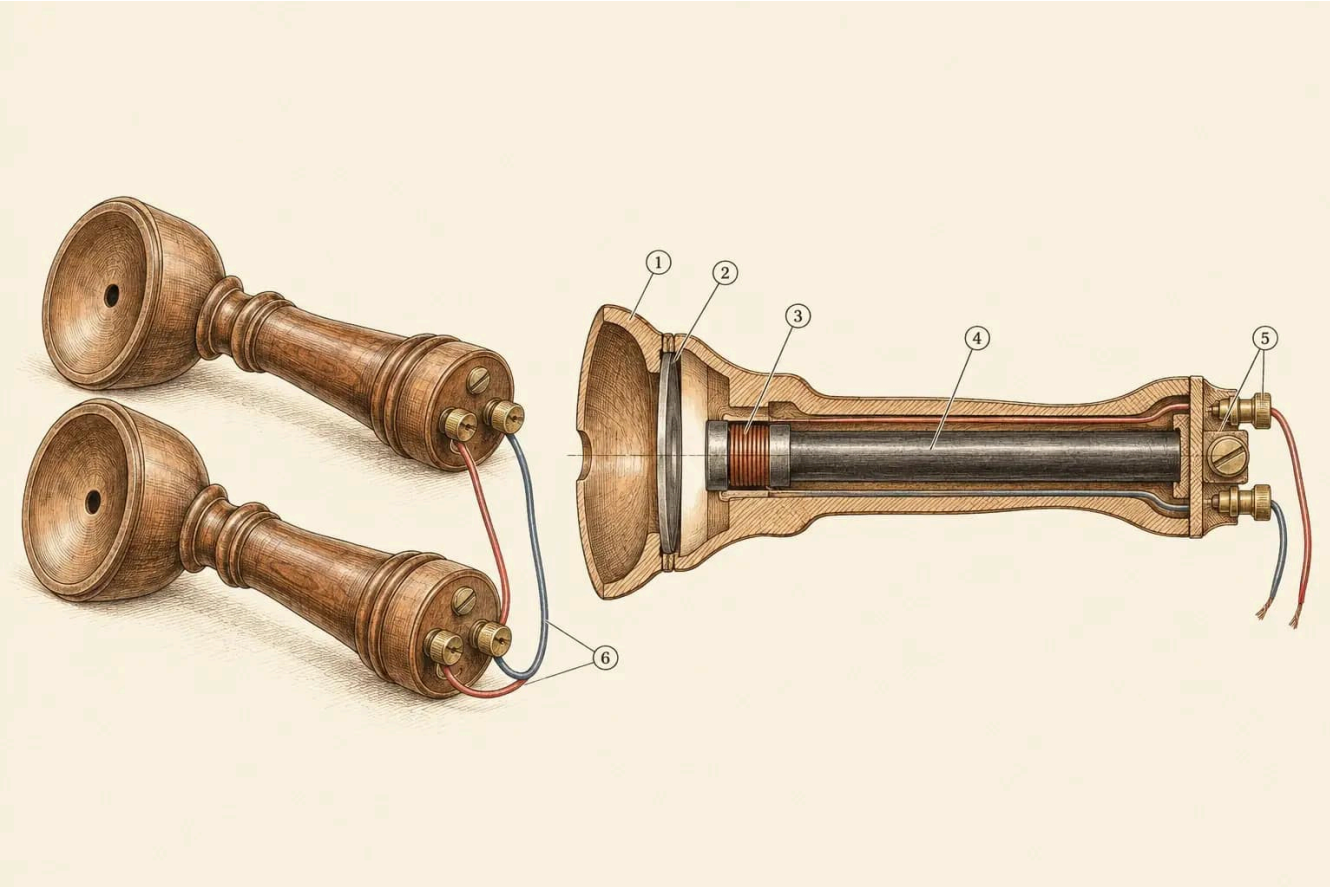
Fact-checked on 2026-10-11

Telephone

A voice carried down a wire

1876 · Electric age · Electric age

Requires: Electric Telegraph (p. 278)



1 Mouthpiece and earpiece 2 Iron diaphragm 3 Coil 4 Bar magnet 5 Terminals 6 Line wire

A telephone turns the vibrations of the voice into a varying electric current, sends it along a wire, and turns it back into sound at the other end. Alexander Graham Bell patented it in March 1876; within two years Bell's magnet telephones were in commercial use, and carbon microphones and exchanges soon made it a public service.

What it is

A telephone carries the voice itself along a pair of wires. A transmitter turns the pressure waves of the voice into an electric current whose strength rises and falls in the same pattern; a receiver at the other end uses that current to move a thin plate and recreate the sound.

The plate shows one of Bell’s hand telephones of 1877 and 1878, a turned wooden instrument nicknamed the butterstamp. The same instrument served for speaking and listening, and it worked without a battery: the voice itself produced the current.

How it works

Inside the wooden case of the butterstamp, a steel bar magnet runs the length of the handle. At its front end sits a short soft-iron pole piece wound with a coil of fine insulated copper wire. Just in front of the pole, separated from it by a gap a fraction of a millimetre wide, is a thin disc of iron, the diaphragm, clamped at its edge behind the mouthpiece. The two ends of the coil come out to terminals at the back, and from there a pair of wires runs to the other telephone.

A string telephone carries sound mechanically: the voice shakes one can's bottom, and the taut string shakes the other.

When someone speaks into the mouthpiece, the air pressure on the diaphragm rises and falls, and the disc bends in and out by a tiny amount. Each time it comes closer to the pole, more of the magnet's field passes through the iron; each time it moves away, less. A changing magnetic field through a coil produces a voltage in it, so the coil sends along the line a small alternating current that follows the shape of the sound wave.

In the carbon transmitter, the diaphragm squeezes a cell of carbon granules, so the current from a battery rises and falls with the voice.

At the far end the same current flows through the coil of the second telephone. It adds to or subtracts from the pull of the permanent magnet on that instrument's diaphragm, which therefore moves in step with the speaker's diaphragm and sets the air in front of it vibrating. The energy comes entirely from the voice, so the sound is faint and the range short. From the late 1870s, telephones added a carbon transmitter: the diaphragm presses on carbon, whose electrical resistance falls as it is squeezed, so the current from a battery is varied by the voice instead of being made by it. That gave a much louder signal.

How to build it

Two small loudspeakers show the same principle, the reversible link between sound, movement and current. They are built differently from Bell's instrument: in a loudspeaker the coil is fixed to the cone and moves with it in the field of a magnet, whereas in the butterstamp the coil and magnet stay still and only the iron diaphragm moves. Wired together, two loudspeakers make a telephone with no battery.

Gather the parts. You need two small loudspeakers of the same kind, 8 ohms, 5 to 8 cm across, bought loose or taken from battery-powered toys with the batteries removed (never take them out of radios or other mains-powered sets, even unplugged: some parts stay charged), and a few metres of twin bell wire or speaker cable.

Wire them. Strip a centimetre of insulation from each end of the cable. Connect one wire to the first terminal of each speaker and the other wire to the second terminal of each, either with screw terminals or by twisting and taping the joints.

Talk. Start with a short cable, then run it between two rooms with the door closed, so that your partner cannot hear you directly. Speak loudly and close into one cone while your partner holds the other speaker to an ear; then disconnect one wire and try again to check that the sound comes through the line. Expect a faint voice; results vary

with the speakers, so if nothing comes through, try a shorter cable or speakers of another size. Swap roles: each speaker works as both transmitter and receiver, as the butterstamp did.

Compare. Make a string telephone too, with two cans or paper cups and a few metres of string knotted through a hole in each bottom. Keep the string taut and away from obstacles, and compare the two.

> **Safety.** This circuit needs no battery and must never be connected to mains electricity or to a telephone line, both of which carry dangerous voltages. Open cans have sharp edges, so file or tape them. Do not shout directly into someone's ear through either telephone.

History and evolution

Several people worked on sending speech electrically before Bell. In 1861 Philipp Reis demonstrated an instrument in Frankfurt and gave it the name telephone, but it remained a curiosity. Antonio Meucci filed a caveat for a "sound telegraph" in 1871 and let it lapse in 1874; his claim to priority is still argued.

Bell, then working in Boston, filed his patent application on 14 February 1876, the same day Elisha Gray filed a caveat describing a similar idea, and which of the two arrived first is disputed. Patent 174,465 was issued on 7 March. Three days later, with a liquid transmitter, Bell spoke his first clearly intelligible sentence to his assistant Thomas Watson. He soon abandoned the liquid transmitter for the magnet telephone, patented on 30 January 1877. On 12 February 1877 a speaker in Boston was heard by an audience in Salem, about 26 km away.

Bell's liquid transmitter of March 1876: the voice shakes the membrane, the wire dips more or less deeply into acidified water, and the current varies.

Thomas Edison devised a carbon transmitter in 1877, and Henry Hunnings in England used loose carbon granules. The first commercial exchange opened in New Haven, Connecticut, on 28 January 1878, with 21 subscribers connected by hand at a switchboard. Almon Strowger's automatic exchanges later let subscribers make their own connections, and from 1896 a numbered dial made that easier. By the 1950s the United States had more than half of the world's telephones.

Key figures

Bell's patent
No. 174,465, filed 14 February 1876, issued 7 March 1876

Magnet telephone with no battery
US patent 186,787, 30 January 1877

Bell's first intelligible sentence
10 March 1876, Boston: "Mr. Watson, come here, I want to see you" (Bell's notebook)

First commercial exchange
New Haven, 28 January 1878: 21 subscribers at $1.50 a month

Sources

1. Telephone · Engineering and Technology History Wiki (IEEE) https://ethw.org/Telephone
2. Early telephone by Alexander Graham Bell, 1877 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co32960/early-telephone-by-alexander-graham-bell-1877
3. US186787A: Improvement in electric telegraphy (A. G. Bell, 1877) · Google Patents https://patents.google.com/patent/US186787A/en
4. First Commercial Telephone Exchange – Today in History: January 28 · Connecticut Humanities https://connecticuthistory.org/the-first-commercial-telephone-exchange-today-in-history
5. Telephone · Wikipedia https://en.wikipedia.org/wiki/Telephone
6. Replica of Bell's liquid transmitter of March 1876 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co33314/replica-of-bells-liquid-transmitter-of-march-1876-1880-1958-telephone
7. The Telephone: a lecture entitled Researches in Electric Telephony (A. G. Bell, Society of Telegraph Engineers, 1877) · Project Gutenberg https://www.gutenberg.org/ebooks/55787
8. Some experiments with the telephone (Lord Rayleigh, Scientific Papers) · Cambridge University Press https://www.cambridge.org/core/books/abs/scientific-papers/some-experiments-with-the-telephone/3FE1242F3DA62548052EB38CDF24909D
9. Vibration of Plates (A. W. Leissa, NASA SP-160, 1969) · NASA https://ntrs.nasa.gov/citations/19700009156
10. Early receivers · Telephone Collecting https://telephonecollecting.org/Bobs%20phones/Pages/Essays/Early%20Receivers/Early%20Receivers.htm
11. Copper Wire Tables (NBS Handbook 100, 1966) · National Bureau of Standards https://nvlpubs.nist.gov/nistpubs/Legacy/hb/nbshandbook100.pdf
12. US7760869B2: Method and apparatus for controlling the transmit volume level of a speakerphone (mouth reference point and TIA-810-B test level) · Google Patents https://patents.google.com/patent/US7760869B2/en

Fact-checked on 2026-10-12

Incandescent Light Bulb

A glowing filament in a vacuum

1879 · Electric age · Electric age

Requires: Electric Generator (p. 266), Glass (p. 129)

1 Glass bulb 2 Carbon filament 3 Platinum lead-in wires 4 Glass stem seal 5 Exhaust tip 6 Screw base

An incandescent lamp makes light by passing current through a thin filament until it glows white-hot, inside a glass bulb emptied of air so that the filament does not burn. Joseph Swan and Thomas Edison made it practical in 1879, and it lit homes and streets for more than a century.

What it is

The incandescent lamp is a glass bulb with a fine thread inside, the filament, which glows when an electric current passes through it. Before it, homes were lit by flames: candles, oil lamps and gas jets, which smoked and often started fires. Electric arc lamps existed, but they were far too bright for a room.

The lamp on the plate is the kind Edison's factory made in the early 1880s. Its descendants were the usual household lamp for most of the twentieth century, until compact fluorescent and then LED lamps took their place.

How it works

Any material heated enough gives off light. Electrical resistance turns the energy of the current into heat, and a thin filament passes from dull red through orange to white heat. The hotter it runs, the whiter and more efficient

the light, and the faster the filament evaporates.

In air, a white-hot carbon or metal thread burns up in moments, so the bulb is emptied of air, or later filled with a gas that does not react. The pump is attached through a narrow glass tube at the top, which is melted shut afterwards; that is the small exhaust tip on old lamps.

The wires that carry the current to the filament must pass through the glass. Glass and metal expand by different amounts when heated, and a mismatched seal cracks as the lamp warms. Platinum expands at almost the same rate as the glass used in early bulbs, so those lamps had short platinum wires through a glass stem, joined to cheaper copper inside the base.

In a Sprengel pump each falling drop of mercury traps a little air and carries it down the tube.

Edison designed the lamp together with the supply system. A filament of high electrical resistance draws little current at around 100 volts, so lamps can be wired in parallel, each with its own switch, on copper mains of reasonable size.

Only about 5 to 10 percent of the electricity in an incandescent lamp comes out as visible light; the rest leaves as heat.

How to build it

A lasting lamp needs a glassblower, a vacuum pump that reaches a very low pressure, and a filament sized for its supply voltage. Only the first step below is a safe home demonstration; the others outline how the first lamps were made in a workshop.

See the principle. Clamp a short piece of thin pencil lead between two metal clips on a ceramic tile and cover it with an upturned glass jar. Feed it from a bench power supply set to about 12 volts with its current limit turned down, then raise the limit slowly. The lead glows orange, then burns through as it meets the oxygen under the jar, which shows why the bulb must be emptied of air.

Carbonise the filament. Workshops packed loops of bamboo or cotton thread in powdered charcoal in a lidded, vented crucible and heated it red-hot in a furnace for hours. Starved of air, the fibre turns to carbon instead of ash; the escaping gases are flammable and contain carbon monoxide.

Seal the leads. Two short platinum wires, or another metal matched to the glass, were fused into a glass stem, the filament was clamped to their tips with carbon paste, and the stem was fused into the neck of a blown bulb with a thin exhaust tube at the top. A low-voltage filament must be shorter and thicker than a 100-volt one.

Pump and flash. With the bulb on the pump, a gentle current through the filament drove gas out of the carbon and the glass. When the pressure stopped falling, the tube was melted shut with a flame.

Fit the base. A brass screw base was cemented to the neck with plaster, one wire soldered to the shell and the other to the centre contact.

> **Safety.** Mains voltage can kill: run experiments only from a current-limited bench supply under 24 volts, never from a wall socket, and never short a car or lithium battery across a filament. Filaments, glass and clips get hot enough to burn skin and set paper alight, so work on a tile, away from anything flammable. An evacuated bulb can implode and throw glass; wear goggles and work behind a clear shield. Mercury vapour is toxic: do not build or use a mercury pump at home. Never heat a sealed container: carbonising gives off flammable gas and carbon monoxide and belongs in a vented furnace outdoors, not in a home.

History and evolution

Carbonised bamboo fibres lasted far longer than the paper and thread used in the first lamps.

Humphry Davy made a platinum strip glow with current from a large battery in 1802, and in 1840 Warren de la Rue placed a platinum coil inside a vacuum tube. Platinum was too costly; carbon was cheap but burned in the air that the pumps of the day left behind.

In England, Joseph Swan worked on carbonised paper filaments from around 1850. An 1860 trial in a poorly evacuated bulb failed. From 1875 he used the new Sprengel mercury pump, and between December 1878 and February 1879 he showed working carbon lamps in Newcastle upon Tyne. In December 1880 he fitted lamps at Cragside, the home of the industrialist William Armstrong.

At Menlo Park in New Jersey, Thomas Edison's laboratory chose a high-resistance carbon filament. On 22 October 1879 a lamp with a carbonised cotton thread burned for 13.5 hours; the team then raised the current, and about an hour later the bulb overheated and cracked. On the evening of 31 December 1879 Edison lit his laboratory and the street outside for visitors, using horseshoe filaments of carbonised cardboard. In 1880 he settled on bamboo, with reported lives of around 1,200 hours, and in 1882 the Pearl Street Station began supplying lamps in lower Manhattan. After a patent dispute in Britain, Swan's and Edison's companies merged in 1883 as "Ediswan".

Around 1910 drawn tungsten wire replaced carbon and gave a whiter, more efficient light.

Around 1910 William Coolidge at General Electric found how to draw brittle tungsten into fine wire. At white heat tungsten evaporates much more slowly than carbon, so lamps could run hotter. Irving Langmuir then filled bulbs with an inert gas, nitrogen at first, which slows evaporation further, and coiled the filament. From 2009 the European Union, followed by many other countries, began phasing out ordinary incandescent lamps; compact fluorescent lamps and later LEDs replaced them.

Key figures

Edison's first long test
13.5 hours, then about one more at higher power (22 October 1879)

Carbonised bamboo filament
Lives of around 1,200 hours reported (from 1880)

Swan's Newcastle demonstrations
December 1878 to February 1879

Share of power turned into light
Roughly 5 to 10%; the rest is heat

Sources

1. Edison's Incandescent Lamp · IEEE Engineering and Technology History Wiki https://ethw.org/Edison%27s_Incandescent_Lamp
2. Lighting: From Research to Development · Thomas A. Edison Papers, Rutgers University https://edison.rutgers.edu/life-of-edison/biographical-essays/lighting/from-research-to-development
3. Lighting: The Carbon-Filament Lamp · Thomas A. Edison Papers, Rutgers University https://edison.rutgers.edu/life-of-edison/biographical-essays/lighting/the-carbon-filament-lamp
4. Joseph Swan · The Institution of Engineering and Technology (IET) Archives https://www.theiet.org/membership/library-archives/the-iet-archives/biographies/joseph-swan/
5. Joseph Swan · Newcastle University, Northern Innovation https://research.ncl.ac.uk/northerninnovation/exhibits/josephswan/
6. Milestones: Pearl Street Station, 1882 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Pearl_Street_Station

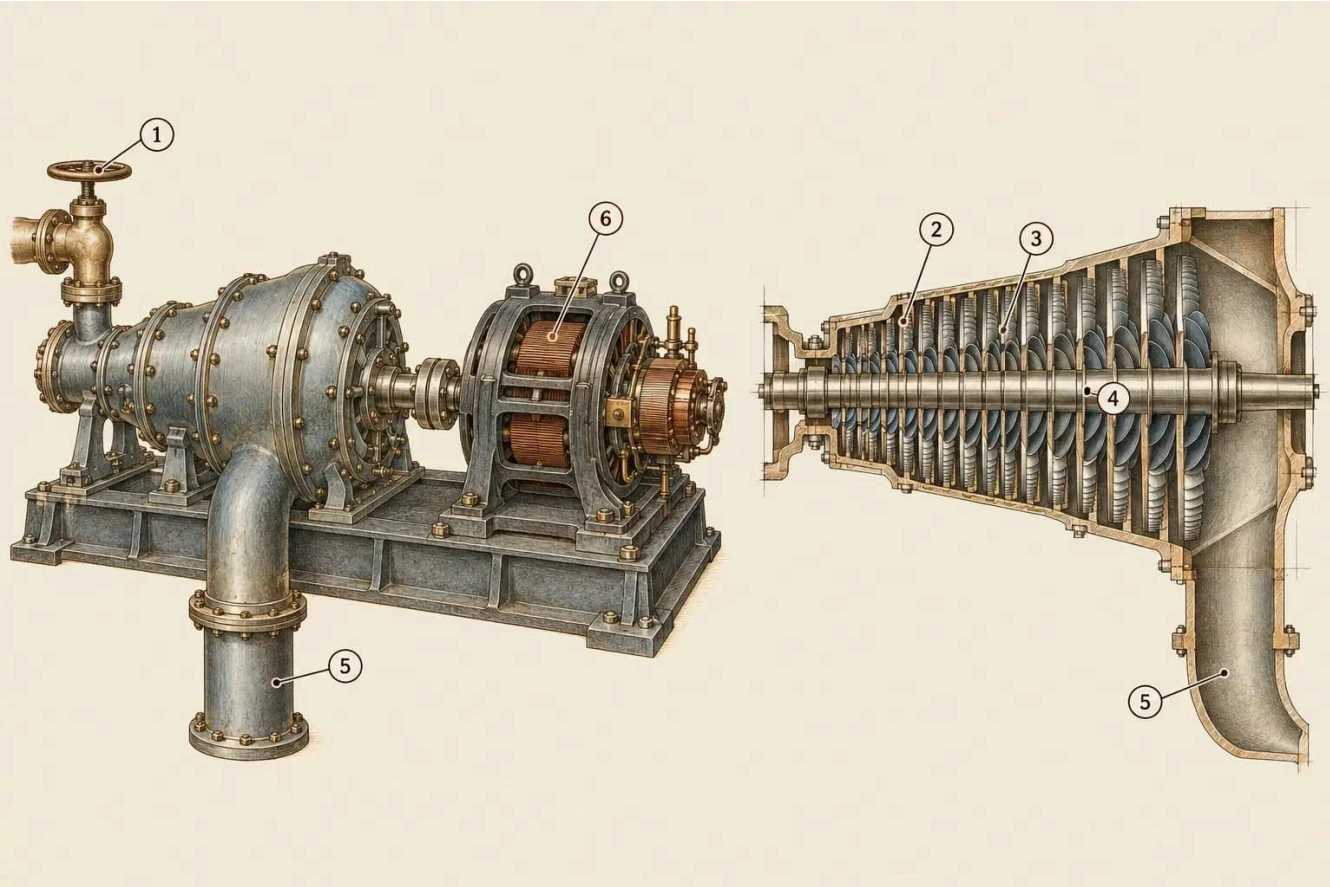
Fact-checked on 2026-10-11

Steam Turbine

Steam spinning the world's generators

1884 · Electric age · Electric age

Requires: Steam Engine (p. 221), Steel (p. 137), Electric Generator (p. 266)



1 Steam inlet and stop valve 2 Fixed blades on the casing 3 Moving blades on the rotor 4 Rotor shaft 5 Exhaust to the condenser 6 Dynamo

A steam turbine lets steam expand through rows of fixed and moving blades, turning its pressure into speed and that speed into the rotation of a shaft. Charles Parsons coupled one to a dynamo in 1884; turbines of this kind now drive the generators that produce most of the world's electricity.

