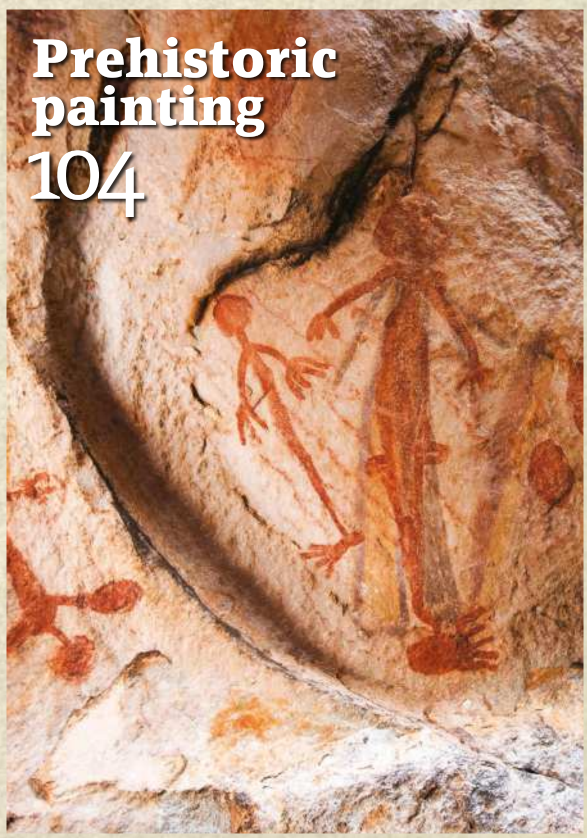
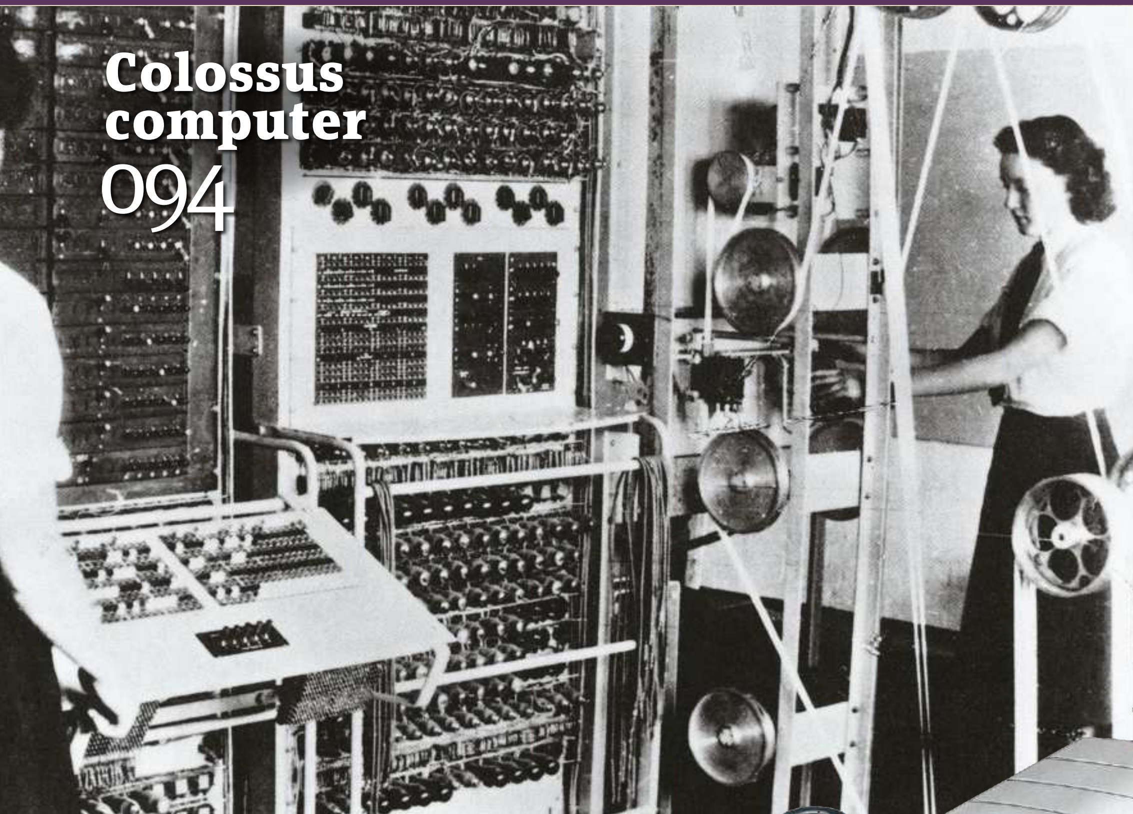