What it is

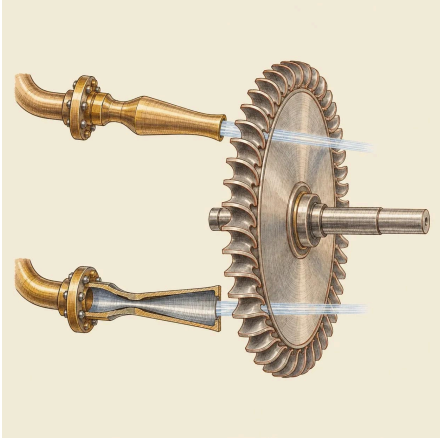
A steam turbine is a wheel driven by steam, with no piston and no crank. Steam flows through rows of blades set around a shaft and leaves the machine at a much lower pressure; the energy it gives up on the way turns the shaft. The motion is smooth and fast, which suits an electric generator.

Coal and nuclear plants boil water to drive these machines. Gas-fired combined-cycle plants raise steam from the hot exhaust of a gas turbine, and solar thermal and most geothermal plants use heat from the sun or the ground. Together they make steam turbines the source of most of the world’s electricity.

How it works

Steam gives up its energy by expanding. In a nozzle, a passage that narrows, its pressure falls and it speeds up. At the narrowest point, the throat, it can reach the speed of sound; to go faster, it needs a passage that widens beyond the throat, the flaring shape of de Laval's nozzles. In each stage, a ring of fixed blades on the casing works as a set of nozzles and throws the steam onto a ring of curved moving blades on the rotor, which turn the jet aside and are pushed round.

In an impulse stage almost all the pressure drop happens in the fixed nozzles, and the moving blades only catch the jet. In a reaction stage, the kind Parsons chose, the passages between the moving blades narrow too, so the steam keeps expanding as it crosses them and pushes them back as it leaves. In a Parsons stage the expansion is shared about equally between the fixed and the moving row.



De Laval's impulse wheel: flaring nozzles send jets through a single ring of blades.

Released through one nozzle, a large pressure drop gives a jet of over 1,000 metres per second, and blades work best at about half the jet's speed, so a single wheel must spin dangerously fast and needs gearing. Parsons split the drop into many small steps, so the shaft turns at a rate a dynamo can use.

As the pressure falls, the steam fills more room, so the blades grow longer towards the exhaust: 1.9 metres in the last row of the turbines built for Hinkley Point C, in England.

Steam released into the air stops expanding at atmospheric pressure. A condenser, a chamber of tubes cooled by river, sea or tower water, turns the exhaust steam back into liquid and keeps a near vacuum at the end of the turbine, so the steam goes on expanding and working inside the turbine before it is condensed. Parsons's first condensing turbines, at Cambridge in 1892, matched the best piston engines of their size.

This loop is the Rankine cycle: a pump forces water into the boiler, which turns it into steam; the steam expands through the turbine, and the condenser turns it back into water for the pump. Pumping a liquid costs little next to what the steam gives, so the cycle has a net output. The pump descends from the piston pump, boiler and condenser from the steam engine; a refrigerator runs a similar loop in reverse.

On a 50-hertz grid, a two-pole generator on the shaft turns at 3,000 revolutions per minute, at 3,600 on 60 hertz. Transformers then raise the voltage for the lines.

How to build

A power-station turbine is fed by a boiler, which is a pressure vessel: do not build one. This model runs on air. You need an aluminium pie dish, two corks, a knitting needle, straws, a cardboard box, glue, and a hair dryer on its cold setting or a bicycle pump.

Cut a bladed wheel. Cut a 10 cm disc. Make 12 to 16 cuts from the rim, stopping 2 cm short of the centre, and twist every vane the same way by about 30 degrees.

Mount it. Glue the wheel to a cork on the needle, which turns in two pieces of straw fixed across the box.

Compare a pipe and a nozzle. With the same pump, distance and angle, blow air at the vanes through a wide tube, then through a cut-down straw held at a slant, and note which turns the wheel faster.

Add a stage. Glue a second wheel, vanes twisted the same way, to a second cork on the same needle, 3 cm behind the first. Between them, fix to the box a card ring with vanes twisted the other way and a central hole wide enough to touch neither the needle nor the wheels. Blow along the needle through the front wheel, then remove the ring and compare: the fixed vanes should turn the air leaving the first wheel back onto the second.

Measure the voltage. Couple a small DC hobby motor to the needle with a piece of tube and connect a multimeter set to DC volts. If the wheel can turn the motor, the reading rises with its speed.

Do not try the model with steam. Boiling water turns into more than a thousand times its volume of steam, and a heated vessel that is sealed or blocked builds pressure until it bursts. Real boilers follow certified designs, carry safety valves and are examined regularly by a competent person; a home-made boiler has none of these safeguards.

> **Safety.** Steam scalds in a fraction of a second, even from a kettle spout, where it is invisible: keep hands and faces away. Never seal, plug or block a heated vessel. A spinning foil wheel has sharp edges and can throw a vane, so wear glasses and keep hair clear. Use only a small hobby motor and a meter, never the mains, and keep the hair dryer away from water.

History and evolution

Hero's aeolipile: two jets of steam spin the sphere on its pivots.

In the first century CE, Hero of Alexandria described the aeolipile, a hollow ball spun by steam from bent nozzles, the first known device to turn steam into rotation. In 1629 Giovanni Branca published the drawing of a machine in which a jet of steam blows on a paddle wheel; it was very likely never built. In Sweden, Gustaf de Laval patented a small steam reaction wheel in 1883, then in 1889 a geared single-stage impulse turbine.

In 1884 Charles Parsons, a partner at Clarke, Chapman in Gateshead, coupled a turbine of many reaction stages directly to a dynamo. It gave 7.5 kilowatts at 18,000 revolutions per minute, and about 200 such sets were lighting ships by 1888. In 1890 Forth Banks, in Newcastle, became the first power station to use turbines.

To prove the turbine at sea, Parsons built Turbinia, a 31-metre launch that reached 34.5 knots, and on 26 June 1897 ran her unannounced past the warships at the Spithead review. In 1905 an Admiralty committee recommended turbines for every class of warship.

In the United States, Charles Curtis sold his rights to General Electric in 1896. His 5,000-kilowatt set of 1903, then the world's most powerful, stood 7.6 metres high against 18 for a piston engine of similar power. Sets reached 660 megawatts at Drax in the 1970s, and each of the two turbines built for Hinkley Point C is rated at 1,770 megawatts.

Turbinia at speed: three turbines on three shafts drove nine propellers.

Key figures

First Parsons turbo-dynamo
1884: 7.5 kW at 18,000 rpm

First condensing turbines
Cambridge, 1892: three sets of 100 kW at 4,800 rpm

Turbinia
34.5 knots; shown at Spithead on 26 June 1897

Speed of a grid turbine
3,000 rpm on 50 Hz grids, 3,600 on 60 Hz; half that for large nuclear sets

Share of US electricity, 2022
About 53%: 42.5% from steam plants, 10.7% from the steam side of combined-cycle plants

Sources

1. Parsons' steam turbine generator, 1884 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co51109
2. Charles Algernon Parsons 1854–1931 · Science Museum Group https://collection.sciencemuseumgroup.org.uk/people/ap26725/parsons-charles-algernon
3. 100 K.W. Parsons' Radial Flow Steam Turbine alternator with Generator, partly sectioned · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co8625819/100-k-w-parsons-radial-flow-steam-turbine-alternator-with-generator-partly-sectioned
4. Forward thinkers: Sir Charles Parsons, inventor of the steam turbine · Institution of Mechanical Engineers https://www.imeche.org/news/news-article/forward-thinkers-sir-charles-parsons-inventor-of-the-steam-turbine
5. Turbinia (1894) · Tyne Built Ships https://www.tynebuiltships.co.uk/T-Ships/turbinia1894.html
6. Curtis 5000-kW Vertical Turbine (ASME Landmark) · Engineering and Technology History Wiki, ASME https://ethw.org/ASME-Landmark:Curtis_5000-kW_Vertical_Turbine
7. Charles Gordon Curtis · ASME https://www.asme.org/topics-resources/content/charles-gordon-curtis
8. Carl Gustaf Patrik De Laval · Grace's Guide to British Industrial History https://www.gracesguide.co.uk/Carl_Gustaf_Patrik_De_Laval
9. C. A. Parsons and Co: Electricity Generation and Transmission · Grace's Guide to British Industrial History https://www.gracesguide.co.uk/C._A._Parsons_and_Co:_Electricity_Generation_and_Transmission
10. Heron of Alexandria · MacTutor, University of St Andrews https://mathshistory.st-andrews.ac.uk/Biographies/Heron/
11. Giovanni Branca · EBSCO Research Starters https://www.ebsco.com/research-starters/literature-and-writing/giovanni-branca
12. Fluid Machinery, Lecture 24: steam turbines · NPTEL, Indian Institutes of Technology https://archive.nptel.ac.in/content/storage2/courses/112104117/chapter_6/6_9.html
13. Nozzle Design · NASA Glenn Research Center https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/nozzle-design/
14. The Rankine cycle · MIT, Unified Engineering thermodynamics notes https://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node65.html
15. How electricity is generated · U.S. Energy Information Administration https://www.eia.gov/energyexplained/electricity/how-electricity-is-generated.php
16. Arabelle goes to new lengths · Nuclear Engineering International https://www.neimagazine.com/analysis/arabelle-goes-to-new-lengths/
17. Introduction to pressure equipment · Health and Safety Executive https://www.hse.gov.uk/pressure-systems/about.htm
18. Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam (IAPWS-IF97) · International Association for the Properties of Water and Steam https://www.iapws.org/relif/IF97-Rev.html
19. TRANSFORM.Fluid.Machines.SteamTurbine: Stodola ellipse law and Baumann wetness correction (after D. H. Cooke, J. Eng. Gas Turbines Power 107, 1985) · OpenModelica, Oak Ridge National Laboratory TRANSFORM library https://build.openmodelica.org/Documentation/TRANSFORM.Fluid.Machines.SteamTurbine.html

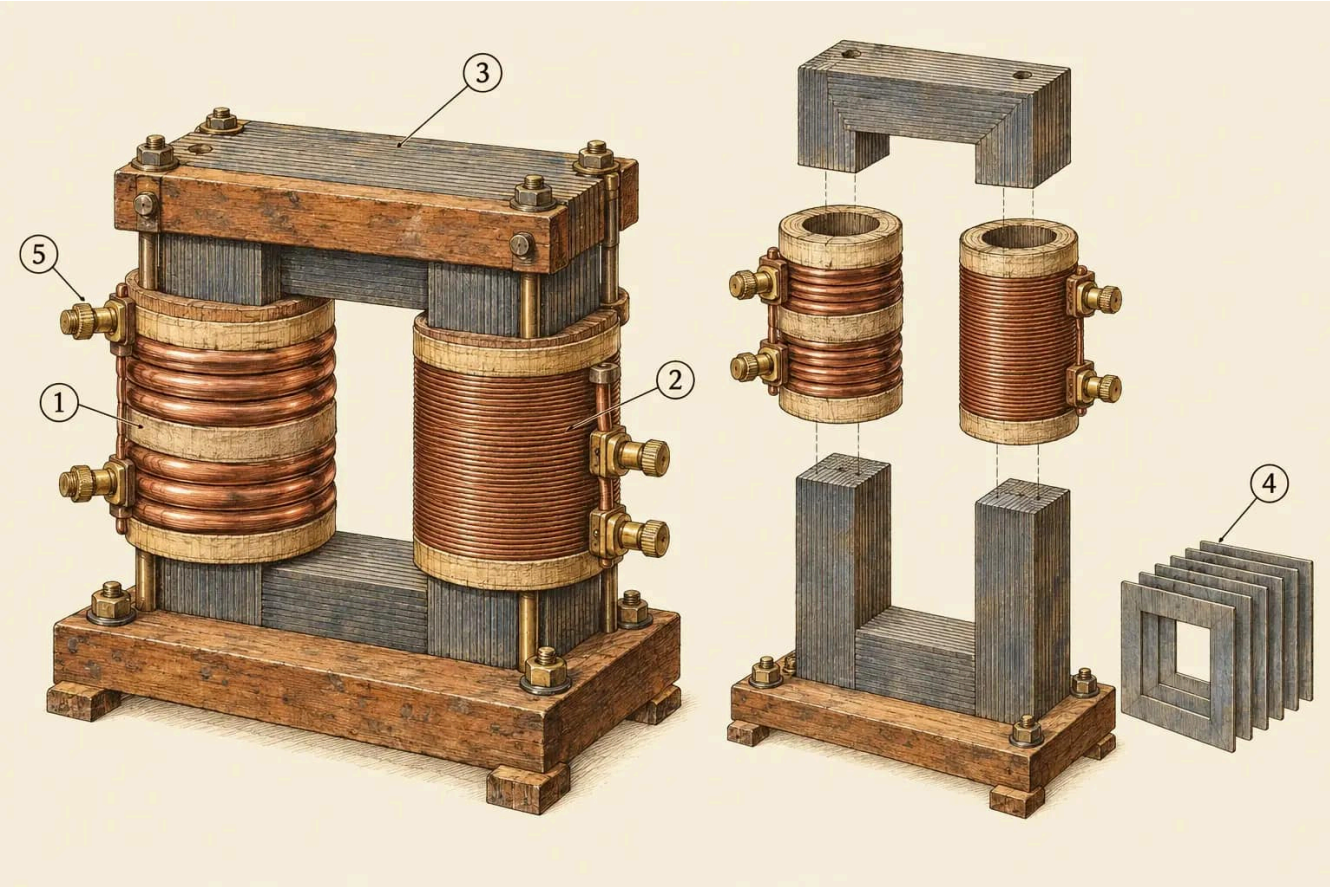
Fact-checked on 2026-10-14

Transformer

Raising and lowering the voltage

1885 · Electric age · Electric age

Requires: Electric Generator (p. 266), Iron Smelting (p. 133)



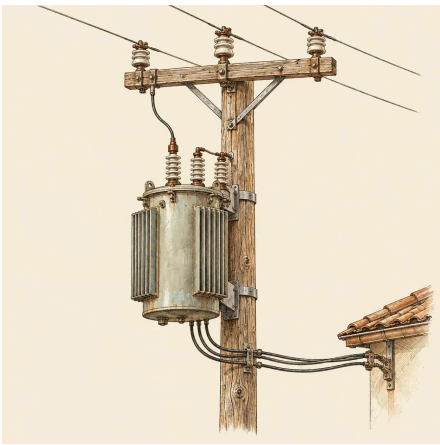
1 Primary coil: few turns of thick wire 2 Secondary coil: many turns of fine wire 3 Laminated iron core 4 Thin iron sheets of the core 5 Terminal post

A transformer is two coils of wire on one iron core: an alternating current in the first induces a voltage in the second, higher or lower according to the ratio of their turns. It lets power travel at high voltage over long lines and arrive at the voltage appliances use, and it is the main reason alternating current became the standard for the world's grids.

What it is

A transformer changes the voltage of an alternating current. It has no moving parts: two coils of insulated copper wire, the primary and the secondary, wound on a closed iron core. Power enters one coil and leaves the other at a higher or lower voltage, with the current changed the opposite way.

Power stations raise the voltage of their generators for the long lines. Substations lower it in steps, and a last transformer on a pole or in a cabin brings it down to the 230 or 120 volts of a socket. Phone chargers, doorbells and welding sets contain smaller ones.



A pole transformer lowers the voltage of the street line to the voltage used in the house.

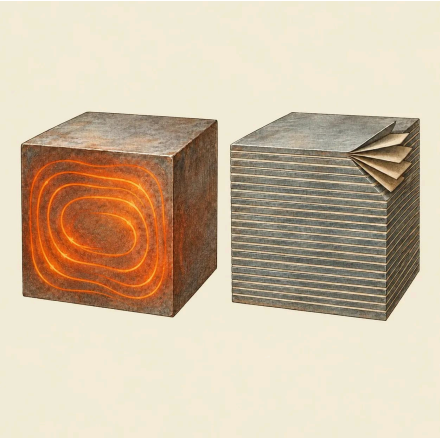
How it works

The current in the primary makes the iron core a magnet. Because the current alternates, that magnetism grows, collapses and reverses, going through fifty or sixty full cycles a second. The changing flux passes through the secondary and induces a voltage in each turn: Faraday's induction, which works only while the flux changes.

Every turn of both coils sees the same flux, so the voltages of the two coils are in the ratio of their turns. With 1,000 turns on the primary and 50 on the secondary, 4,600 volts in give 230 volts out. In an ideal transformer, with no losses, the low-voltage side carries twenty times the current and is wound with thicker wire.

On direct current none of this works: a steady flux induces nothing, and the primary becomes a short length of wire across the supply that overheats. Transformers need alternating current, which is why AC became the standard for grids; today's high-voltage direct-current links use converters to turn AC into DC and back into AC at the far end.

High voltage pays because the heat lost in a wire grows with the square of the current. Send 100 kilowatts into a line whose wires total 2 ohms. At 1,000 volts the current is 100 amperes, and the wires waste 20 kilowatts, a fifth of the power. At 10,000 volts the current is 10 amperes and the loss falls to 200 watts, or 0.2 percent.



A solid core heats up from the currents circling inside it; thin sheets insulated from each other cut them down.

The flux also induces currents circling inside the iron, called eddy currents, and a solid core would heat up like a stove plate. So the core is a stack of sheets a few tenths of a millimetre thick, each insulated from the next by varnish or oxide. The eddy loss falls with the square of the sheet thickness. Early builders used bundles of iron wire for the same reason; modern cores use silicon steel.

Grids use three-phase current: three alternating currents shifted by a third of a cycle, on three wires, transformed by three sets of coils on one core.

How to build

A bench demonstration at a few volts, never a mains project. You need a steel bolt about 10 cm long, a second bare bolt and two flat steel strips, 20 to 30 m of enamelled copper wire 0.3 to 0.5 mm thick, insulating tape, fine

sandpaper, a multimeter that reads AC volts and, for the last test, a centre-zero galvanometer.

Wind the coils. Over a layer of tape, wind a primary of 100 turns on the bolt. Tape it, wind a 100-turn secondary over it, tape again and wind a 50-turn secondary on top. Sand the enamel off each end.

Choose a safe source. Use a bought plug-in adapter whose label reads “AC output” at 12 volts or less, or a function generator giving a sine wave of a few volts at about 1 kHz with no DC offset. Most adapters give DC and will not work. A 12-volt incandescent car bulb of about 5 watts in series with the primary limits the current.

Measure. Read the AC voltage across the primary and each secondary, then disconnect: the solid bolt warms up. With the adapter, expect a few tenths of a volt, since most of the voltage drops across the bulb. The 50-turn coil gives about half the voltage of the 100-turn one, and both read less than the primary, because the flux of a single bolt closes through the air. Lay the bare bolt beside the wound one and bridge their heads and their tails with the steel strips, so the iron forms a closed frame around the coils: the readings rise.

Try a battery. With a 4.5-volt battery in place of the adapter, bulb still in series, connect a centre-zero galvanometer to the secondary on its least sensitive range, or through a resistor of a few kilohms. Its needle kicks one way when you close the circuit, the other way when you open it, and rests at zero in between.

Read a rating plate. On a doorbell transformer, find the input and output voltages, such as 230 V / 12 V, and the power in volt-amperes (VA). Large units add frequency, cooling and impedance; read those from outside the fence.

> **Safety.** Never give a secondary more turns than the primary, and remember that an adapter’s output with no load can be a fifth above its label. Opening a circuit through a coil makes a brief voltage spike, so switch with a switch or by an insulated wire, never with fingers on bare ends. Never wind coils for the mains, and never open, modify or rewire mains-powered equipment, even unplugged: microwave-oven and neon-sign transformers deliver lethal currents. A step-down transformer fed backwards raises the voltage, and capacitors in a device can stay charged after it is unplugged. Coils stay hot after use. Never climb poles, enter substations or touch fallen lines. Mains wiring is work for a licensed electrician.

History and evolution

Michael Faraday showed induction with his two-coil iron ring in August 1831, Joseph Henry found it independently in America, and around 1850 Heinrich Ruhmkorff in Paris made the induction coil a standard instrument.

In 1884 Lucien Gaulard and John Dixon Gibbs lit lamps along a 40 km line from Turin to Lanzo with their “secondary generators”, wired in series on open iron cores, so switching one lamp disturbed the others.

At the Ganz works in Budapest, Károly Zipernowsky, Miksa Déri and Ottó Bláthy saw that a closed iron core and transformers connected in parallel would hold the voltage steady. They filed patents between January and March 1885, named the device “transformer”, and lit the Budapest National Exhibition with their system that May.

An early Budapest transformer: the iron wire wraps the copper ring and closes the magnetic path.

George Westinghouse bought the Gaulard–Gibbs rights, and his engineer William Stanley built closed-core transformers that lit the main street of Great Barrington, Massachusetts, in March 1886. Edison’s direct current at about 110 volts reached only a few streets around each station, and his companies campaigned on the dangers of AC. Westinghouse lit the 1893 Chicago fair with AC, and in 1896 power from Niagara Falls reached Buffalo.

By 1888 Galileo Ferraris and Nikola Tesla had used currents out of step to make a rotating field for motors; in 1891 a three-phase line carried 300 horsepower 175 km from Lauffen to Frankfurt. Today's main lines run at hundreds of thousands of volts.

Key figures

Principle found
29 August 1831, Faraday's iron ring at the Royal Institution

Closed-core transformer
Patent applications filed January–March 1885 by Zipernowsky, Déri and Bláthy of the Ganz works, Budapest

First AC distribution with transformers in the United States
Great Barrington, Massachusetts, March 1886 (William Stanley)

Lauffen–Frankfurt line, 1891
175 km at 15,000 volts, three-phase, over 75% delivered

Losses on a line
Same power, same line: ten times the voltage, a hundredth of the loss

Sources

1. Michael Faraday's ring-coil apparatus · The Royal Institution https://rigb.org/node/143
2. History of the Transformer (F. Uppenborn, 1889) · Project Gutenberg https://gutenberg.org/files/56365/56365-h/56365-h.htm
3. Centenary of the transformer (P. Asztalos, 1986) · Periodica Polytechnica Electrical Engineering, Budapest University of Technology and Economics https://pp.bme.hu/ee/article/view/4637
4. Gaulard and Gibbs secondary generator · Museo Galileo, Florence https://catalogue.museogalileo.it/object/GaulardGibbsSecondaryGenerator.html
5. Milestones: Alternating Current Electrification, 1886 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Alternating_Current_Electrification,_1886
6. Milestones: Long Distance Electric Power Transmission Using Three-Phase Alternating Current, 1891 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Long_Distance_Electric_Power_Transmission_Using_Three-Phase_Alternating_Current,_1891
7. Milestones: Rotating Fields and Early Induction Motors, 1885-1888 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Rotating_Fields_and_Early_Induction_Motors,_1885-1888
8. Milestones: Pearl Street Station, 1882 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Pearl_Street_Station,_1882
9. History of Transformers · Edison Tech Center https://edisontechcenter.org/Transformers.html
10. The War of the Currents: AC vs. DC Power · U.S. Department of Energy https://www.energy.gov/articles/war-currents-ac-vs-dc-power
11. Eddy currents · schoolphysics https://www.schoolphysics.co.uk/age16-19/Electricity%20and%20magnetism/Electromagnetic%20induction/text/Eddy_currents/index.html
12. Transformer · HyperPhysics, Georgia State University https://hyperphysics.gsu.edu/hbase/magnetic/transf.html
13. Introduction to Electric Power Systems (J. L. Kirtley), 3.4 Transformers · LibreTexts https://eng.libretexts.org/Bookshelves/Electrical_Engineering/Electro-Optics/Introduction_to_Electric_Power_Systems_(Kirtley)/03%3A_Polyphase_Networks/3.04%3A_Transformers
14. Commission Regulation (EU) No 548/2014, Annex I: ecodesign requirements for transformers · legislation.gov.uk https://www.legislation.gov.uk/eur/2014/548/annex/I/division/1/adopted

Fact-checked on 2026-10-14

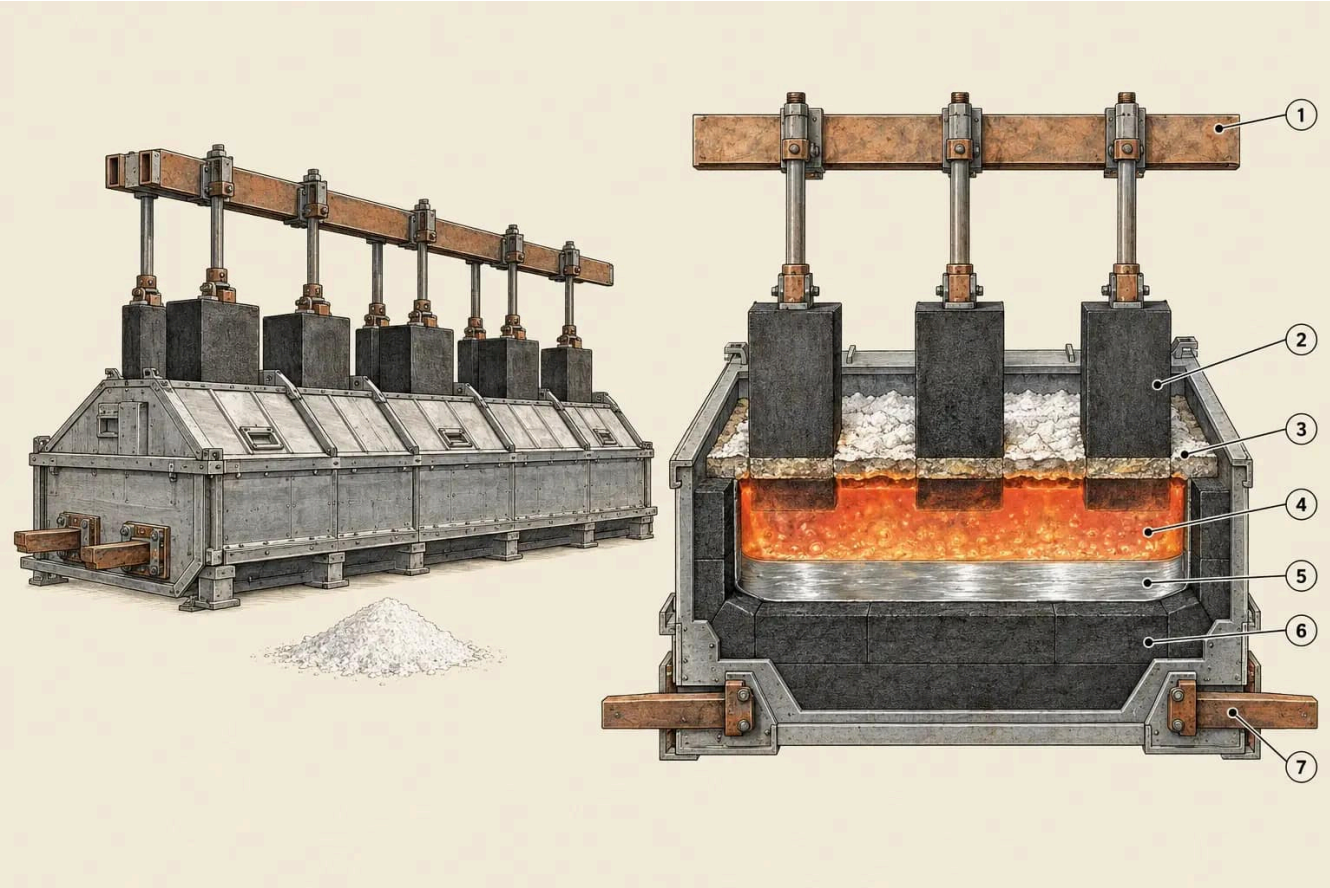
Aluminium

Alumina turned into metal by electricity

1886 · Electric age · Electric age

Requires: Electric Generator (p. 266), Water Turbine (p. 258)

Leads to: Aeroplane (p. 338)



1 Busbar and anode rods 2 Carbon anodes 3 Crust of frozen bath and alumina 4 Molten cryolite bath with dissolved alumina 5 Molten aluminium 6 Carbon cathode lining 7 Steel shell and collector bars

Aluminium is the most common metal in the Earth's crust, but it is locked in oxides that fire and charcoal cannot break. Since 1886 it has been made by refining bauxite to alumina, dissolving the alumina in molten cryolite and splitting it with a large direct current.

What it is

Aluminium is a light, silvery metal, about a third as dense as steel. It makes up roughly 8% of the Earth’s crust by weight, more than any other metal, yet it is almost never found as metal. It is bound to oxygen in clays, feldspars and most common rocks, and that bond is too strong for the charcoal fire that frees iron or copper.

The ore is bauxite, a reddish rock left by tropical weathering. A refinery turns it into alumina, a white oxide powder, and a smelter splits the alumina with electricity in the Hall–Héroult cell shown on the plate, still the only industrial way to make new aluminium.

How it works

From bauxite to alumina. In the Bayer process, crushed bauxite is digested in hot caustic soda under pressure, at 140 to 280 °C depending on the ore. The aluminium minerals dissolve; iron oxides and sand settle out as a red residue. Cooled and seeded with crystals from an earlier batch, the liquor grows aluminium hydroxide, which is roasted at up to about 1,100 °C into alumina.

From ore to metal: two to three tonnes of bauxite give a tonne of alumina, and two tonnes of alumina a tonne of aluminium.

From alumina to metal. Alumina melts above 2,000 °C, but a bath of molten cryolite, a fluoride of sodium and aluminium, with added aluminium fluoride, dissolves it at about 950 to 980 °C. The cell is a steel box lined with carbon blocks, which form the negative electrode. Carbon anodes hang into the bath from rods clamped to a heavy busbar.

Direct current flows from the anodes through the bath to the lining and splits the dissolved alumina. Aluminium, denser than the bath, gathers as a liquid at the bottom. Oxygen goes to the anodes and burns their carbon into carbon dioxide, about 0.4 to 0.5 kg of carbon per kilogram of metal, so worn anodes are replaced in turn. A crust of frozen bath and alumina keeps the heat in. Alumina is fed through it, and the metal is siphoned off at intervals.

The current also keeps the bath molten. Pots are wired in series, each carrying well over a hundred thousand amperes at four to five volts. Every atom of aluminium takes three electrons, so the cell uses about 13 to 15 kilowatt-hours per kilogram, less than half of which goes into the reaction itself. Power is the largest cost, so smelters stand where it is cheap, beside the dams of Canada, Norway or Iceland or near large power stations, with transformers and rectifiers to supply direct current.

In air an oxide film a few nanometres thick forms at once on the metal; it stops corrosion and re-forms when scratched. A few per cent of copper, magnesium, silicon or zinc make it strong enough for aircraft. Recycling only has to melt scrap: 8.3 gigajoules per tonne against 186 for new metal in 2019, a saving of about 95%.

How to build

Do not make or melt aluminium at home. The bath gives off toxic fluoride fumes and runs near 1,000 °C, and a drop of water trapped under molten metal flashes into steam and throws the metal out; melted cans add fumes from paints and linings. A workshop can sort the metal, work it cold, and show electrolysis at a few volts.

The magnet clings to the steel tin and ignores the aluminium can.

Sort it. A magnet attracts steel but not aluminium. To tell it from other non-magnetic metals, weigh a piece and measure the water it displaces: aluminium comes out near 2.7 grams per cubic centimetre, copper and brass above 8. Rinse off food and keep painted or coated pieces apart.

Bend and drill. Soft grades bend cold in a vice between hardwood blocks; hard alloys crack on a sharp fold, so bend them round a rounded block. To drill, centre-punch, clamp the sheet onto wood and use a sharp bit with a drop of oil: sheet held by hand can catch and spin.

Join it cold. Aluminium is hard to weld: its oxide melts above 2,000 °C, the metal at 660 °C, and it does not glow before it slumps. Use rivets, bolts or a structural adhesive, with aluminium fasteners where possible.

In the wet, and above all near the sea, aluminium corrodes against copper, steel and even stainless steel; separate them with plastic washers or paint.

Show the principle. Put two pencil leads in a glass of water with a teaspoon of washing soda and connect them to a 9-volt battery. Hydrogen bubbles at the negative lead, oxygen at the positive: the current splits water as the smelter splits alumina.

> **Safety.** No molten metal and no molten-salt electrolysis outside an industrial plant. Cut sheet is sharp: wear gloves to handle it and deburr every cut, but take the gloves off before using a drill, and protect your eyes. Washing soda irritates skin and eyes, so wear goggles. Never use table salt in the demonstration, because it gives off chlorine; keep the hydrogen away from flames, and use only a small battery, never the mains.

History and evolution

Hans Christian Ørsted obtained a tiny, impure sample from aluminium chloride in 1825. Friedrich Wöhler made a powder in 1827 and small beads in 1845.

In France, Henri Sainte-Claire Deville reduced the chloride with sodium and showed an ingot at the Paris exhibition of 1855. Napoleon III backed him and is said to have kept aluminium cutlery for his most important guests. In December 1884 a 100-ounce aluminium pyramid crowned the Washington Monument, at $1.10 an ounce, about the price of silver.

Aluminium tableware of the Second Empire, when the metal was worth as much as silver.

In 1886 two men aged 22 found the same answer. On 23 February in Oberlin, Ohio, Charles Martin Hall, with home-made batteries, obtained globules of aluminium from alumina dissolved in cryolite. Paul Héroult, who had spent his inheritance on a dynamo, filed a French patent on 23 April. Hall's Pittsburgh company, later Alcoa, began production in 1888; Héroult's process went to work at Neuhausen, by the Rhine Falls. Karl Josef Bayer filed his seeded precipitation of alumina in 1887 and his pressure digestion of bauxite in 1892; together they made pure alumina cheap.

A pound cost about $4.86 in 1888 and under a dollar in the early 1890s. The Wright brothers' 1903 engine had an aluminium crankcase; heat-treated alloys such as duralumin, sold from about 1909, went into airships and aircraft. Smelters made about 74 million tonnes of new metal in 2025.

Key figures

Cell temperature
About 950–980 °C

Ore to metal
2–3 t of bauxite per tonne of alumina; about 2 t of alumina per tonne of metal

Primary output
About 74 million tonnes in 2025 (USGS estimate), 45 million of them in China

Electricity
About 13–15 kWh per kilogram of aluminium

Recycling
About 5% of the energy of new metal (8.3 against 186 GJ per tonne, 2019)

Sources

1. Aluminum: Common Metal, Uncommon Past · Science History Institute, Distillations https://www.sciencehistory.org/stories/magazine/aluminum-common-metal-uncommon-past/
2. The Washington Monument's aluminum capstone · National Park Service https://www.nps.gov/articles/000/wamocap.htm
3. Production process: Refining · International Aluminium Institute https://alustory.international-aluminium.org/?p=374
4. Production process: Reduction · International Aluminium Institute https://alustory.international-aluminium.org/?p=1905
5. Aluminium recycling saves 95% of the energy needed for primary aluminium production · International Aluminium Institute https://international-aluminium.org/landing/aluminium-recycling-saves-95-of-the-energy-needed-for-primary-aluminium-production/
6. Alumina refining · Australian Aluminium Council https://aluminium.org.au/?p=227
7. Aluminium smelting · Australian Aluminium Council https://aluminium.org.au/how-aluminium-is-made/aluminium-smelting-chart/
8. Ionic liquids as electrolytes in aluminum electrolysis (Wu et al., 2022) · Frontiers in Chemistry https://www.frontiersin.org/journals/chemistry/articles/10.3389/fchem.2022.1014893/full
9. Aluminum (Mineral Commodity Summaries 2026) · U.S. Geological Survey https://pubs.usgs.gov/periodicals/mcs2026/mcs2026-aluminum.pdf
10. Aluminum (Al) · U.S. Geological Survey https://pubs.usgs.gov/sir/2017/5118/elements/Aluminum/Al_txt.html
11. Aluminium : historique · Encyclopædia Universalis https://www.universalis.fr/encyclopedie/aluminium/2-historique/
12. Hall, Charles · Encyclopedia.com https://www.encyclopedia.com/science/news-wires-white-papers-and-books/hall-charles
13. K. J. Bayer, Process of obtaining alumina, US 382,505 (filed 1887) · Google Patents https://patents.google.com/patent/US382505A/en
14. K. J. Bayer, Process of making alumina, US 515,895 (filed 1892) · Google Patents https://patents.google.com/patent/US515895A/en
15. Aluminium · Wikipedia https://en.wikipedia.org/wiki/Aluminium

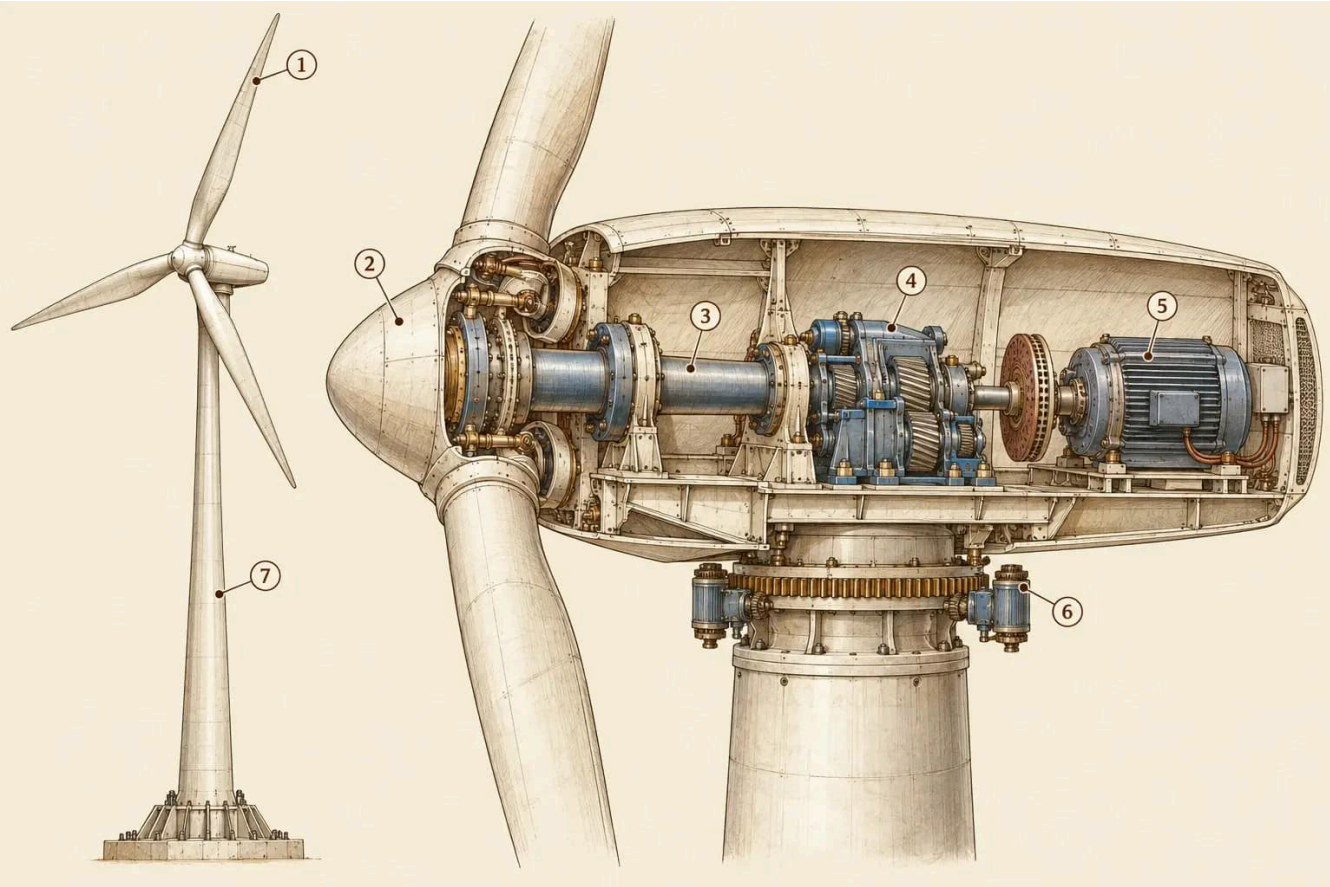
Fact-checked on 2026-10-14

Wind Turbine

Wind turned into electricity

1887 · Electric age · Electric age

Requires: Windmill (p. 181), Electric Generator (p. 266), Lead-Acid Battery (p. 294), Steel (p. 137)



1 Blade 2 Hub with pitch bearings 3 Main shaft (low speed) 4 Gearbox 5 Generator 6 Yaw ring and motors 7 Tower

A wind turbine is a rotor of long, wing-shaped blades that the wind turns, driving an electric generator at the top of a tower. Small ones charge batteries; large ones, with rotors more than a hundred metres across, feed the grid through a transformer.

What it is

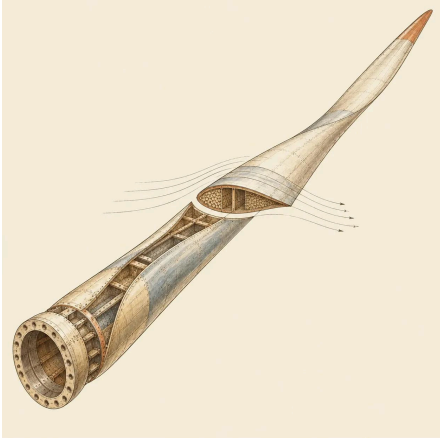
A wind turbine is a windmill built to make electricity: the rotor turns a shaft, and the shaft drives a generator. The machine drawn here has the layout of almost every large turbine today. Three slender blades (1) face the wind in front of a steel tower (7), and the nacelle on top holds the drive train and turns to follow the wind.

How it works

The power in the wind is $P = ½·ρ·A·v^3$: ρ is the density of air, about 1.2 kg/m^3, A the area swept by the rotor and v the wind speed. A rotor 3 metres across sweeps about 7.1 m^2. At 6 m/s the wind through it carries $½ × 1.2 × 7.1 × 6^3 ≈ 920$ watts; at 12 m/s, eight times as much, about 7.4 kW. That is why turbines stand on tall towers, where the wind is stronger.

A rotor cannot take all of that power. It extracts energy by slowing the air, but the slowed air must still move away, or no fresh air could come through. Around 1920 the German physicist Albert Betz showed that the best possible share is 16/27, or 59.3%. Real turbines typically capture about 35 to 45% over their working range; a large modern rotor at its best operating point comes close to 48%, and the gearbox and generator lose a little more.

Modern blades are aerofoils and work by lift, like an aircraft wing. Moving fast across the wind, a blade meets air coming mostly from the side, and the lift on its section pulls it round. The tip-speed ratio, the speed of the blade tip divided by the wind speed, is about 7 on three-bladed grid turbines: in a 10 m/s wind the tips travel at about 70 m/s.



The blade section is a wing. It twists along its length because the tip moves much faster than the root.

In the hub (2), each blade sits in a large bearing so that it can be turned about its own axis. This pitch control lets the rotor capture as much as it can below the rated wind speed and limits the power above it. The turbine starts at the cut-in speed, about 3 to 5 m/s, and reaches full power at its rated speed. Above the cut-out speed, about 25 to 29 m/s, it turns its blades edge-on, the rotor slows, and a brake holds it. A wind vane on the nacelle signals the direction, and yaw motors (6) turn the nacelle on a toothed ring, as the fantail did on a windmill.

On large machines the main shaft (3) turns at about 8 to 20 revolutions a minute. In a classic drivetrain, a gearbox (4) speeds this up about a hundredfold for the generator (5), which turns at more than a thousand revolutions a minute. Other designs use a medium-speed generator with less gearing, or no gearbox at all and a large, slow generator with many magnet poles. Power electronics match the output to the grid's frequency, and a step-up transformer raises the voltage.

How to build

A small turbine can charge a 12-volt lead-acid battery. Build it from a published, tested plan that specifies the blades, the mast and the overspeed protection; the steps below show what such a plan covers. Check local planning rules and talk to the neighbours first.

Choose the site. Near the ground the wind is weak and turbulent. A common rule puts the bottom of the rotor at least 9 metres above any obstacle within 90 metres. An anemometer at the planned height gives a first idea after a few weeks; a full year shows the seasons.

Pick the generator. A permanent-magnet DC motor, for example from a treadmill, works as a generator. Turn it with a drill at known speeds, with a 12-volt load connected, and measure voltage and current: it should deliver a useful current above about 14 volts at a few hundred revolutions a minute, a speed the rotor can reach.

Make the rotor. Plans for small machines often cut the blades from plastic pipe or carve them from light, straight-grained wood. Use the plan's pipe grade, wall thickness and blade shape: pipe blades tire and can crack at the root. Clamp each root between two metal plates on the hub, balance the rotor until it stays put in any position, and replace a blade at the first crack. A rotor 1.1 metres across catches about 70 watts of wind at 5 m/s; 10 to 20 watts at the battery is a rough guess that only a measurement can confirm.

Mast and tail. A flat tail vane on a boom keeps the rotor facing the wind. Mount the motor on a pivot at the top of a steel pipe with a hinged foot, and anchor guy wires at half to three-quarters of the mast's height from its base, so that it can be tilted down. Use the plan's mast, anchors rated for the load and a hand winch to raise it.

Blades cut from plastic pipe, a treadmill motor and a sheet-metal tail.

Protect it from overspeed. In a gust, or without an electrical load, a rotor can spin until it breaks. An outdoor turbine needs automatic protection: many small turbines have a hinged tail that furls, turning the rotor out of strong wind; others rely on stall or on blades that change pitch. Without such protection a turbine must not run outdoors, and even with it, stop and lower a small turbine before a storm.

Wire it. Connect the generator to the battery through a fuse and a blocking diode, which stops the battery from driving the motor. A diversion charge controller, rated for the generator's current and wired as its own diagram shows, watches the battery voltage and switches the power into a dump load once the battery is full: resistors rated for the full output at battery voltage, since a mains heater takes far too little at 12 volts. A switch that shorts the generator slows the rotor in light wind but does not lock it; tie a blade to the mast before handling the rotor.

For a desk version, put a toy motor with card blades in front of a fan and measure the voltage at each fan speed.

> **Safety.** Blade tips move much faster than they seem: never stand in the plane of the rotor. Never climb a mast while the turbine can turn; stop it and tilt the mast down. Keep people farther away than the mast's height while raising or lowering it, and keep the whole mast and its fall zone well clear of overhead power lines. Lead-acid batteries contain sulfuric acid and give off explosive hydrogen while charging: keep them in a ventilated box, away from sparks and living rooms. A short circuit across a battery can melt wires and start a fire. Never connect a turbine to a building's wiring or to the grid yourself; that needs an approved inverter and a qualified electrician.

History and evolution

In July 1887 James Blyth, a Glasgow professor, put up a windmill with four cloth sails at his holiday cottage in Marykirk, Scotland. Its dynamo charged accumulators that lit the cottage. A wind-driven dynamo had been shown in Vienna in 1883, but Blyth's is the first well-documented one in regular use.

In the winter of 1887–88 Charles F. Brush built a wind dynamo in Cleveland, Ohio, with 144 cedar blades on an 18-metre tower. It charged 12 batteries. Its dynamo is usually given as 12 kW, though a later newspaper account says 1.2 kW. From 1891 Poul la Cour tested turbines at Askov in Denmark; later he also trained rural electricians to build them.

Brush's machine in Cleveland: 144 cedar blades on a rotor 17 metres across.

American farms bought battery-charging turbines in large numbers; the Jacobs brothers alone made about 20,000 before closing in 1956, once the grid reached the farms. On 19 October 1941 the two-bladed Smith–Putnam turbine in Vermont, rated at 1.25 MW, was connected to the grid; it lost a blade in 1945. In 1957 Johannes Juul built a 200 kW turbine at Gedser, Denmark, with three blades, stall control and an induction generator. This "Danish concept" shaped the turbines built from the late 1970s.

In 2025 a 26 MW prototype with a 310-metre rotor went up for testing in China. That year wind produced 8.5% of the world's electricity.

Key figures

First wind electricity in regular use

James Blyth, Marykirk (Scotland), July 1887

Power in the wind

$P = ½·ρ·A·v^3$: twice the wind speed gives eight times the power

Betz limit

At most 59.3% (16/27) of the wind's power; large rotors peak near 48%

Working range

Starts at about 3–5 m/s; shuts down above about 25–29 m/s

Share of world electricity

8.5% in 2025

Sources

1. July 1887: James Blyth harnesses the wind · American Physical Society, APS News https://www.aps.org/apsnews/2022/07/james-blyth-harnesses-wind
2. James Blyth (1839-1906) · The Mills Archive Trust https://millsarchive.org//biography/james-blyth-1839-1906
3. Charles Brush Used Wind Power 120 Years Ago · Teaching Cleveland https://teachingcleveland.org/charles-brush-used-wind-power-120-years-ago/
4. Charles Brush and Some Notes on Early Wind Turbine Development (P. Gipe) · Wind-Works https://wind-works.org/charles-brush-and-some-notes-on-early-wind-turbine-development/
5. Charles F. Brush · Wikipedia https://en.wikipedia.org/wiki/Charles_F._Brush
6. Old Wind and Electricity (Engines of Our Ingenuity, episode 552, J. H. Lienhard) · University of Houston https://engines.egr.uh.edu/episode/552
7. Poul la Cour · Wikipedia https://en.wikipedia.org/wiki/Poul_la_Cour
8. The inventor who turned a folk high school into a laboratory · Carlsberg Foundation https://carlsbergfondet.dk/en/anniversary-stories/the-inventor-who-turned-a-folk-high-school-into-a-laboratory/
9. Flashbacks: The First Wind Power Boom · NRECA, RE Magazine https://www.cooperative.com/remagazine/articles/Pages/Flashbacks-The-First-Wind-Power-Boom.aspx
10. Original Company · Jacobs Wind https://jacobswind.net/history/original-company/
11. 79th anniversary of first wind turbine interconnection with the grid in North America (P. Gipe) · Wind-Works https://wind-works.org/79th-anniversary-of-first-wind-turbine-interconnection-with-the-grid-in-north-america/
12. Gedser wind turbine · Wikipedia https://en.wikipedia.org/wiki/Gedser_wind_turbine
13. How a Wind Turbine Works (text version) · U.S. Department of Energy, Wind Energy Technologies Office https://www.energy.gov/eere/wind/how-wind-turbine-works-text-version
14. Betz limit · Energy Education, University of Calgary https://energyeducation.ca/encyclopedia/Betz_limit
15. Simulation of Variable Speed Wind Turbines based on Open-Source Solutions (2021) · International Journal of Electrical Engineering & Education, via arXiv https://arxiv.org/pdf/2103.01759
16. Definition of a 5-MW Reference Wind Turbine for Offshore System Development (NREL/TP-500-38060, 2009) · National Renewable Energy Laboratory https://docs.nlr.gov/docs/fy09osti/38060.pdf
17. Small Wind Electric Systems: A U.S. Consumer's Guide (DOE/GO-102007-2465, August 2007) · U.S. Department of Energy / National Renewable Energy Laboratory https://docs.nlr.gov/docs/fy07osti/42005.pdf
18. World electricity data · Ember https://ember-energy.org/countries-and-regions/world/
19. Dongfang installs world's largest single-capacity offshore wind turbine for testing · offshoreWIND.biz https://www.offshorewind.biz/2025/09/03/dongfang-installs-worlds-largest-single-capacity-offshore-wind-turbine-for-testing

Fact-checked on 2026-10-14

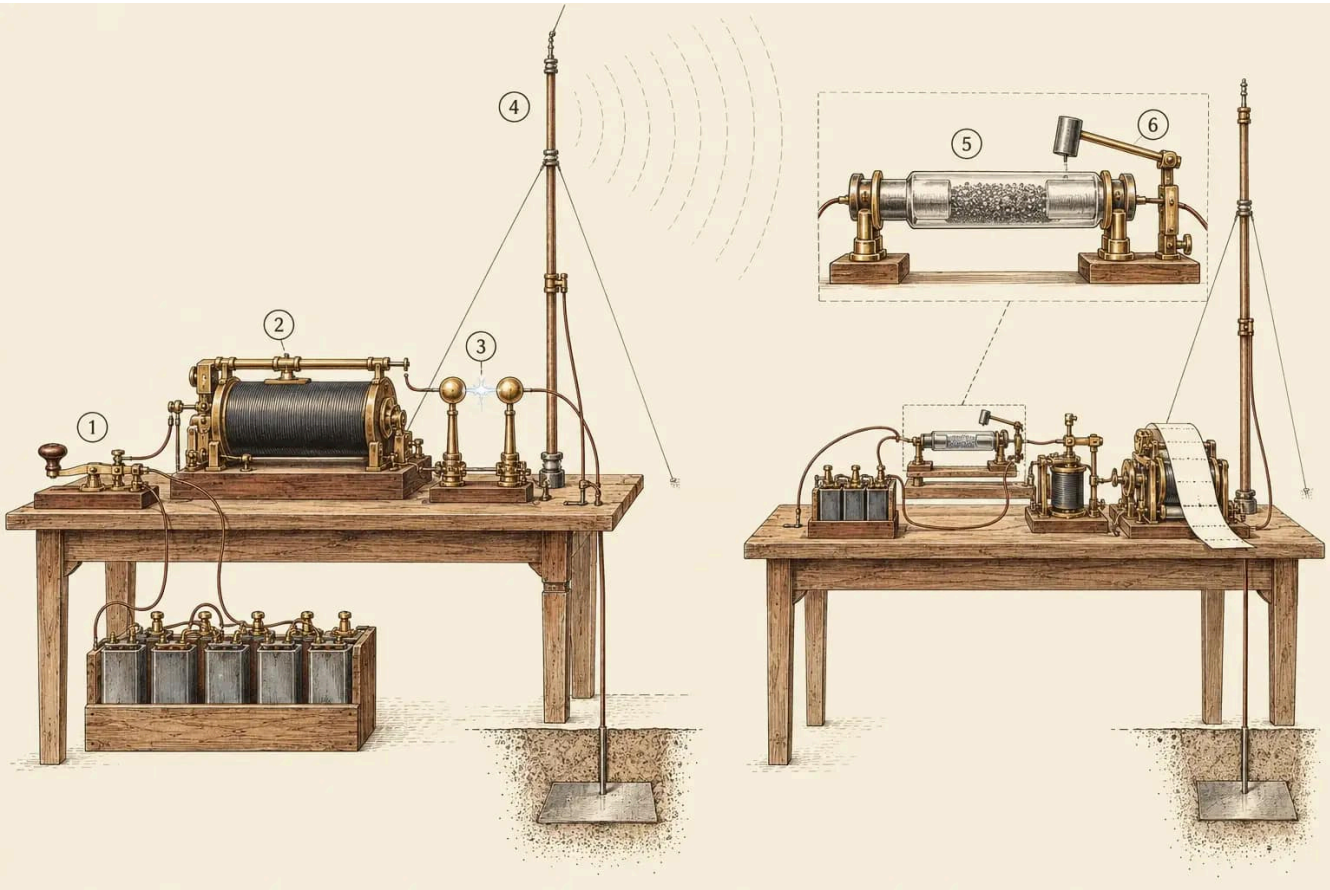
Radio

Messages without wires

c. 1895 · Electric age · Electric age

Requires: Electric Telegraph (p. 278), Electric Generator (p. 266)

Leads to: Transistor (p. 347)



1 Morse key 2 Induction coil 3 Spark gap 4 Aerial 5 Coherer 6 Tapper

Radio sends signals through space as electromagnetic waves, made by a rapidly oscillating current in one wire and picked up by another wire far away. Guglielmo Marconi turned laboratory experiments into a working wireless telegraph in 1895, and broadcasting of speech and music followed in the early twentieth century.

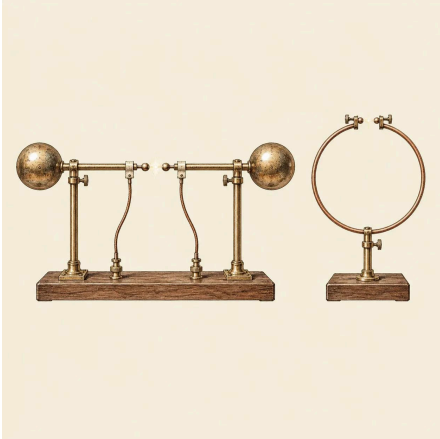
What it is

A radio transmitter makes a current swing back and forth very fast in a wire, the aerial or antenna, which sends out electromagnetic waves travelling at the speed of light. Where the waves meet another wire, they set up a tiny copy of the original current, and a receiver turns it into sound or into marks on paper.

The plate shows the first practical system, Marconi's spark telegraph of 1896, which could send only the dots and dashes of Morse code. By the early 1920s, stations were broadcasting speech and music to receivers in people's homes.

How it works

In the transmitter, a battery feeds an induction coil through the Morse key. The coil steps the voltage up to many thousands of volts and charges two brass balls separated by a small gap. When the voltage is high enough, a spark jumps the gap and, while it lasts, lets the charge surge back and forth through the aerial at very high frequency. Each spark sends out a short burst of waves. A brief press of the key gives a dot at the receiver, a longer one a dash.



When a spark crossed Hertz's oscillator, a tiny spark jumped the gap in the ring across the room.

Marconi raised a long vertical wire on a mast and connected the other side of the spark gap to a metal plate buried in the ground. With this grounded aerial the range grew from a few hundred metres to kilometres.

In a cat's whisker detector, a fine wire on a galena crystal lets current pass in one direction only.

The receiver also had an aerial and an earth, with a coherer between them: a small glass tube of loose metal filings between two silver plugs. The filings normally conduct badly. Arriving waves make them cling together and conduct, so a local battery can push current through them and work a relay, which drives a bell or a Morse inker. A small hammer, the tapper, then knocks the tube to shake the filings loose for the next signal.

Spark transmitters spread their energy over a wide band of frequencies and interfered with one another. Tuned circuits, made of a coil and a capacitor, let each station keep to its own frequency. Later transmitters sent a continuous wave and varied its strength to follow a voice, which is amplitude modulation, or AM. In the receiver a detector, first a crystal and later a vacuum tube, removes the radio wave and leaves the sound.

How to build it

The simplest working radio is the crystal set. It needs no battery, since all its power comes from the station's waves. The coil and capacitor below tune over much of the medium-wave AM band, depending on the aerial, and the set works best within reach of a strong transmitter.

Put up an aerial. Stretch 15 to 30 metres of copper wire as high and straight as you can between two trees or posts, with insulators at both ends, and bring a lead-in wire down to the set.

Make an earth. Drive a copper or galvanised rod a metre into damp ground and connect it with a short, thick wire. Never use a gas pipe.

Wind the coil. On a cardboard or plastic tube about 8 cm across, wind 60 to 90 turns of enamelled copper wire 0.3 to 0.5 mm thick, side by side. Make a tap every ten turns and scrape the enamel off where you will connect.

Add a tuning capacitor. A variable capacitor with a maximum of about 350 to 500 picofarads, bought or taken from an old battery radio, goes across the coil and tunes between stations. Do not open old mains-powered sets: their capacitors can hold a dangerous charge long after unplugging. Without a variable capacitor, you can still tune roughly by moving the aerial from tap to tap.

Fit a detector. A germanium diode is easiest. A lump of galena touched lightly by a fine wire also works, with patience.

Wire and listen. Connect the earth to the bottom of the coil and the aerial to one of the taps: fewer turns tune higher frequencies, more turns lower ones, and a long aerial often works best on a tap partway up. Connect the detector and the earpiece in series, and put that pair across the coil as well. Use a high-impedance crystal earpiece with a resistor of about 50 to 100 kilohms across it, or old high-impedance headphones; modern low-impedance earbuds load the circuit too heavily. Turn the capacitor slowly.

> **Safety.** An outdoor aerial attracts lightning: disconnect it and connect it to earth before a storm approaches, and never touch it during one. The earth rod of the set is not lightning protection; a permanent outdoor aerial needs a proper arrester and earthing installed to local rules. Keep every wire well away from power lines, since contact can kill, and do not climb roofs without a secure ladder and a second person. Do not build a transmitter: most transmitters need a licence, and spark transmitters are banned everywhere because they jam other services. Induction coils produce thousands of volts and give painful, dangerous shocks.

History and evolution

In 1865 James Clerk Maxwell predicted that electric and magnetic fields could travel together as waves. Between 1886 and 1888 Heinrich Hertz, in Karlsruhe, produced such waves with sparks, detected them across his laboratory with a ring of wire and showed that they behaved like light. Édouard Branly (1890) and Oliver Lodge (1894) developed the coherer, a tube of metal filings that conducts when the waves arrive. On 7 May 1895 Alexander Popov showed a receiver with a self-tapping coherer in St Petersburg, built to record distant lightning.

Guglielmo Marconi, working at his family's Villa Griffone near Bologna, aimed at telegraphy from the start. In summer 1895, with a grounded vertical aerial, he sent signals about two kilometres past the Celestini hill, and a helper on the far side fired a shot to confirm them. In 1896 he moved to England and filed his patent. On 12 December 1901, at Signal Hill in Newfoundland, he and George Kemp heard the three dots of the letter S sent from Poldhu in Cornwall, through a wire held up by a kite. Some historians think they heard only static, but regular transatlantic service began in 1907.

The triode valve amplified weak signals, which improved reception and helped broadcasting spread.

On 21 December 1906 Reginald Fessenden sent speech and music by radio from Brant Rock, Massachusetts, before invited witnesses. He later wrote that on Christmas Eve he broadcast a programme to ships at sea; that account dates from 1932, and no record of it from 1906 has been found. On 2 November 1920 the Westinghouse station KDKA in Pittsburgh broadcast the results of the presidential election, and transistors made radios pocket-sized in the 1950s.

Key figures

Radio waves demonstrated
Heinrich Hertz, 1886 to 1888

Marconi's signals cross a hill
About 2 km, summer 1895

Marconi's reported transatlantic reception
12 December 1901, the Morse letter S

Speech and music by radio
21 December 1906, Fessenden's demonstration at Brant Rock

Sources

1. Milestones: Marconi's Early Experiments in Wireless Telegraphy, 1895 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Marconi%27s_Early_Experiments_in_Wireless_Telegraphy,_1895
2. Milestones: Reception of Transatlantic Radio Signals, 1901 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Reception_of_Transatlantic_Radio_Signals,_1901
3. Milestones: Popov's Contribution to the Development of Wireless Communication, 1895 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Popov%27s_Contribution_to_the_Development_of_Wireless_Communication,_1895
4. Experiments and Results in Wireless Telephony (John Grant, 1907) · The American Telephone Journal, via earlyradiohistory.us https://earlyradiohistory.us/1907fes.htm
5. Results by Radio: Election Day 1920 · The Henry Ford https://www.thehenryford.org/collections/explore/articles/detail/articles/2020/10/15/results-by-radio-election-day-1920
6. Fessenden: World's First Broadcaster? · Radio World (James O'Neal) https://www.radioworld.com/news-and-business/fessenden-worlds-first-broadcaster
7. Circular 120: Construction and Operation of a Simple Homemade Radio Receiving Outfit (1922) · US Bureau of Standards, via NIST https://nvlpubs.nist.gov/nistpubs/Legacy/circ/nbscircular120.pdf
8. Simple Inductance Formulas for Radio Coils (H. A. Wheeler, 1928) · Proceedings of the IRE https://doi.org/10.1109/JRPROC.1928.221309
9. Amateur Radio After World War One (1919-1925): 360 and 485 metres set aside for broadcasting, 1921 · Thomas H. White, United States Early Radio History https://earlyradiohistory.us/sec015.htm
10. Government Agricultural Broadcasting: 485 metres for crop reports and weather forecasts · Thomas H. White, United States Early Radio History https://earlyradiohistory.us/agric.htm

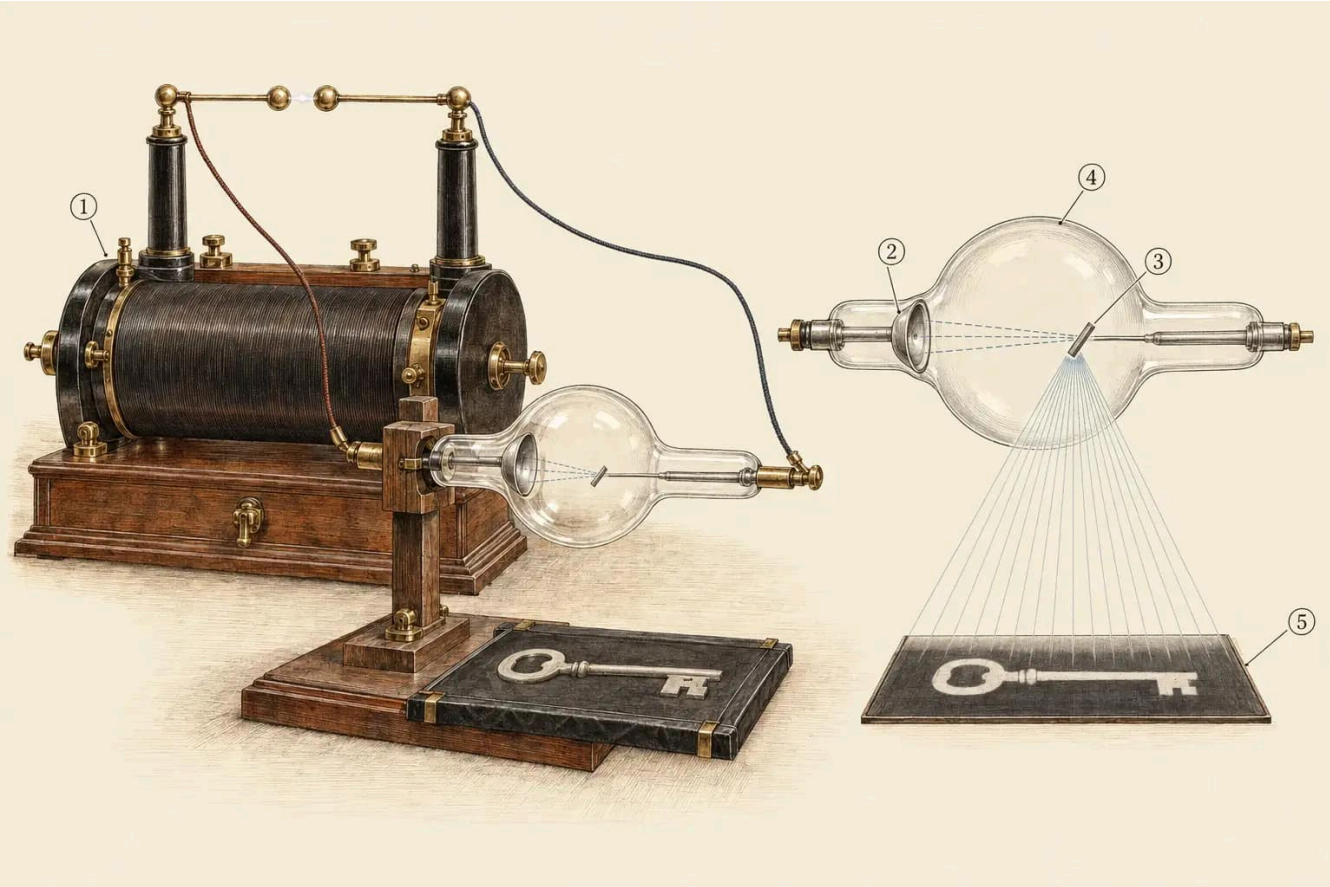
Fact-checked on 2026-10-11

X-Ray Imaging

Seeing through the body

1895 · Electric age · Electric age

Requires: Electric Generator (p. 266), Photography (p. 254)



1 Induction coil 2 Concave cathode 3 Tilted platinum anticathode 4 Glass globe 5 Photographic plate

X-ray imaging sends invisible, penetrating rays through the body onto a plate or detector, so that bones and dense tissues cast shadows. Wilhelm Röntgen discovered the rays in Würzburg on 8 November 1895, and by early 1896, weeks after he announced them, doctors in Europe and America were using them to find fractures and bullets.

What it is

X-rays are electromagnetic waves like light, but with much shorter wavelengths, roughly 0.01 to 10 nanometres against 400 to 700 for visible light, which lets them pass through materials that stop light. Dense matter absorbs more of them than light matter, so an object placed between an X-ray source and a sensitive plate leaves a shadow picture of its inside: bone, which contains calcium, stands out clearly against the flesh around it.

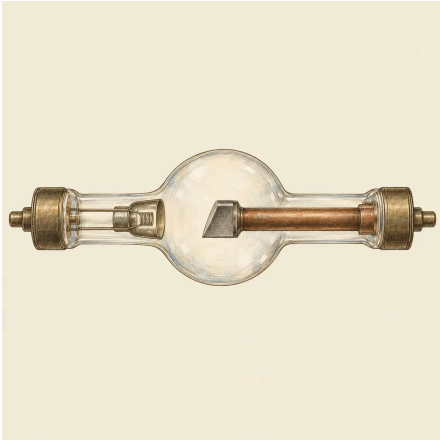
The apparatus on the plate is the kind used in 1896 and the following years. An induction coil turns the low voltage of a battery into tens of thousands of volts. Two wires carry that voltage to a “focus” tube, a glass globe pumped almost empty of air, with a concave aluminium cathode at one end and a small platinum plate, the anticathode,

tilted at 45 degrees in the centre. Below the tube lies a photographic plate wrapped in black paper, with the object to be pictured on top of it.

How it works

The tube still holds a trace of gas. The high voltage ionises it, and the positive ions, striking the cathode, knock electrons out of the metal, which the voltage then drives across the tube. These cathode rays, as they were then called, are invisible streams of electrons, and the amount of gas left in the tube governs how they behave. The concave cathode focuses them onto a small spot on the platinum anticathode. When the fast electrons are stopped in the metal, a small part of their energy comes out as X-rays; nearly all of it becomes heat. X-rays leave the target in many directions; because it is tilted, a useful beam comes out sideways through the glass toward the photographic plate, while the rest spreads round the room unless it is shielded.

The rays travel in straight lines from that small spot, which is why it matters: the smaller the spot, the sharper the shadows. Where the rays pass easily, through air or flesh, they blacken the photographic emulsion; where bone or metal absorbs them, the plate stays lighter. Printed or viewed directly, the plate shows the skeleton of a hand, a coin in a purse or a bullet in a limb.



The Coolidge tube of 1913: a heated tungsten filament supplies the electrons, so the output can be set precisely.

Early gas tubes were erratic: their behaviour changed as the remaining gas was used up. In 1913 William Coolidge of General Electric made a tube with a hard vacuum and a heated tungsten filament as the cathode. The current, and with it the amount of X-rays, could now be set by the filament temperature and their penetrating power by the voltage, which made doses repeatable. Modern tubes still follow that design.

How to build it

An X-ray apparatus cannot be built safely at home, and in most countries operating one needs a licence. X-rays damage living cells without being felt; the early workers learned this through burns, amputations and fatal cancers. This section describes how the first machines were made in laboratories, then gives two simple experiments that show the same principles.

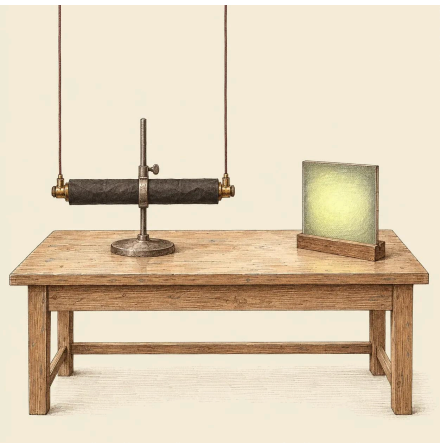
How it was done in 1896. Instrument makers wound induction coils of many kilometres of fine silk-covered wire over an iron core, fed them from batteries through a vibrating interrupter, and connected them to tubes made by glassblowers. The tubes were evacuated with mercury pumps over hours, sealed, and seasoned until they gave steady rays. A plate holder wrapped in black paper lay under the tube; exposures for a hand took several minutes at first, sometimes far longer, and less as tubes improved.

See shadows with light. In a dark room, fix a bright torch about 2 m from a wall and hold a pencil halfway. Tape a card with a 5 mm hole over the torch, then take it off so the whole lens shines: the small source gives a sharp shadow, the large one blurred edges, just as a small focal spot does in an X-ray tube. Then press the torch against a fingertip: it glows red, because red light gets through a centimetre of flesh.

See fluorescence. Röntgen noticed the rays because a screen coated with barium platinocyanide glowed. With an adult in charge and following the lamp's safety instructions, shine a low-power ultraviolet torch of the 365 nm "UV-A" kind on a glass of tonic water in a dark room: the quinine in it absorbs the invisible light and glows blue. Highlighter ink and some washing powders do the same.

> **Safety.** Never connect old vacuum tubes or cathode-ray tubes to a high voltage: when electrons strike the glass or metal inside, they can emit X-rays. Induction coils and other high-voltage supplies can deliver dangerous or fatal shocks. Ultraviolet light harms eyes and skin: never look into the torch, keep the beam off eyes and skin, wear UV-blocking glasses and choose a low-power torch sold for UV-A only. Medical X-rays are given by trained staff, with the dose kept as low as the examination allows.

History and evolution



Röntgen's discovery: a tube wrapped in black card, and a fluorescent screen nearby that glows all the same.

On the evening of 8 November 1895, Wilhelm Conrad Röntgen, professor of physics at Würzburg, was studying an electric discharge in a tube wrapped in black card. A paper screen coated with barium platinocyanide, lying some distance away, glowed each time the tube was switched on, although no light could leave the card. Over the next weeks he worked alone and showed that the unknown rays passed through paper, wood and flesh but were absorbed much more strongly by bone and by metals such as lead. On 22 December he photographed the hand of his wife, Anna Bertha, showing the bones and her ring. His paper "On a new kind of rays" appeared at the end of the month.

From early 1896, an X-ray plate could show a surgeon where a needle or a bullet lay before he cut.

The news spread at extraordinary speed, and about a thousand publications on X-rays appeared within a year. In early 1896 Herbert Jackson in London and others built focus tubes with a concave cathode and an angled metal target, which gave much sharper images. Surgeons used X-rays to locate bullets and needles; hospitals set up X-ray rooms. Röntgen received the first Nobel Prize in Physics in 1901.

The danger was not understood at first. Burns and hair loss were reported in 1896, and many early operators suffered disfiguring injuries; Clarence Dally, Thomas Edison's assistant, died in 1904 after years of exposure. Lead screens, dose limits and training followed. In 1912 Max von Laue's team showed that X-rays are waves by diffracting them through crystals, which opened the study of crystal structures. Computed tomography, which builds cross-sections from many X-ray measurements, earned Godfrey Hounsfield and Allan Cormack the Nobel Prize in 1979.

Key figures

Discovery
8 November 1895, University of Würzburg

Publication
"Über eine neue Art von Strahlen", end of December 1895; about 1,000 papers on X-rays within a year

First Nobel Prize in Physics
Röntgen, 1901

First radiograph of a hand
Anna Bertha Röntgen's, 22 December 1895

Hot-cathode tube
William Coolidge, 1913

Sources

1. Wilhelm Conrad Röntgen: biographical · Nobel Prize Outreach https://www.nobelprize.org/prizes/physics/1901/rontgen/biographical/
2. Röntgen discovers X-rays · HistoryofInformation.com https://www.historyofinformation.com/detail.php?id=550
3. Jackson X-ray tube (ca. 1896) · ORAU Health Physics Historical Instrumentation Museum https://www.orau.org/health-physics-museum/collection/x-ray-discharge/after-roentgen-tubes/jackson-x-ray-tube.html
4. Original Coolidge x-ray tube · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co32668/original-coolidge-x-ray-tube
5. The Nobel Prize in Physiology or Medicine 1979 · Nobel Prize Outreach https://www.nobelprize.org/prizes/medicine/1979/summary/
6. History of radiation protection · Wikipedia https://en.wikipedia.org/wiki/History_of_radiation_protection
7. John Francis Hall-Edwards: a radiology pioneer · Hektoen International https://hekint.org/2020/06/23/john-francis-hall-edwards-a-radiology-pioneer/
8. Blue plaque: Major Dr John Francis Hall-Edwards · Birmingham Civic Society https://birminghamcivicsociety.org.uk/blue-plaque-major-dr-john-francis-hall-edwards/
9. X-Ray Mass Attenuation Coefficients (NIST Standard Reference Database 126) · National Institute of Standards and Technology https://physics.nist.gov/PhysRefData/XrayMassCoef/
10. Diagnostic Radiology Physics: A Handbook for Teachers and Students, chapter 5 · International Atomic Energy Agency https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1564webNew-74666420.pdf
11. Characteristics of a first-generation x-ray system · Radiology (Radiological Society of North America) https://pubs.rsna.org/doi/10.1148/radiol.11101899
12. X-ray (the Duane–Hunt law) · Encyclopaedia Britannica https://www.britannica.com/science/X-ray

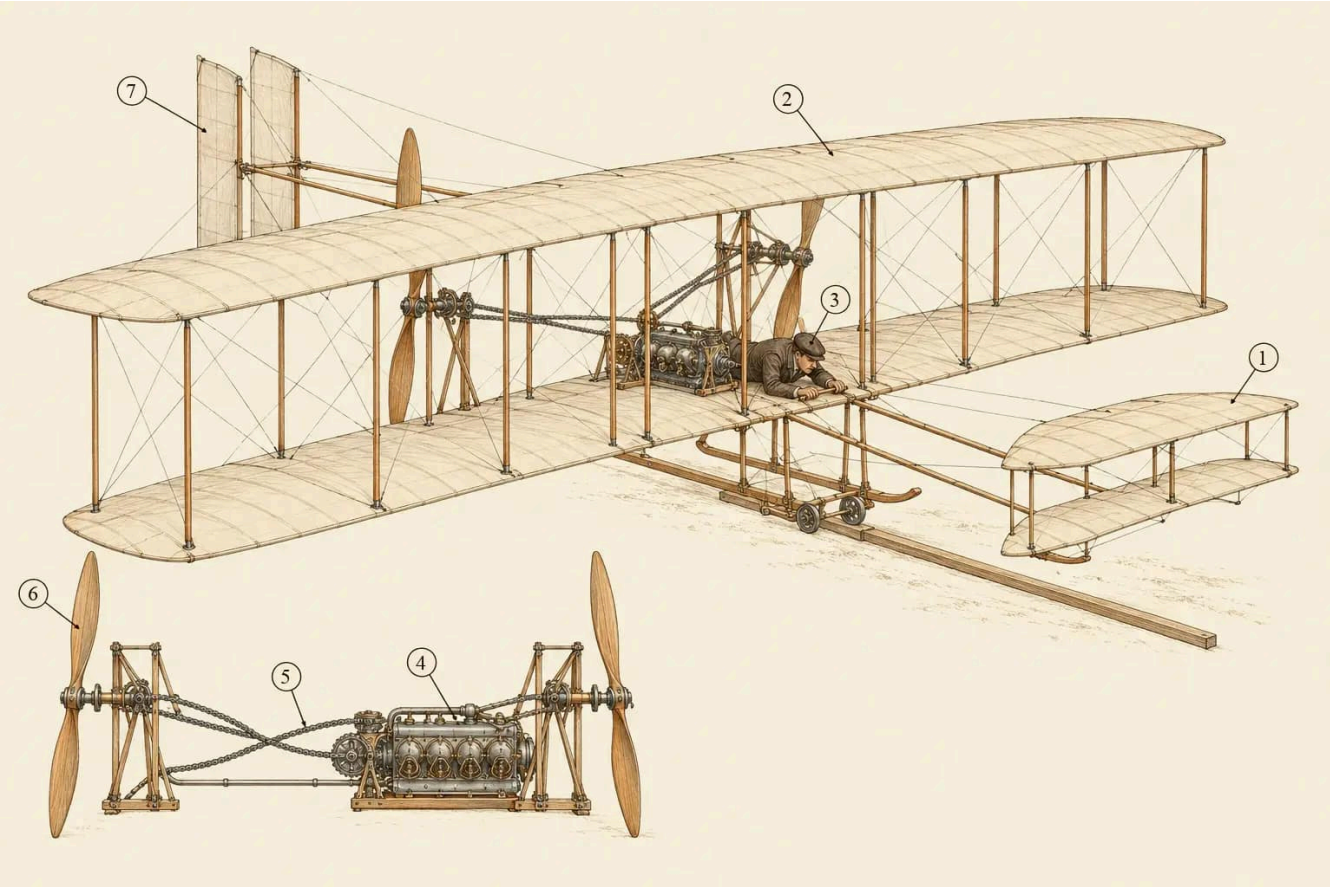
Fact-checked on 2026-10-12

Aeroplane

Lift, thrust and control

1903 · Electric age · Electric age

Requires: Internal Combustion Engine (p. 303), Aluminium (p. 322)



1 Forward elevator 2 Upper wing 3 Pilot's hip cradle 4 Engine 5 Drive chain 6 Propeller 7 Twin rudders

An aeroplane is a powered machine heavier than air that flies on fixed wings, with an engine to drive it forward and movable surfaces to steer it. Wilbur and Orville Wright made the first controlled, sustained powered flights at Kitty Hawk on 17 December 1903.

What it is

An aeroplane flies because air flowing over its wings holds it up. Unlike a balloon it is heavier than the air it moves through, so it has to keep moving to stay aloft. Three things are needed at once: wings that produce lift, an engine and propeller (or jet) that push the machine forward against drag, and controls that let the pilot keep it balanced and point it where it should go.

The machine on this plate is the Wright Flyer of 1903, a biplane of spruce and ash covered in unbleached muslin. The pilot lay face down on the lower wing. A small petrol engine beside him drove two wooden propellers behind the wings through bicycle-type chains. The elevator was at the front and a pair of rudders at the back. It had no wheels and took off from a wooden rail laid on the sand.

How it works

A wing is curved on top and set at a slight angle to the oncoming air. It deflects air downwards, and the air pushes back up on the wing. The pressure above the wing falls and the pressure below rises; the difference, spread over the whole wing area, is the lift. For a given wing and angle, lift grows with the square of the airspeed, so a plane needs a certain minimum speed to fly. Tilting the wing more raises lift only up to a point: beyond it the airflow breaks away from the upper surface and the wing stalls.

The engine has to overcome drag, the resistance of the air. The Wrights treated their propellers as rotating wings and designed them from their own wind-tunnel data. The two propellers turned in opposite directions so that their twisting effects cancelled out.

Air flowing round a cambered wing is turned downwards, and the wing is pushed up in return.

Control was the Wrights' main contribution. A plane can turn about three axes. Pitch (nose up or down) was set by the forward elevator, worked by a lever in the pilot's left hand. Roll (banking the wings) came from wing warping: by shifting his hips in the cradle, the pilot pulled cables that twisted the wingtips in opposite directions, giving one wing more lift than the other. The same cradle moved the rudders to keep the nose from swinging the wrong way in a turn. Ailerons, hinged flaps on the wings, later replaced warping, but the three-axis principle has not changed.

How to build it

Early aeroplanes were built by small workshops with woodworking and bicycle-making skills. What follows explains the decisions involved and how the pioneers worked. It is not a plan, and nobody should try to fly a home-made aircraft without training, inspection and the legal approvals required in their country.

Test before building. The Wrights flew gliders in 1900, 1901 and 1902 and built a small wind tunnel in 1901 to measure the lift and drag of model wings. Their own tables replaced older published data they had found to be wrong.

Frame of light, straight-grained wood. Spars and struts were spruce, curved ribs ash. The structure was a braced box: struts held the two wings apart and steel wires crossed between them. The central bays were rigidly braced, while the outer parts of the wings could twist slightly for warping.

Cover the wings. Muslin was cut on the bias and stretched over the ribs so the threads ran diagonally, which strengthened the covering.

Find a light engine. The Wrights could not find a maker willing to supply an engine light and powerful enough, so their mechanic Charlie Taylor built a four-cylinder water-cooled engine in about six weeks. Its crankcase was cast in aluminium to save weight.

Balance it. Fore and aft, the centre of gravity has to sit at the right place relative to the lift, or the machine pitches up or dives. From side to side the weights must balance too: the engine sat to one side of the pilot, so the Wrights made the right wing slightly longer to compensate.

> **Safety.** A turning propeller is invisible and can kill: never stand in its arc, and never start an engine by hand without training. Petrol and its vapour ignite easily. Wood and fabric structures fail without warning if a joint or wire is damaged. Flying requires training, a sound and inspected aircraft and suitable weather.

History and evolution

Lilienthal steered his gliders by swinging his body under the wings.

The modern approach to flight began with George Cayley in England, who around 1799 separated the three problems of lift, propulsion and control and later flew gliders. In Germany in the 1890s Otto Lilienthal made about two thousand glides from hills and published his measurements. He died in 1896 after a crash.

Wilbur and Orville Wright ran a bicycle business in Dayton, Ohio. They studied earlier aviation research, including Lilienthal's, then tested their ideas with kites and gliders at Kitty Hawk, North Carolina, chosen for its steady winds and soft sand.

On 17 December 1903 Orville flew the Flyer for 12 seconds over about 37 metres (120 feet). The brothers made three more flights that day; the last, with Wilbur at the controls, lasted 59 seconds and covered about 260 metres. A gust then overturned the machine and it never flew again. It has been at the Smithsonian in Washington since 1948.

In their 1901 wind tunnel the Wrights measured the lift and drag of many small model wings.

Others soon followed. Alberto Santos-Dumont flew in Paris in 1906, and Louis Blériot crossed the English Channel in 1909. The First World War turned aircraft into an industry. Metal monoplanes replaced wooden biplanes in the 1930s, and jet engines appeared at the end of the decade. Today airliners carry several hundred people across oceans, and their controls still act about the same three axes on which the Wrights first achieved practical control.

Key figures

First flight
17 December 1903, 12 seconds, about 37 m

Longest flight that day
59 seconds, about 260 m (Wilbur Wright)

Wingspan of the 1903 Flyer
12.3 m

Engine
4 cylinders, about 12 hp, aluminium crankcase

Weight
274 kg empty, 341 kg with pilot

Sources

1. 1903 Wright Flyer · Smithsonian National Air and Space Museum https://airandspace.si.edu/collection-objects/1903-wright-flyer/nasm_A19610048000
2. The Wright Flyer · US National Park Service https://www.nps.gov/articles/wrightflyer.htm
3. 1903 Engine · Wright Brothers Aeroplane Company https://wright-brothers.org/Information_Desk/Just_the_Facts/Engines_&_Props/1903_Engine.htm
4. Otto Lilienthal · Wikipedia https://en.wikipedia.org/wiki/Otto_Lilienthal
5. 1903 Wright Flyer Specifications · Wright Brothers Aeroplane Company https://wright-brothers.org/Information_Desk/Help_with_Homework/Wright_Plans/Wright_Plans_images/1903_Wright_Flyer_Specifications_Isometric_11x17.pdf
6. 1903 Wright Propellers · Wright Brothers Aeroplane Company https://wright-brothers.org/Information_Desk/Just_the_Facts/Engines_&_Props/1903_Props.htm
7. Wright 1903 Aircraft Engine Parts · NASA Glenn Research Center https://www.grc.nasa.gov/www/k-12/airplane/engparts.html

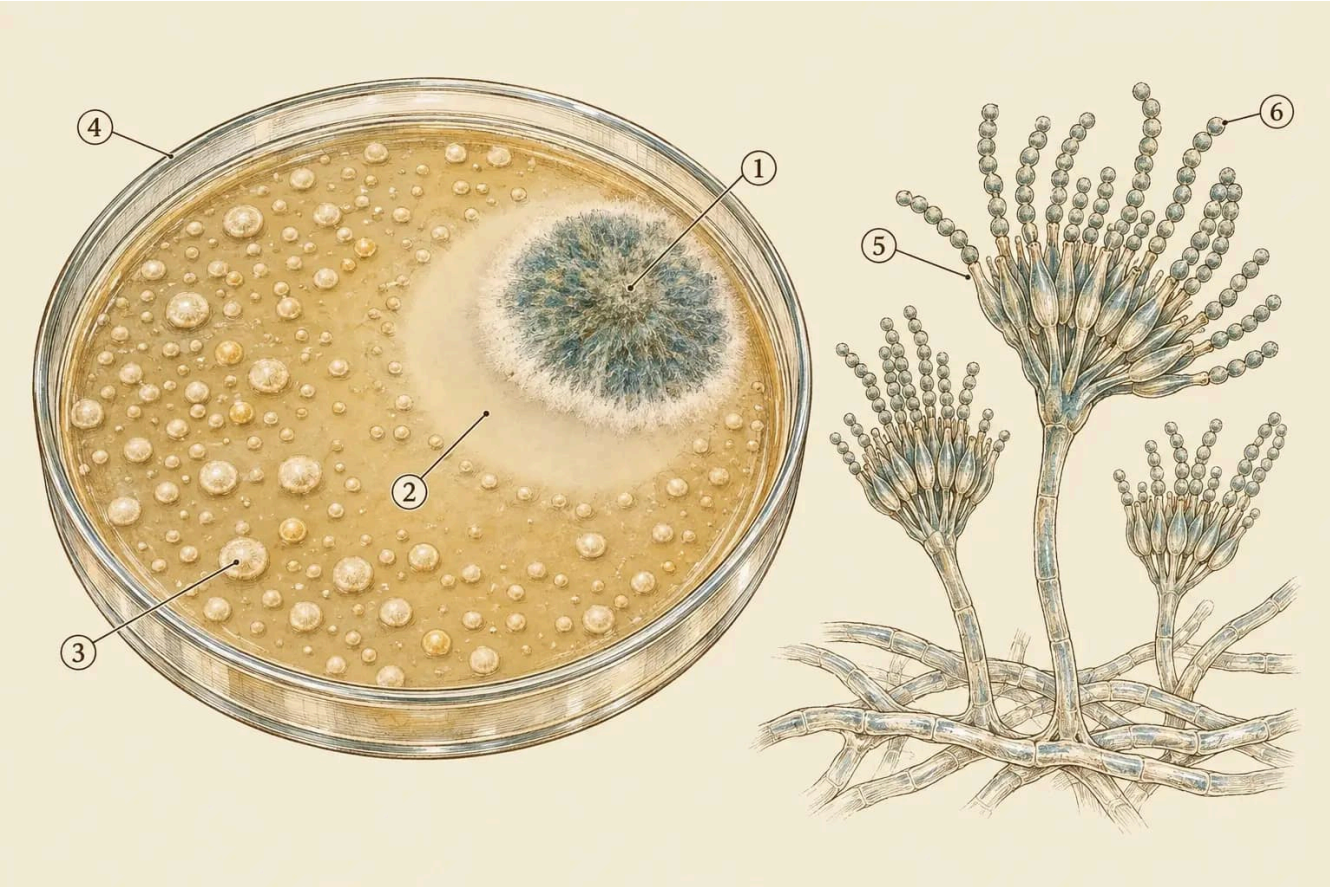
Fact-checked on 2026-10-11

Penicillin

An antibiotic made by a mould

1928 · Electric age · Electric age

Requires: Glass (p. 129), Vaccination (p. 229), Hygiene & Antisepsis (p. 290)



1 Penicillium mould colony 2 Clear zone around the mould 3 Bacterial colonies 4 Glass Petri dish 5 Brush-shaped spore head 6 Chain of spores

Penicillin is a substance made by Penicillium moulds that kills many kinds of bacteria by stopping them from building their cell walls. Alexander Fleming noticed it in 1928, and an Oxford team turned it into the first mould-derived antibiotic in wide medical use during the Second World War.

What it is

Penicillin is an antibiotic, a drug that kills bacteria or stops their growth. Unlike the synthetic sulfonamides of the 1930s, which came out of research on dyes, it is produced by a living organism. Certain strains of *Penicillium*, a genus that includes the blue-green moulds seen on old bread and fruit, produce it. Purified, penicillin became the first antibiotic from a mould that doctors could use widely, and it changed the outlook for infections that had often been fatal, such as blood poisoning, pneumonia and infected wounds. Mould on food, by contrast, is not a medicine and can itself be harmful.

The plate shows Fleming's famous observation on the left: a glass dish of bacterial colonies where a stray mould spore has landed by chance and grown into a colony, with a clear ring around it where the bacteria have died. On

the right is the mould itself under the microscope. Its spores grow in chains on little brush-like heads, which gave the genus its name, from the Latin *penicillus*, a small brush.

How it works

Most bacteria are single cells wrapped in a tough wall that holds them in shape against the pressure of the water inside. The wall is a mesh of sugar chains tied together by short peptide links. As the cell grows and divides, it keeps cutting and rebuilding this mesh.

Penicillin blocks the bacterial enzymes that tie the links. The cell goes on growing, but its new wall is weak. Water pushes in, and the cell bursts. Human and animal cells have no such wall, which is why penicillin can kill bacteria while leaving the patient's own cells largely untouched. At the heart of the molecule is a strained four-sided ring of atoms, the beta-lactam ring, which reacts with those enzymes and puts them out of action.

Penicillin works best on bacteria with a thick, exposed wall, such as streptococci and pneumococci. The bacterium that causes syphilis has a thin wall tucked between two membranes, yet it too is very sensitive to penicillin. Penicillin has no effect on viruses, which have no cell wall at all.

Bacteria can become resistant. Some make an enzyme, penicillinase, that cuts the beta-lactam ring before it can act. Every use of an antibiotic favours the bacteria that survive it, so resistance spreads where antibiotics are used carelessly. Fleming warned of this in his Nobel lecture in 1945. Some people are also allergic to penicillin, occasionally severely. Antibiotics are medicines to be used only on a doctor's prescription.

How it is made

Between 1940 and 1945 the ways of growing the mould, extracting the drug from the broth and measuring it all changed several times.

Surface culture in Oxford. Florey's team grew Fleming's strain of *Penicillium notatum* as a felt floating on a shallow layer of nutrient broth. Norman Heatley first used anything with a wide flat bottom, including bedpans, biscuit tins and pie dishes, then designed a rectangular ceramic vessel that could be stacked on its side for incubation. A Staffordshire pottery, James Macintyre & Co., made several hundred of them, and the first were seeded at Christmas 1940. A small team of young women, nicknamed the penicillin girls, sowed the spores, drew off the broth once the growing mould had released penicillin into it and kept the vessels going around the clock.

Norman Heatley designed ceramic vessels like these to grow the mould in quantity in Oxford.

Extraction. The broth held only a trace of penicillin, and the drug broke down within hours when warm or acid. Heatley used the fact that penicillin is an acid. Acidified and kept cold, it passes from the broth into a solvent that does not mix with water, first ether and then the less flammable amyl acetate. Shaken with water made slightly alkaline, it passes back into water as a salt, in a far smaller volume and freed from much of the impurity. Heatley built an apparatus of glass tubes, bottles and pumps that did this continuously. The concentrated solution was then freeze-dried into a brown powder that kept for months, although early batches were mostly impurity.

Measurement. Before its structure was known, penicillin could only be measured by what it did to bacteria. In Heatley's cylinder-plate assay, small open cylinders stand on a dish of agar seeded with staphylococci, each filled with a sample. The penicillin spreads out into the agar, and after incubation the width of the clear ring around

Heatley's cylinder-plate assay: the stronger the sample in a cylinder, the wider the clear ring around it.

each cylinder, compared with that of a standard, gives the strength. The Oxford team defined its own unit this way and sent samples to other laboratories. In 1944 and 1945 British and American scientists agreed an international unit, equal to 0.6 micrograms of pure sodium benzylpenicillin and close to the Oxford unit, and prepared standard samples.

Deep tanks in the United States. At the Northern Regional Research Laboratory in Peoria, Andrew Moyer, working with Heatley, raised yields about tenfold by late 1941 by adding corn steep liquor, a by-product of making starch from maize, to the broth. The laboratory tested moulds sent from all over the world, and a strain of *Penicillium chrysogenum* (now classed as *P. rubens*) from a mouldy cantaloupe bought in Peoria turned out to be the best. Strains bred from it, including mutants obtained with X-rays and ultraviolet light, did better still. The larger change was to grow the mould throughout the liquid instead of on its surface, in closed steel tanks that were stirred and fed with sterile air. Pfizer already used this method to make gluconic acid, and on 1 March 1944 (one account says 1943) it opened the first large plant for penicillin in Brooklyn, a converted ice factory, with fourteen tanks of 7,500 US gallons (about 28,000 litres) each. A single stray microbe could spoil a whole tank, so the broth and the tanks were sterilised before the mould was added, and the air and pipes kept other organisms out while it grew.

Deep-tank fermentation in the United States turned penicillin into an industrial product.

Semi-synthetic penicillins. Fermentation mainly yields benzylpenicillin, or penicillin G, especially when the broth is fed phenylacetic acid, which the mould builds into the molecule. In 1957 chemists at Beecham Research Laboratories in Surrey isolated the bare core of the molecule, 6-aminopenicillanic acid, and published the work in 1959. By attaching new side chains to this core, chemists made penicillins that survive stomach acid, resist the bacterial enzyme penicillinase or act on more kinds of bacteria, such as cloxacillin and amoxicillin. Today the core is usually cut from fermented penicillin with an enzyme, and factories test every batch for identity, purity and potency, and injectable forms for sterility, before release.

> **Safety.** This section describes how laboratories and factories produced the drug. Penicillin cannot be made safely at home: mould on bread or fruit contains little or none of it and may belong to species that make toxins, and an impure preparation can cause severe infection or shock. Penicillin can also cause serious allergic reactions, and it is used only on prescription.

History and evolution

People had noticed for centuries that some moulds seemed to help wounds, and in the 1890s several researchers reported that moulds could hold back bacteria. None of these findings led to a treatment.

Alexander Fleming, a bacteriologist at St Mary's Hospital in London, went on holiday in the summer of 1928. When he came back in early September he found that a dish of staphylococci had been contaminated by a mould, and that the colonies near it had faded away. He grew the mould, showed that its broth killed many kinds of bacteria,

named the active substance penicillin and published his results in 1929. But penicillin was unstable and hard to extract, and Fleming did not manage to obtain enough of it in pure form to treat patients.

Ten years later, at Oxford, Howard Florey and Ernst Chain took up the problem. Norman Heatley worked out how to extract and concentrate penicillin, and the team grew the mould in hundreds of vessels. On 25 May 1940 they infected eight mice with streptococci and treated four of them. By the next morning the four untreated mice were dead and the treated ones were still alive. In February 1941 a police constable, Albert Alexander, became one of the first patients. He improved at first, but the supply ran out and he died.

Wartime Britain could not produce penicillin on a large scale, so in 1941 Florey and Heatley went to the United States, where a government laboratory in Peoria, Illinois, and several drug companies took up the work. In March 1942 the American supply was enough to treat a single patient. By 1944 factories were making enough for the Allied armies, and from 15 March 1945 it reached American pharmacies through normal commercial channels.

Fleming, Florey and Chain shared the Nobel Prize in Physiology or Medicine in 1945. In the same year Dorothy Hodgkin worked out the structure of penicillin by X-ray crystallography. The search for other antibiotics had meanwhile produced streptomycin, discovered in 1943; the tetracyclines and many others followed, and chemists later made new penicillins by modifying the molecule.

Key figures

Fleming's observation
September 1928, St Mary's Hospital, London

Oxford mouse experiment
25 May 1940

First large deep-tank plant
Pfizer, Brooklyn, 1 March 1944, fourteen tanks of 7,500 US gallons (about 28,000 litres)

First published
June 1929, British Journal of Experimental Pathology

Nobel Prize in Physiology or Medicine
1945, Fleming, Florey and Chain

Sources

1. Alexander Fleming · Science History Institute https://www.sciencehistory.org/education/scientific-biographies/alexander-fleming/
2. Howard Walter Florey · Science Museum Group https://collection.sciencemuseumgroup.org.uk/people/cp38732/howard-walter-florey
3. The real story behind the world's first antibiotic · PBS NewsHour https://www.pbs.org/newshour/health/the-real-story-behind-the-worlds-first-antibiotic
4. History of penicillin · Wikipedia https://en.wikipedia.org/wiki/History_of_penicillin
5. “It looks like a miracle”: penicillin production in Oxford · History of Science Museum, University of Oxford https://www.mhs.ox.ac.uk/backfromthedead/exhibition/production/
6. Pfizer's penicillin pioneers: Jasper Kane and John McKeen · The Chemical Engineer (IChemE) https://www.thechemicalengineer.com/features/cewctw-pfizers-penicillin-pioneers-jasper-kane-and-john-mckeen/
7. How a moldy cantaloupe took Fleming's penicillin from discovery to mass production · The Scientist https://the-scientist.com/how-a-moldy-cantaloupe-took-fleming-s-penicillin-from-discovery-to-mass-production-72304
8. Standardizing the 'magic bullet' · Inventing Europe https://www.inventingeurope.eu/story/standardizing-the-magic-bullet
9. The Discovery of Penicillin · Sir William Dunn School of Pathology, University of Oxford https://www.path.ox.ac.uk/centenary/the-discovery-of-penicillin/
10. Biochromatograms showing the first ever acylation of 6-APA · Science Museum Group https://collection.sciencemuseumgroup.org.uk/objects/co8997116/biochromatograms-showing-the-first-ever-acylation-of-6-apa
11. Penicillin culture vessel, 1940–41 (National Museum of American History, M-06669) · Cooper Hewitt, Smithsonian Design Museum https://collection.cooperhewitt.org/objects/35457197/
12. Further observations on penicillin (The Lancet, 16 August 1941) · University of Oxford, NDORMS https://www.ndorms.ox.ac.uk/files/news/19410816_florey_furtherobservationsonpenicillin_lancet.pdf
13. Alexander Fleming, On the antibacterial action of cultures of a penicillium (1929), reprinted 2001 · Bulletin of the World Health Organization https://scielosp.org/article/bwho/2001.v79n8/780-790
14. Making penicillin in milk bottles: a tale of wartime antibiotic manufacture · The Pharmaceutical Journal https://pharmaceutical-journal.com/article/opinion/making-penicillin-in-milk-bottles-a-tale-of-wartime-antibiotic-manufacture

Fact-checked on 2026-10-12

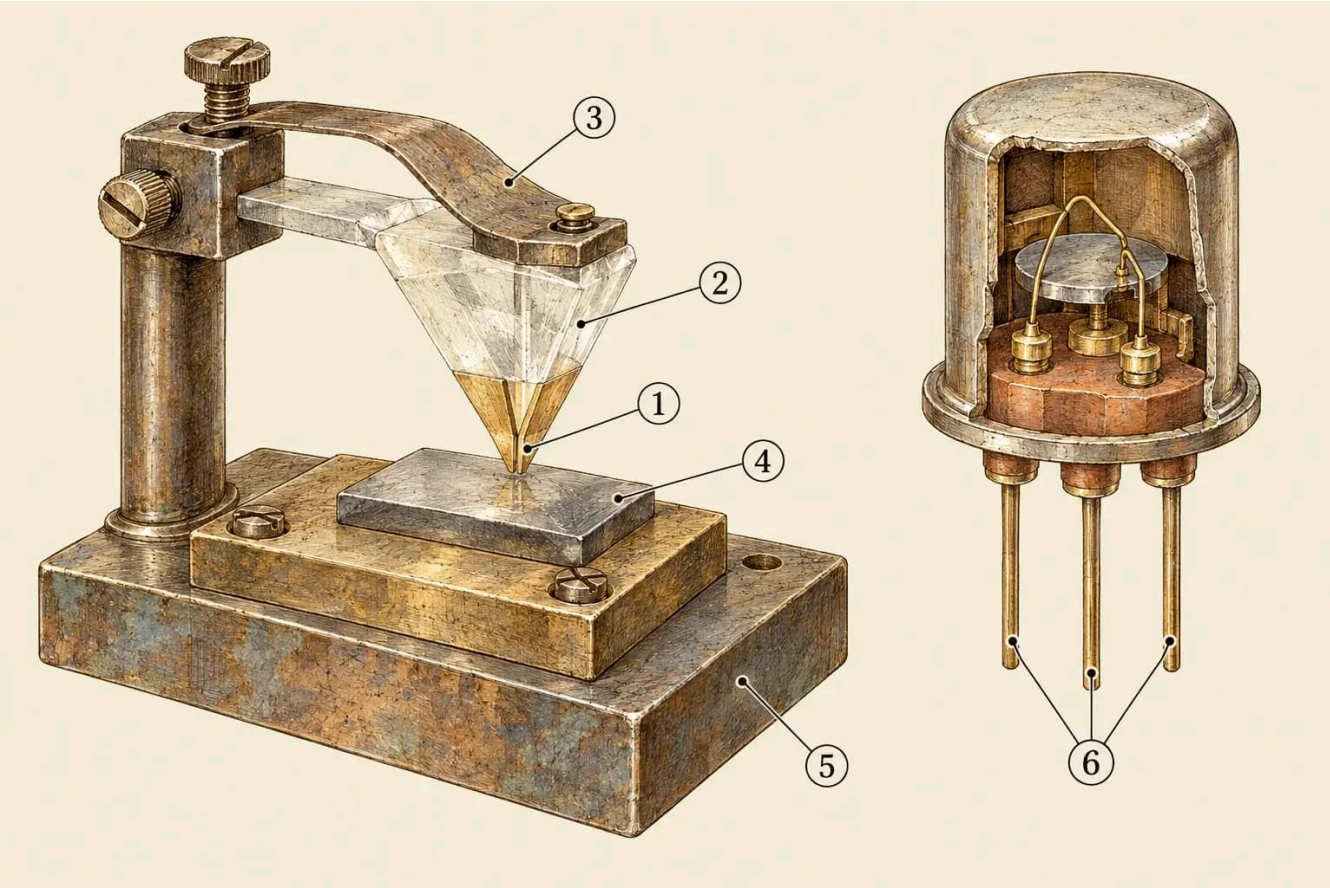
Transistor

A switch without moving parts

1947 · Modern age · Electric age

Requires: Radio (p. 330)

Leads to: Computer (p. 351), Solar cell (p. 355)



1 Gold-foil contacts 2 Plastic wedge 3 Spring 4 Germanium slab 5 Metal base 6 Leads of a junction transistor

A transistor is a small piece of semiconductor in which a weak current or voltage controls a much stronger current, so it can amplify a signal or act as a switch. John Bardeen and Walter Brattain made the first one at Bell Labs in December 1947, and chips now hold billions of them.

What it is

A transistor is a valve for electric current with no moving parts. A small current or voltage applied to one terminal controls a much larger current between the other two. Biased with a suitable steady current or voltage, it reproduces a weak signal with greater amplitude: that is amplification, the job it does in a radio or a hearing aid. Switched between fully conducting and fully blocked, it works as a switch, and a computer is built from billions of such switches.

The plate shows, on the left, the first transistor, the point-contact device Bardeen and Brattain built in 1947: a slab of germanium on a metal base, with a plastic wedge pressed onto it by a spring. A strip of gold foil runs over the tip

of the wedge and is slit with a razor so that two gold contacts touch the germanium a fraction of a millimetre apart. On the right is a junction transistor of the 1950s in its small metal can, with three wire leads.

How it works

Transistors are made from semiconductors such as germanium or silicon. A pure crystal of these elements conducts poorly. Adding a tiny trace of another element, called doping, raises its conductivity sharply. Phosphorus or arsenic gives the crystal spare electrons, which makes n-type material. Boron or gallium leaves gaps, called holes, that behave like positive charges, which makes p-type material.

Where p-type and n-type material meet, a junction forms that lets current pass easily in one direction only. A junction transistor stacks three layers, n-p-n or p-n-p, named the emitter, base and collector. The base is very thin. In an n-p-n transistor, a small current into the base lets a much larger current flow from collector to emitter, often a hundred times larger or more. In a p-n-p transistor all the directions are reversed.

Most transistors made today are field-effect transistors (MOSFETs). There, a voltage on a gate, insulated from the silicon by a thin layer of oxide, creates or closes a narrow conducting channel underneath. Almost no current flows into the gate while it holds its state. In the CMOS circuits used in chips, a transistor draws power mainly when it switches, which is one reason billions of them can share a single chip.

The vacuum tube did the same job before 1950, but it needed a hot filament, a glass envelope and far more power.

How to build it

Modern transistors are made in factories that need ultra-pure silicon, clean rooms and machines worth billions. What follows is a historical overview of how the first ones were made, in the order a rebuilding workshop would follow: first a point-contact detector, then a point-contact transistor, and only later junctions. It is not a recipe; anyone who wants to see a transistor at work should use a manufactured one in a low-voltage circuit.

Get a suitable crystal. Point-contact devices need a piece of n-type germanium of good purity. In the 1940s it came from wartime work on radar detectors. Galena (lead sulphide), the “cat’s whisker” crystal of early radio sets, only makes a crude detector diode.

Prepare the surface. The surface is ground flat and then etched clean, because the contact behaviour depends on it. This step uses strong acids and belongs in a properly equipped laboratory.

Make the contacts. Two sharp metal points, or a gold foil split over a plastic wedge as in 1947, must touch the crystal very close together. A spring holds them under light, steady pressure. The base of the crystal is soldered to a metal block that forms the third terminal.

Form and test. Early makers “formed” the collector contact by passing brief pulses of current through it, which improved the device’s gain, then measured each transistor. Many failed, and only those that passed the tests were kept.

Move to junctions. Grown-junction transistors need crystals pulled from a melt with controlled doping, which requires a furnace with fine temperature control and an inert atmosphere. Alloy-junction transistors, made from the early 1950s, were produced instead by fusing small pellets of indium onto both faces of a thin germanium wafer. Both are industrial processes.

> **Safety.** Etching acids burn skin and eyes; hydrofluoric acid, used to etch silicon, can poison the body through the skin with delayed symptoms, even from a small splash, and must be left to specialists. Germanium and silicon dust should not be breathed. Soldering irons cause burns, and old solder contains lead. Test circuits at low voltage; mains electricity can kill.

History and evolution

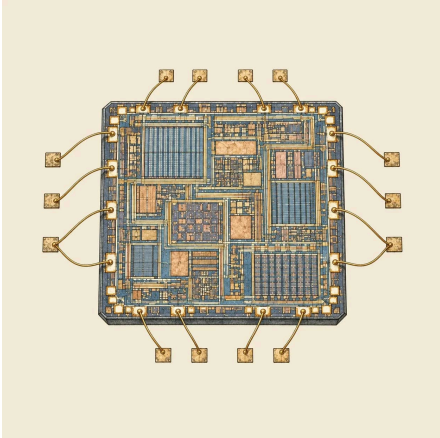
The Regency TR-1 of 1954 needed only four transistors.

Engineers had wanted a solid replacement for the vacuum tube since the 1920s. Julius Lilienfeld filed a patent for a field-effect device in 1925, but no working prototype is documented. After the Second World War, Bell Labs set up a solid-state physics group under William Shockley to find an amplifier for the telephone network. Shockley's field-effect design failed. John Bardeen traced the failure to electrons trapped at the surface of the crystal, and he and Walter Brattain then tried driving current through point contacts instead.

On 16 December 1947 their device amplified a signal. A week later they showed it to Bell Labs managers. The company announced the invention in New York on 30 June 1948, and the engineer John Pierce coined the name "transistor". In Paris that same year, Herbert Mataré and Heinrich Welker built a similar device independently, which they called the "transistron".

Point-contact transistors were fragile. In January 1948 Shockley conceived the junction transistor, which Bell Labs could produce from 1951. The Regency TR-1 pocket radio of 1954 used four germanium transistors from Texas Instruments and sold more than 100,000 units. Silicon, which copes better with heat, then replaced germanium.

In 1958 Jack Kilby at Texas Instruments built the first integrated circuit on a small bar of germanium. Mohamed Atalla and Dawon Kahng demonstrated the MOS transistor at Bell Labs in 1960. Bardeen, Brattain and Shockley shared the 1956 Nobel Prize in Physics. Since then transistors have kept shrinking, and the MOS transistor is now made in greater numbers than any other manufactured object.



An integrated circuit puts many transistors and their connections on a single piece of silicon.

Key figures

First working device
16 December 1947, Bell Labs, New Jersey

Public announcement
30 June 1948, New York

Transistors made to date
About 13×10^{21}, 99.9% of them MOS (estimate by analyst Jim Handy)

Bardeen and Brattain's patent filed
17 June 1948 (US 2,524,035)

Nobel Prize in Physics
1956, Bardeen, Brattain and Shockley

Sources

1. 1947: Invention of the point-contact transistor · Computer History Museum https://www.computerhistory.org/siliconengine/invention-of-the-point-contact-transistor/
2. 1948: Conception of the junction transistor · Computer History Museum https://www.computerhistory.org/siliconengine/conception-of-the-junction-transistor/
3. Milestones: First semiconductor integrated circuit (IC), 1958 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:First_Semiconductor_Integrated_Circuit_(IC),_1958
4. 13 sextillion and counting: the long and winding road to the most frequently manufactured human artifact in history · Computer History Museum https://computerhistory.org/blog/13-sextillion-counting-the-long-winding-road-to-the-most-frequently-manufactured-human-artifact-in-history/
5. Regency TR-1 · Wikipedia https://en.wikipedia.org/wiki/Regency_TR-1
6. Transistor · Wikipedia https://en.wikipedia.org/wiki/Transistor
7. The Transistor, A Semi-Conductor Triode (Bardeen and Brattain, Physical Review 74, 230) · American Physical Society https://doi.org/10.1103/PhysRev.74.230
8. Some Circuit Aspects of the Transistor (Ryder and Kircher, Bell System Technical Journal 28, 367) · Bell Telephone Laboratories https://archive.org/details/bstj28-3-367
9. The Surface State Job · Computer History Museum https://computerhistory.org/blog/the-surface-state-job/

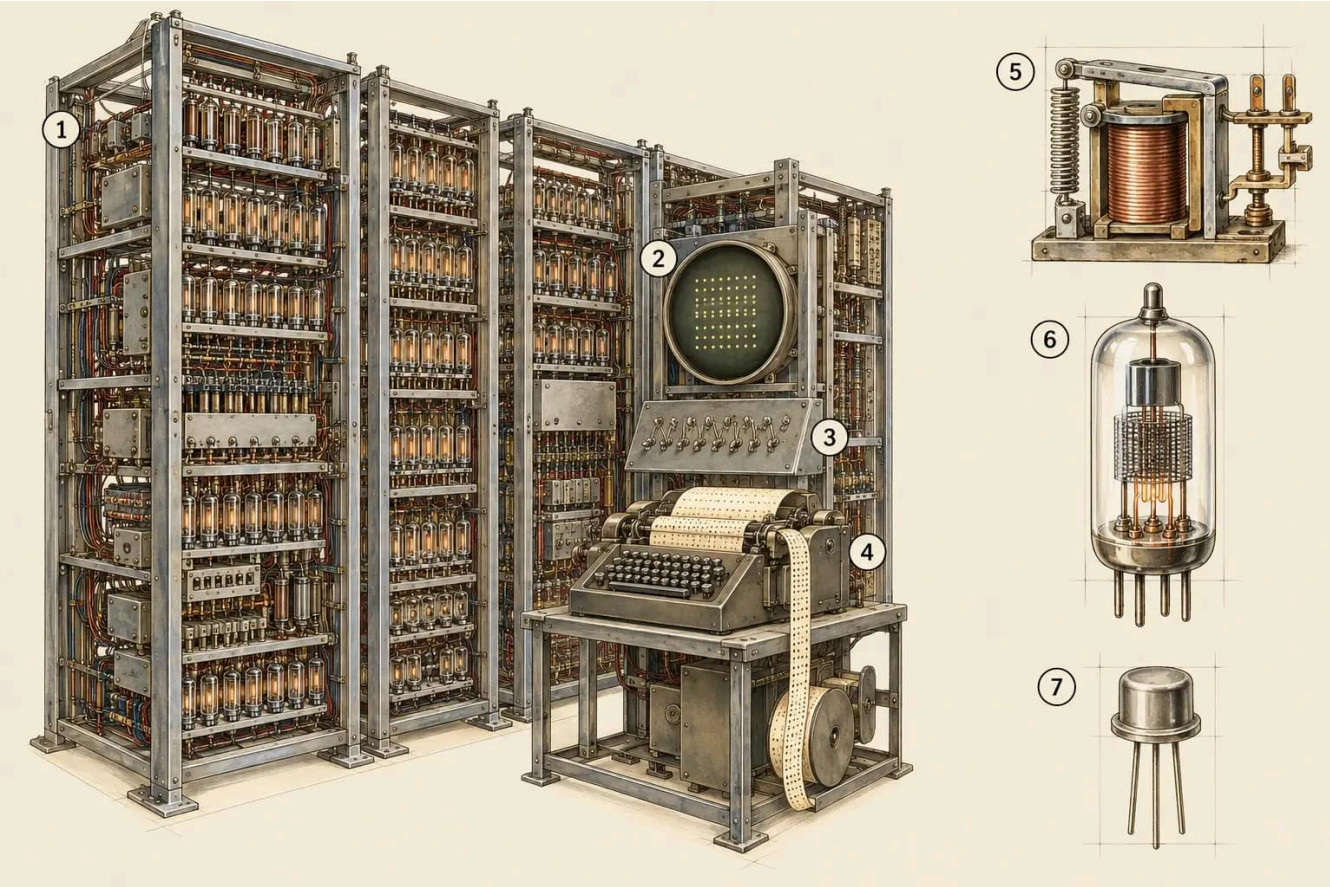
Fact-checked on 2026-10-11

Computer

A machine with its program in memory

1948 · Modern age · Electric age

Requires: Transistor (p. 347), Positional Numerals (p. 94)



1 Racks of vacuum tubes 2 Cathode-ray memory tube: one dot per bit 3 Switch panel for keying in data 4 Teleprinter and punched paper tape 5 Relay: a switch moved by an electromagnet 6 Vacuum tube: its grid switches the current 7 Transistor: the solid-state switch

A computer is a programmable calculating machine; the modern kind keeps its program in its own memory and works in binary, with switches that are either on or off. The first to run a program from electronic memory was the Manchester "Baby", on 21 June 1948, and phones and laptops still follow its plan.

What it is

A computer carries out a program, a list of instructions, on data. In the stored-program design described here, the program sits in the same memory as the numbers it works on, so the machine can load a new one, change it, or write another, without being rebuilt. That idea sets the stored-program computer apart from earlier programmable machines, which took their instructions from tape, cards, plugs or switches.

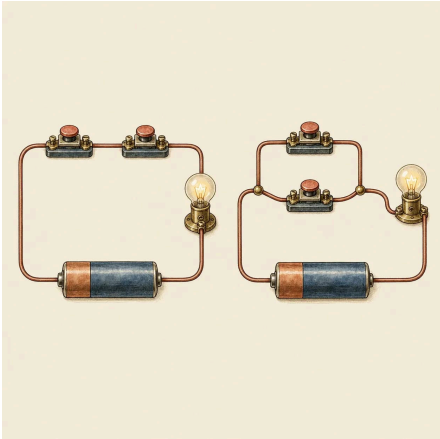
Today's computers work in binary, with the digits 0 and 1, because two states are easy to make reliable: a switch is open or closed. ENIAC and some other early machines still counted in decimal. For a society rebuilding its tools, it

calculates, controls machines such as pumps and power networks, and carries messages.

How it works

Binary numbers. Binary is positional like our decimal numerals, but each place is worth twice the one to its right: 1, 2, 4, 8, 16. Thirteen is 8 + 4 + 1, written 1101. Eight binary digits, or bits, cover the whole numbers from 0 to 255.

Gates. Two switches in series light a lamp only when both are closed: an AND gate. Two in parallel light it when either is closed: an OR gate. A relay whose contact opens when its coil is powered makes a NOT gate, turning 1 into 0. A relay is worked by an electromagnet, a vacuum tube by the voltage on its grid, a transistor by the signal on its base or gate. AND, OR and NOT together can express any rule from input bits to output bits.



Buttons in series light the bulb only if both are pressed; in parallel, either one is enough.

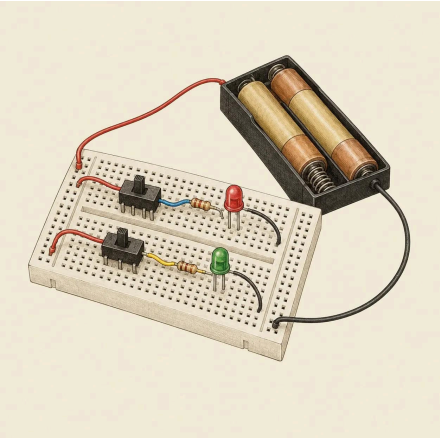
Adding with gates. In binary, 1 + 1 makes 10: sum 0, carry 1. The sum bit is 1 when exactly one input is 1, a rule called exclusive OR (XOR); the carry is 1 only when both are, which is AND. Together they form a half adder. A full adder also takes the carry from the column to its right, and eight in a chain add two 8-bit numbers, column by column, as a pupil does on paper.

Memory. Two NOR gates (OR followed by NOT), each output feeding one input of the other, form a latch: a pulse on one free input sets it to 1, a pulse on the other resets it to 0, and it holds that bit while the power stays on. Manchester stored bits as charged dots on a cathode-ray tube, EDSAC as sound pulses in tubes of mercury. Each word, a group of bits, has a number, its address.

The cycle. A register called the program counter holds the address of the next instruction. The processor fetches that instruction, decodes it, executes it, and starts again. An instruction may add a number from memory to the accumulator, store a result, or jump elsewhere if a value is negative; that conditional jump lets a program loop and choose. Keyboards and sensors bring data in; screens, printers and motors take results out.

How to build

A modern processor needs a chip factory, but its logic can be learnt on a table.



Test each switch and LED on its own first; an LED always needs a resistor in series.

Gather the parts. A solderless breadboard, two or three AA cells in a holder (3 to 4.5 V) or a 5 V USB supply, two double-pole changeover switches, two LEDs, two resistors of 330 to 470 ohms, and wire. Each LED goes in with its long leg (anode) towards the switch and its short leg (cathode) to 0 V. Write the truth table first: for inputs A B = 00, 01, 10, 11, the sum is 0, 1, 1, 0 and the carry 0, 0, 0, 1.

Wire the carry. Take the supply to the common of the first pole of A, its “on” contact to the common of the first pole of B, and that “on” contact through a resistor to an LED, whose other leg returns to 0 V. It lights only for 11: that is AND.

Wire the sum. On the second poles, join the “on” contact of A to the “off” contact of B, and the “off” contact of A to the “on” contact of B.

Feed the common of A from the supply and take the common of B through a resistor to the second LED, cathode to 0 V. It lights when the switches differ: XOR. Check the four cases against the table.

Chain a bigger adder. A full adder is two half adders plus an OR gate merging their carries. From here, logic chips are easier: a 4-bit adder takes two 74HC86 (XOR), two 74HC08 (AND) and one 74HC32 (OR). Power them as the datasheet shows (pin 14 to plus, pin 7 to 0 V, a 100 nF capacitor across the two). Each carry out feeds the next carry in and the first carry in goes to 0 V; each switch input gets a 10-kilohm resistor to 0 V, and each output LED a 1-kilohm resistor.

Run a computer on paper. Draw eight numbered memory boxes, an accumulator and a program counter set to 0. Write LOAD 5 in box 0, ADD 6 in box 1, STORE 7 in box 2, STOP in box 3, then 3 in box 5 and 4 in box 6. Play the processor: read the box the counter points to, do it, add one to the counter. Box 7 ends up holding 7. Now code each instruction as two digits, the operation then the address, with LOAD 1, ADD 2, STORE 3 and STOP 0: the program becomes 15, 26, 37, 00, numbers among the data.

> **Safety.** Batteries or a 5 V USB supply only, never mains. Every LED needs its resistor. A shorted battery or power bank can heat its wires enough to burn. Disconnect the supply before rewiring. A chip output cannot power a relay coil: drive the coil through a transistor rated for its current, with a diode across it, striped end (cathode) towards the positive supply, to absorb the spike at switch-off.

History and evolution

Charles Babbage's Analytical Engine, conceived in 1834, had a store, a mill for arithmetic and a program on punched cards; it was never built. Ada Lovelace published a sequence of operations for it in 1843. Herman Hollerith's electric card tabulators counted the US census of 1890.

A simplified sketch of the part of his first Difference Engine, one seventh of it, that Babbage had assembled in 1832; it still works.

In 1936 Alan Turing described a universal machine that reads its instructions from the same tape as its data. Konrad Zuse showed his relay-built Z3 in Berlin on 12 May 1941. From February 1944, Tommy Flowers's electronic Colossus helped break the German Lorenz cipher at Bletchley Park; it stayed secret until the 1970s. ENIAC, by J. Presper Eckert and John Mauchly in Philadelphia, announced in 1946, was general-purpose but programmed by moving cables. Each has a claim to be first, depending on whether one asks for electronics, generality or a stored program.

John von Neumann's 1945 report on the EDVAC, drawn from work with Eckert, Mauchly and others, described a machine keeping program and data in one memory. The first to run was the Manchester "Baby" of Frederic Williams, Tom Kilburn and Geoff Tootill, on 21 June 1948. Maurice Wilkes's EDSAC at Cambridge followed on 6 May 1949 and soon served users.

Manchester ran a transistor computer in November 1953. Integrated circuits, first made in 1958, entered computers in the 1960s, and in 1971 Intel's 4004 put a whole processor on one chip.

Key figures

Zuse Z3, relays, program on punched film
Shown in Berlin on 12 May 1941

Colossus, electronic, set up with plugs and switches
Working at Bletchley Park from February 1944; about 1,600 valves, 2,400 to 2,500 in later models

ENIAC
Announced February 1946; about 18,000 vacuum tubes, 30 US tons (about 27 t), 150 kW

First stored program run
21 June 1948, Manchester: 17 instructions, memory of 32 words of 32 bits

Intel 4004, first commercial microprocessor
1971, about 2,300 transistors on one chip

Sources

1. Timeline of Computer History: Computers · Computer History Museum https://www.computerhistory.org/timeline/computers/
2. The Modern History of Computing (B. Jack Copeland) · Stanford Encyclopedia of Philosophy https://plato.stanford.edu/entries/computing-history/
3. Mark 1 Story: The Baby · University of Manchester, Department of Computer Science https://www.curation.cs.manchester.ac.uk/computer50/www.computer50.org/mark1/new.baby.html
4. Milestones: Manchester University "Baby" Computer and its Derivatives, 1948–1951 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:Manchester_University_%22Baby%22_Computer_and_its_Derivatives,_1948-1951
5. Colossus · The National Museum of Computing https://www.tnmoc.org/colossus
6. ENIAC · Penn Engineering, University of Pennsylvania https://www.engineering.upenn.edu/about/history-heritage/eniac/
7. A brief informal history of the Computer Laboratory · University of Cambridge Computer Laboratory https://www.cl.cam.ac.uk/events/EDSAC99/history.html
8. The Engines · Computer History Museum https://www.computerhistory.org/babbage/engines/
9. Ada Lovelace · Computer History Museum https://www.computerhistory.org/babbage/adalovelace/
10. Tabulation and Processing · U.S. Census Bureau https://www.census.gov/about/history/bureau-history/census-innovations/technology/tabulation-and-processing.html
11. Milestones: First Semiconductor Integrated Circuit (IC), 1958 · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:First_Semiconductor_Integrated_Circuit_(IC),_1958
12. 1971: Microprocessor integrates CPU function onto a single chip · Computer History Museum https://www.computerhistory.org/siliconengine/microprocessor-integrates-cpu-function-onto-a-single-chip/
13. 74HC86; 74HCT86 Quad 2-input EXCLUSIVE-OR gate (data sheet) · Nexperia https://assets.nexperia.com/documents/data-sheet/74HC_HCT86.pdf
14. 74HC08; 74HCT08 Quad 2-input AND gate (data sheet) · Nexperia https://assets.nexperia.com/documents/data-sheet/74HC_HCT08.pdf
15. 74HC32; 74HCT32 Quad 2-input OR gate (data sheet) · Nexperia https://assets.nexperia.com/documents/data-sheet/74HC_HCT32.pdf
16. SN74HC86 Quadruple 2-Input Exclusive-OR Gates (data sheet) · Texas Instruments https://www.ti.com/lit/ds/symlink/sn74hc86.pdf
17. Full Adder · HyperPhysics, Georgia State University https://hyperphysics.gsu.edu/hbase/Electronic/fulladd.html
18. Binary Adder and Binary Addition · Electronics Tutorials https://www.electronics-tutorials.ws/combination/comb_7.html

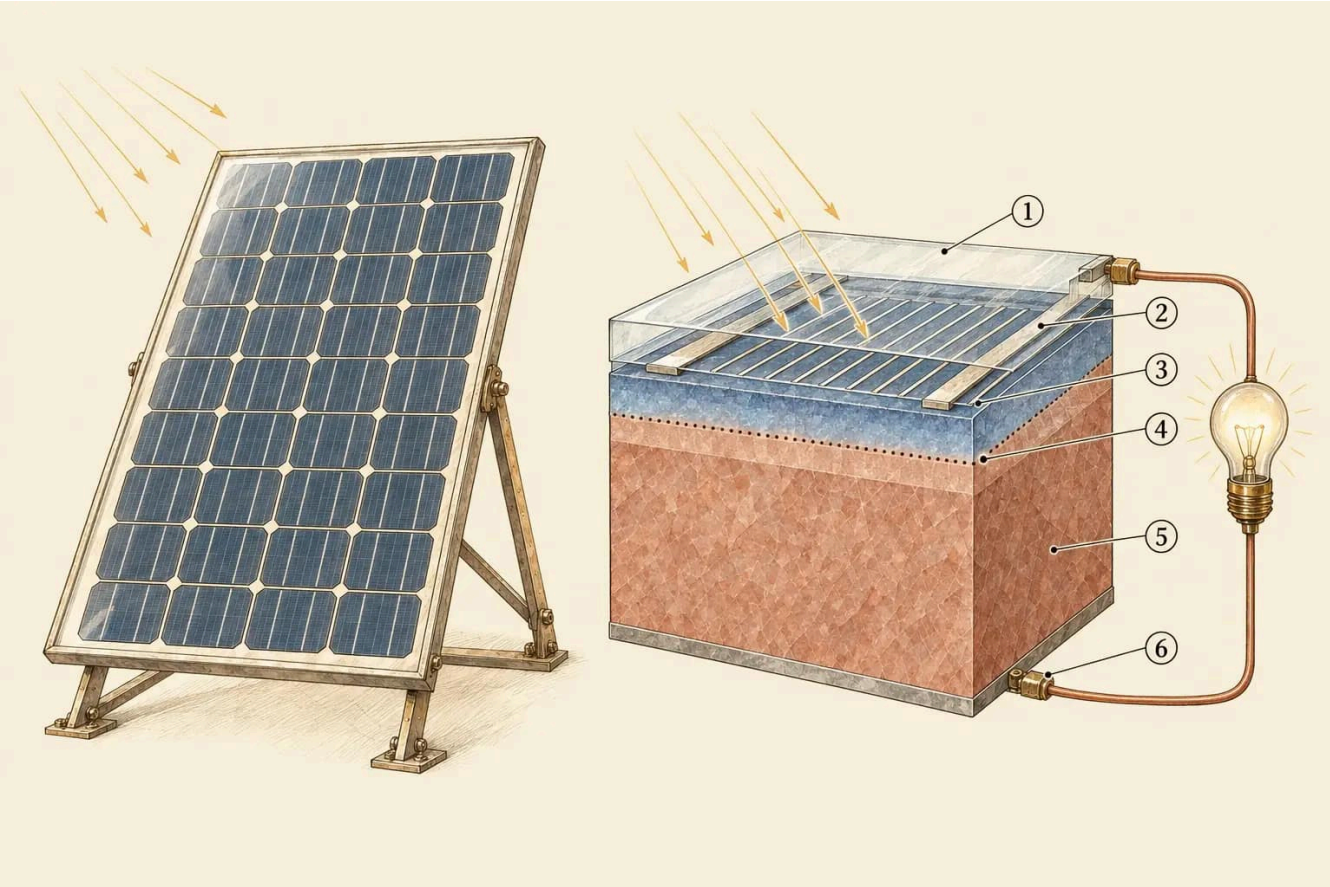
Fact-checked on 2026-10-14

Solar cell

Sunlight turned into current

1954 · Modern age · Electric age

Requires: Transistor (p. 347), Battery (p. 234), Glass (p. 129)



1 Glass cover 2 Front contact grid 3 Thin n-type layer (phosphorus) 4 p–n junction 5 p-type base (boron) 6 Back contact

A solar cell is a thin slice of semiconductor in which light frees electrons and a built-in electric field drives them out as a current, with no moving parts and no fuel. Bell Labs showed the first practical silicon cell in 1954, and solar power supplied 8.7% of the world's electricity in 2025.

What it is

A solar cell turns light straight into electric current, with no moving parts and no fuel. Most cells are square slices of silicon a little wider than a hand. Each gives about half a volt in sunlight, so dozens are wired together behind glass to make a panel, like the one of 36 cells on the plate.

The date chosen here is April 1954, when Bell Labs showed a silicon cell that converted about 6% of sunlight into electricity, enough to run real equipment. Becquerel had seen light produce a current in 1839, but the selenium cells made from 1883 converted under 1%.

How it works

Pure silicon conducts poorly. Doping it with a trace of phosphorus gives it spare electrons (n-type); a trace of boron leaves gaps called holes, which act as positive charges (p-type). A classic cell is a boron-doped wafer whose front face has been soaked with phosphorus to less than a thousandth of a millimetre. Where the two regions meet, electrons and holes cancel out in a narrow zone, leaving fixed charges that hold a permanent electric field across this p–n junction.

Cells are sawn from a single crystal of silicon grown from the melt; a wafer today is about 0.14 mm thick.

A photon of light with enough energy knocks an electron out of its bond and leaves a hole behind. Near the junction, the field pushes the electron to the n side and the hole to the p side. The electrons gather in the front fingers, flow through the outside circuit, lighting a lamp or charging a battery, and return through the back contact.

An unconnected cell shows about 0.6 to 0.7 V, and about 0.5 V while delivering power. The voltage changes little with brightness, but the current follows the light: half the light, about half the current. Cells in series add their voltages, so 36 cells work at about 17 V, enough to charge a 12 V battery. Panels in parallel add their currents. One shaded cell holds back its whole series string, which is why panels carry bypass diodes.

Silicon lets infrared light beyond about 1.1 micrometres pass through unused, and photons with more energy than needed waste the surplus as heat. In 1961 William Shockley and Hans-Joachim Queisser showed that these losses keep a single-junction cell to about a third of sunlight at best. Silicon has further losses inside the crystal itself, which bring its own limit down to about 29%; the best laboratory cell reached 28.1% by 2026. Heat also lowers output: a conventional silicon cell loses about 0.4 to 0.5% of its power for each degree Celsius, mostly through lower voltage.

How to build it

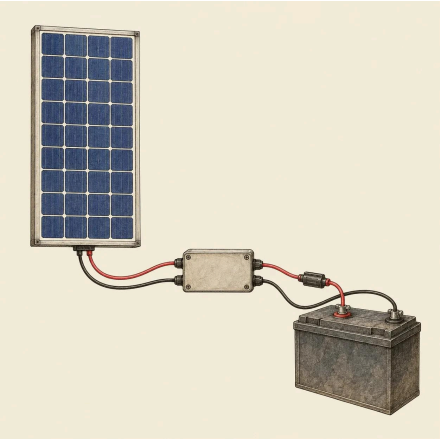
Making cells is factory work. A small 12 V system built from bought panels, with compatible parts and each maker's instructions, is within reach of a careful amateur.

Size the panel. Four 5 W LED lamps for 4 hours and a 10 W radio for 2 hours use 100 watt-hours (Wh) a day. A panel gives about its rated power × peak sun hours (the day's sunlight counted as hours of full sun, in the darkest month) × 0.7 for heat, dust and wiring losses. A 100 W panel with 3 peak sun hours gives about 210 Wh, a fair margin.

Choose the battery. Plan for one to three cloudy days. Lead-acid lasts longer if rarely drained below half. Lithium iron phosphate can use most of its capacity, but only with its own management electronics and a controller set for lithium; most must not be charged below freezing. Two days of 100 Wh from a 12 V lead-acid battery used to half call for at least 33 Ah: take 40 Ah.

Fit a charge controller. Never wire a panel straight to a battery. The controller tapers the charge so the battery is never overcharged, then holds it full, and loads wired to its load output are cut before the battery runs flat. A simple PWM controller should be rated for at least 1.25 times the panel's short-circuit current. For an MPPT model, compare its voltage, current and power limits with the panel's datasheet, remembering that open-circuit voltage rises in cold weather.

Fuse and cables. Fit a fuse rated for direct current in the positive cable, right next to the battery. Its rating must be below the cable's capacity and above the largest normal current, and it must be able to break the very large



Panel, charge controller and battery, with the fuse on the positive cable next to the battery.

current a battery delivers into a short. At 10 A, a panel 5 m away (10 m of copper) loses about 0.3 V through 6 mm² outdoor cable; thinner wire wastes more.

Mount and clean. Face the panel towards the equator, unshaded through the middle of the day, tilted at about the latitude for year-round use. Rinse dust off with water and a soft brush. An inverter can turn the 12 V into mains voltage, as dangerous as the grid itself.

Test one cell. In sun, read a small cell's voltage on the DC volts setting of a multimeter. Then select DC amps, move the red lead to the 10 A socket and touch the cell's terminals: this reads its short-circuit current. First check that the current printed on the cell is well below the meter's 10 A limit, and keep the probes on for only a few seconds. In shade the voltage barely moves while the current drops. Put the red lead back in the volts socket afterwards, and never measure a battery's current this way.

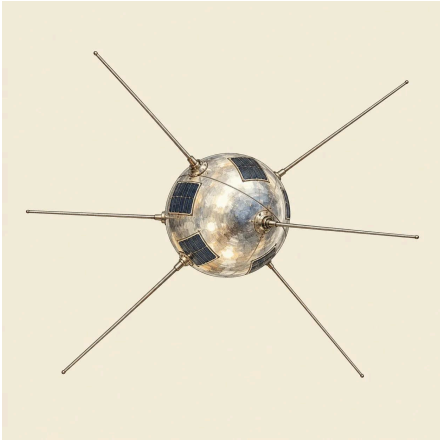
> **Safety.** A panel makes voltage whenever light reaches it: cover it while wiring. Direct current can hold an arc when a connector is pulled under load, so to work on the system, cover the panel, disconnect the panel first and the battery last, and reconnect in the reverse order. A short across a battery melts tools and starts fires, and the fuse cannot stop a spanner laid across both terminals: use insulated tools and terminal covers. Charging lead-acid batteries release hydrogen: ventilate, no sparks, wear eye protection. On a roof, use a harness and anchor point or call professionals. Anything connected to the mains, including inverters, is work for a qualified electrician.

History and evolution

In 1839 Edmond Becquerel, aged 19, lit electrodes coated with silver chloride in acid and measured a small current. In 1873 Willoughby Smith, testing undersea telegraph cables, found that selenium conducts better in light, and in 1883 Charles Fritts made cells of selenium under see-through gold leaf. In 1905 Albert Einstein explained that light comes in packets whose energy depends on its colour.

In 1940 Russell Ohl at Bell Labs found that a silicon sample with phosphorus on one side and boron on the other gave a current under light: the first p–n junction, about 1% efficient. In 1953 his colleague Daryl Chapin, seeking power for telephone equipment in remote places, got 0.5% from selenium. Calvin Fuller and Gerald Pearson's doped silicon did much better, and the cell Bell Labs showed on 25 April 1954 drove a toy Ferris wheel.

The first silicon cells cost far too much for ordinary use, and their first steady customer was space. Vanguard 1, launched in March 1958, carried six small panels of 18 cells each: its battery-powered transmitter stopped in June 1958, the solar one kept sending until May 1964. As factories grew, module prices fell from about $132 per watt in 1975 to $0.27 in 2024 (in 2025 dollars). Most cells made today start from phosphorus-doped wafers with boron at the front. In 2025 solar panels produced 8.7% of the world's electricity, according to Ember (April 2026).



Vanguard 1, 1958: six small panels of solar cells on a sphere about 16 cm across.

Key figures

First practical cell

Announced by Bell Labs on 25 April 1954, about 6% efficient

Efficiency today

28.1% for the best laboratory silicon cell; just under 25% for the best commercial modules (Fraunhofer ISE, July 2026)

Share of world electricity

8.7% in 2025, up from 1.1% in 2015 (Ember, April 2026)

Voltage of one silicon cell

About 0.6–0.7 V with no load, about 0.5 V while delivering power

Heat loss

About 0.4–0.5% less power for each °C a conventional silicon cell warms; each panel's datasheet gives its own figure

Sources

1. April 25, 1954: Bell Labs demonstrates the first practical silicon solar cell · American Physical Society, APS News https://aps.org/apsnews/2009/04/bell-labs-silicon-solar-cell
2. Milestones: First practical photovoltaic solar cell · IEEE Engineering and Technology History Wiki https://ethw.org/Milestones:First_Practical_Photovoltaic_Solar_Cell
3. 1940: Discovery of the p-n junction · Computer History Museum https://www.computerhistory.org/siliconengine/discovery-of-the-p-n-junction/
4. First photovoltaic devices · PVEducation (C. Honsberg and S. Bowden) https://pveducation.org/es/fotovoltaica/first-photovoltaic-devices
5. Open-circuit voltage · PVEducation (C. Honsberg and S. Bowden) https://www.pveducation.org/pvcdrom/solar-cell-operation/open-circuit-voltage
6. Effect of light intensity · PVEducation (C. Honsberg and S. Bowden) https://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-light-intensity
7. Effect of temperature · PVEducation (C. Honsberg and S. Bowden) https://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-temperature
8. Limiting efficiency of crystalline silicon solar cells due to Coulomb-enhanced Auger recombination (Kerr, Cuevas, Campbell, 2003) · Australian National University https://researchportalplus.anu.edu.au/en/publications/limiting-efficiency-of-crystalline-silicon-solar-cells-due-to-cou/
9. Einstein and the photoelectric effect · American Physical Society, APS News https://www.aps.org/apsnews/2005/01/einstein-photoelectric-effect
10. Vanguard 1 · Linda Hall Library https://www.lindahall.org/about/news/scientist-of-the-day/vanguard-1/
11. Vanguard 1 celebrates 50 years in Earth's orbit (Spaceport News, 21 March 2008, p. 7) · NASA Kennedy Space Center https://www3.nasa.gov/centers/kennedy/pdf/218158main_mar21color.pdf
12. Solar cell array design handbook, vol. 1 (JPL SP 43-38, 1976) · NASA / Jet Propulsion Laboratory https://ntrs.nasa.gov/api/citations/19770007250/downloads/19770007250.pdf
13. Photovoltaics Report (14 July 2026) · Fraunhofer Institute for Solar Energy Systems ISE https://ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html
14. Solar PV module prices, 1975–2024 · Our World in Data https://ourworldindata.org/grapher/solar-pv-prices
15. Global Electricity Review 2026: electricity demand and supply trends · Ember https://ember-energy.org/latest-insights/global-electricity-review-2026/electricity-demand-and-supply-trends/
16. Solar electric system design, operation and installation (C. Roos, 2009) · Washington State University Extension Energy Program https://digitalarchives.wa.gov/do/046161B1997D0FFD8FA86C78CAFFAB5C.pdf
17. SmartSolar MPPT 100/30 and 100/50 manual: operation · Victron Energy https://www.victronenergy.com/media/pg/Manual_SmartSolar_MPPT_100-30__100-50/en/operation.html
18. Series resistance · PVEducation (C. Honsberg and S. Bowden) https://www.pveducation.org/pvcdrom/solar-cell-operation/series-resistance
19. Shunt resistance · PVEducation (C. Honsberg and S. Bowden) https://www.pveducation.org/pvcdrom/solar-cell-operation/shunt-resistance
20. Single diode equivalent circuit models · Sandia National Laboratories, PV Performance Modeling Collaborative https://pvpmc.sandia.gov/modeling-guide/2-dc-module-iv/single-diode-equivalent-circuit-models/
21. Production of upgraded metallurgical grade (UMG) silicon for a low-cost high-efficiency and reliable PV technology (Míguez Novoa et al., Frontiers in Photonics, 2024) · arXiv https://arxiv.org/abs/2604.04095

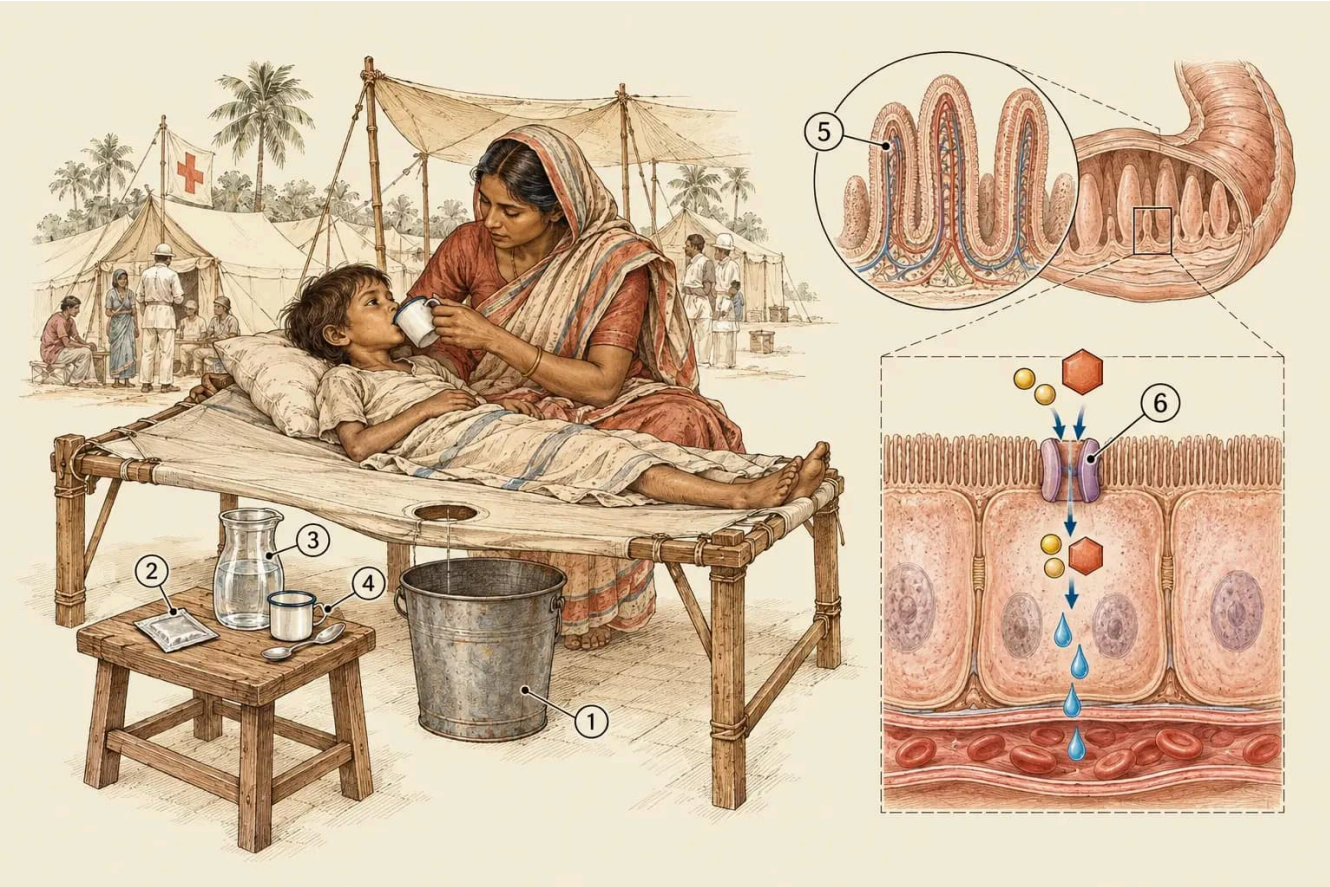
Fact-checked on 2026-10-14

Oral rehydration

Salt, sugar and water against cholera

1968 · Modern age · Electric age

Requires: Drinking Water (p. 34), Measures and standards (p. 124)



1 Cholera cot with its bucket 2 Sachet of oral rehydration salts 3 Jug of safe water 4 Cup and spoon 5 Villi of the small intestine 6 Sodium–glucose transporter in a lining cell

Oral rehydration therapy replaces the water and salts lost in diarrhoea with a drink of clean water, salts and glucose in a fixed balance, which the gut keeps absorbing even during cholera. Proved in trials in Dhaka and Calcutta in 1968 and packed in standard sachets since the 1970s, it is credited with saving tens of millions of children.

What it is

Diarrhoea kills by drying the body out. In cholera, a toxin makes the lining of the small intestine pour water and salts into the gut, and an adult can lose litres of watery stool within hours. The blood volume falls, the kidneys fail, and without treatment death can follow the same day. Most diarrhoea in children is milder, caused by viruses or other bacteria, but it still kills hundreds of thousands of them a year.

Oral rehydration therapy replaces those losses by mouth. The patient drinks a solution of clean water, common salt, glucose, potassium and citrate, mixed from a sachet of oral rehydration salts (ORS). It does not stop the diarrhoea; it keeps the patient alive while the body clears the infection.

The plate shows a cholera camp in Bengal in the early 1970s. A child lies on a cholera cot, whose hole and bucket let nurses measure every loss, while his mother gives the drink by cup. On the right, a section of the gut lining shows why it works.

How it works

The small intestine is lined with villi, tiny finger-like folds covered by a single layer of cells. Each cell carries in its outer membrane a protein that moves sodium and glucose into the cell together: two sodium ions for every molecule of glucose. Robert Crane proposed this coupling in Prague in 1960, and experiments on rabbit gut in 1964 confirmed that sugar drives sodium absorption. Chloride follows the sodium, and water follows the dissolved salts and sugar.

The cholera toxin drives secretion but leaves this transporter working. A drink with both sodium and glucose is therefore absorbed even while the gut is losing fluid, and enough of it keeps pace with the losses.

Plain water brings no salt, so on its own it cannot replace what is lost, and in large amounts it dilutes the sodium left in the blood. Sweet drinks such as sodas or fruit juice contain too much sugar and too little salt. The excess sugar stays in the gut and draws water into it, which makes the diarrhoea worse. The low-osmolarity formula recommended by WHO in the early 2000s holds less sodium and glucose than the first solution. In children with diarrhoea other than cholera, it cut stool volume by a fifth to a quarter, depending on the study, and unplanned drips by about a third.

How it is made and used

This section describes how health systems supply ORS and teach its use. It is not a home recipe.

Industrial sachets. Pharmaceutical plants mix purified glucose, sodium chloride, potassium chloride and trisodium citrate to the WHO formula and seal the dry powder in moisture-proof foil, each sachet sized for a stated volume of water. In 2024 UNICEF alone delivered 29.2 million sachets to 56 countries, often packed with zinc tablets, for well under one US dollar a course.

A health worker shows a mother how to empty the whole sachet into the volume of safe water printed on it.

Teaching families. At a clinic or a home visit, a health worker shows the parent how to dissolve one sachet in the exact volume of safe water printed on it, boiled and cooled if the source is doubtful. The solution is given in small, frequent sips from a cup or spoon, more slowly if the child vomits, and any left after a day is thrown away. Breastfeeding and normal meals continue throughout. WHO also recommends a 10–14 day course of zinc for children with diarrhoea, which shortens episodes and lowers the chance of another soon after.

Recognising dehydration. Health workers look for restlessness, sunken eyes and eager thirst, which mean some dehydration. A child with at least two of the following is severely dehydrated: lethargy or unconsciousness, sunken eyes, being unable to drink or drinking poorly, and pinched skin that goes back very slowly. Such patients, and anyone in shock, receive intravenous fluids in a health facility first, then continue with ORS.

When to seek care at once. Parents are taught to return immediately if the child becomes drowsy, cannot drink, keeps vomiting, passes blood in the stool, passes no urine for many hours, or does not improve. Very young babies and malnourished children need a health worker from the start.

A skin fold that takes two seconds or more to go back is one sign of severe dehydration.

> **Safety.** Use ready-made ORS packets, dissolved in exactly the volume of safe water printed on them. Too much powder makes the solution dangerous, and too much water makes it less effective. If no packet is at hand, keep giving safe water, broth or breast milk, avoid very sweet drinks, and seek care. ORS does not replace medical care: dehydration can kill a small child within hours, so anyone with danger signs must be taken to a health facility without delay.

History and evolution

In 1832, in Leith near Edinburgh, Thomas Latta followed a suggestion by William O'Shaughnessy and injected salt water into the veins of dying patients. Some revived, but Latta died the next year, and the method was neglected for half a century.

By the 1960s intravenous saline, refined by the US Navy doctor Robert Phillips, brought cholera deaths below 1%, but it needed sterile fluid, needles and trained staff. Researchers in Dhaka, then in East Pakistan, and at a Johns Hopkins centre in Calcutta tested glucose and salt by mouth. In 1968 Norbert Hirschhorn showed that glucose cut net stool loss, and David Nalin and Richard Cash reported that patients given the drink needed 80% less intravenous fluid. The plate takes 1968 as its date.

Latta's injections needed a syringe, a vein and a doctor at the bedside.

During the 1971 war, cholera broke out among refugees from East Pakistan near Bongaon, in India. With intravenous fluid short, Dilip Mahalanabis's team kept drips for the most severe cases and treated the rest by mouth. Of 3,703 patients admitted to their centre, 3.6% died, while early in the outbreak cholera had killed close to 30% of its victims. The report appeared only in 1973.

WHO and UNICEF agreed on a single formula in 1975, and in 1978 The Lancet called the discovery "potentially the most important medical advance this century". From 1980 to 1990 the Bangladeshi organisation BRAC sent workers door to door to teach more than 12 million mothers a home drink of salt and raw sugar. WHO recommended a lower-osmolarity formula in the early 2000s, and a joint statement with UNICEF in 2004 promoted it together with zinc.

Estimates of the children saved run from more than 50 million between 1982 and 2007 to over 70 million by 2019, though clean water, sanitation and vaccines also played a part.

Key figures

Nalin and Cash's trial

The Lancet, August 1968: 80% less intravenous fluid needed

WHO low-osmolarity formula

245 mOsm/L, against 311 for the original solution

Children saved, 1982–2007

More than 50 million (Fontaine, Garner and Bhan estimate)

Bongaon treatment centre, 1971

3.6% of 3,703 cholera patients died, against close to 30% early in the outbreak

Diarrhoea deaths under age five

About 444,000 a year (WHO, 2024)

Sources

1. Diarrhoeal disease (fact sheet, 7 March 2024) · World Health Organization https://www.who.int/news-room/fact-sheets/detail/diarrhoeal-disease
2. Cholera (fact sheet) · World Health Organization https://www.who.int/news-room/fact-sheets/detail/cholera
3. Clinical management of acute diarrhoea: WHO/UNICEF joint statement (2004) · World Health Organization https://www.who.int/publications/i/item/WHO_FCH_CAH_04.7
4. Oral rehydration salts (ORS) and zinc · UNICEF Supply Division https://www.unicef.org/supply/oral-rehydration-salts-ors-and-zinc
5. Zinc and ORS (S. Singh, 2007) · Pediatric Oncall Journal, vol. 4 no. 1 https://www.pediatriconcall.com/pediatric-journal/view/fulltext-articles/165/J/0/0/251/0
6. Robert K. Crane: Na+-glucose cotransporter to cure? (K. L. Hamilton, 2013) · Frontiers in Physiology https://www.frontiersin.org/journals/physiology/articles/10.3389/fphys.2013.00053/full
7. Oral rehydration therapy: a low-tech solution that has saved millions of lives · Our World in Data https://ourworldindata.org/oral-rehydration-therapy
8. Magic bullet: the history of oral rehydration therapy (J. N. Ruxin, 1994) · Medical History, vol. 38 no. 4 https://pmc.ncbi.nlm.nih.gov/articles/PMC1036912/
9. Leith in the time of cholera: the story of Thomas Latta (G. A. Venters) · Hektoen International https://hekint.org/2017/02/01/leith-in-the-time-of-cholera-the-story-of-thomas-latta/
10. Treatment of cholera: Robert Allan Phillips (1967 Clinical Medical Research Award) · Lasker Foundation https://laskerfoundation.org/winners/treatment-of-cholera/
11. A simple solution: the history of ORS in Bangladesh · The World (PRX) https://theworld.org/stories/2013/06/25/simple-solution-history-ors-bangladesh
12. Oral fluid therapy of cholera among Bangladesh refugees (Mahalanabis et al., 1973) · Johns Hopkins Medical Journal, vol. 132 no. 4 https://pure.johnshopkins.edu/en/publications/oral-fluid-therapy-of-cholera-among-bangladesh-refugees-5/
13. Treating cholera · Centers for Disease Control and Prevention https://www.cdc.gov/cholera/treatment/

Fact-checked on 2026-10-14

Index

Aeroplane 338
Aluminium 322
Anaesthesia 286
Aqueduct 141
Arch and Vault 70
Battery 234
Beer 74
Bicycle 246
Bow & Arrow 18
Bread 26
Bricks 39
Bronze 120
Canning & Pasteurisation 242
Celestial Navigation 205
Charcoal 62
Cheese 55
Computer 351
Control of Fire 9
Crane & Pulley 145
Crop Rotation 106
Distillation 169
Drinking Water 34
Dyeing 66
Electric Generator 266
Electric Motor 270
Electric Telegraph 278
Eyeglasses 192
Gears 149
Glass 129
Gunpowder 177
Horse Collar 173
Hot-Air Balloon 225
Hygiene & Antisepsis 290
Incandescent Light Bulb 310
Internal Combustion Engine 303
Iron Smelting 133
Irrigation 51
Lead-Acid Battery 294
Leather Tanning 98
Lime and lime mortar 30
Lock & Key 111
Magnetic Compass 189
Measures and standards 124
Mechanical Clock 196
Microscope 209
Oral rehydration 360
Paper 165
Penicillin 342
Photography 254
Piston Pump 157
Plough 58
Portland Cement 250
Positional Numerals 94
Potter's Wheel 116
Pottery 22
Printing Press 200
Radio 330
Refrigeration 274
Reinforced Concrete 299
Roman Concrete 161
Rope & Cordage 13
Sail 86
Salting & Curing 47
Sewing Machine 262
Soap 90
Solar cell 355
Spinning Wheel 185
Steam Engine 221
Steam Locomotive 238
Steam Turbine 314
Steel 137
Stone Tools 5
Sundial 102
Telephone 306
Telescope 213
Thermometer and barometer 217
Transformer 318
Transistor 347
Vaccination 229
Vulcanised Rubber 282
Water Turbine 258
Water Wheel 153
Weaving 43
Wheel & Axle 78
Wind Turbine 326
Windmill 181
Writing 82
X-Ray Imaging 334

How the codex is made

Every plate is written from sources: museums, encyclopedias, academic and engineering references. Dates and figures are checked against at least two independent sources, listed at the bottom of each plate, and each plate is reviewed before it is published. When sources disagree, the text says so.

The illustrations of the plates are produced with an image-generation tool, then checked by hand: every mechanism, count and connection is compared with the sources. The interactive figures are drawn in code from a model of the machine.

Technical words are explained in the glossary.

Intellectual property

The texts, plates and figures of The Last Codex are original works by Etienne Debost, published under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 licence (CC BY-NC-ND 4.0, https://creativecommons.org/licenses/by-nc-nd/4.0/). You may copy and share them, including the whole site for offline reading, provided you name The Last Codex and its address, leave them unchanged and make no commercial use of them. Any other use needs written permission. The site's design and code are not covered: all rights reserved.

Icons: game-icons.net (CC BY 3.0) and Phosphor (MIT). Typefaces: EB Garamond, Source Sans 3 and IBM Plex Mono (SIL Open Font License).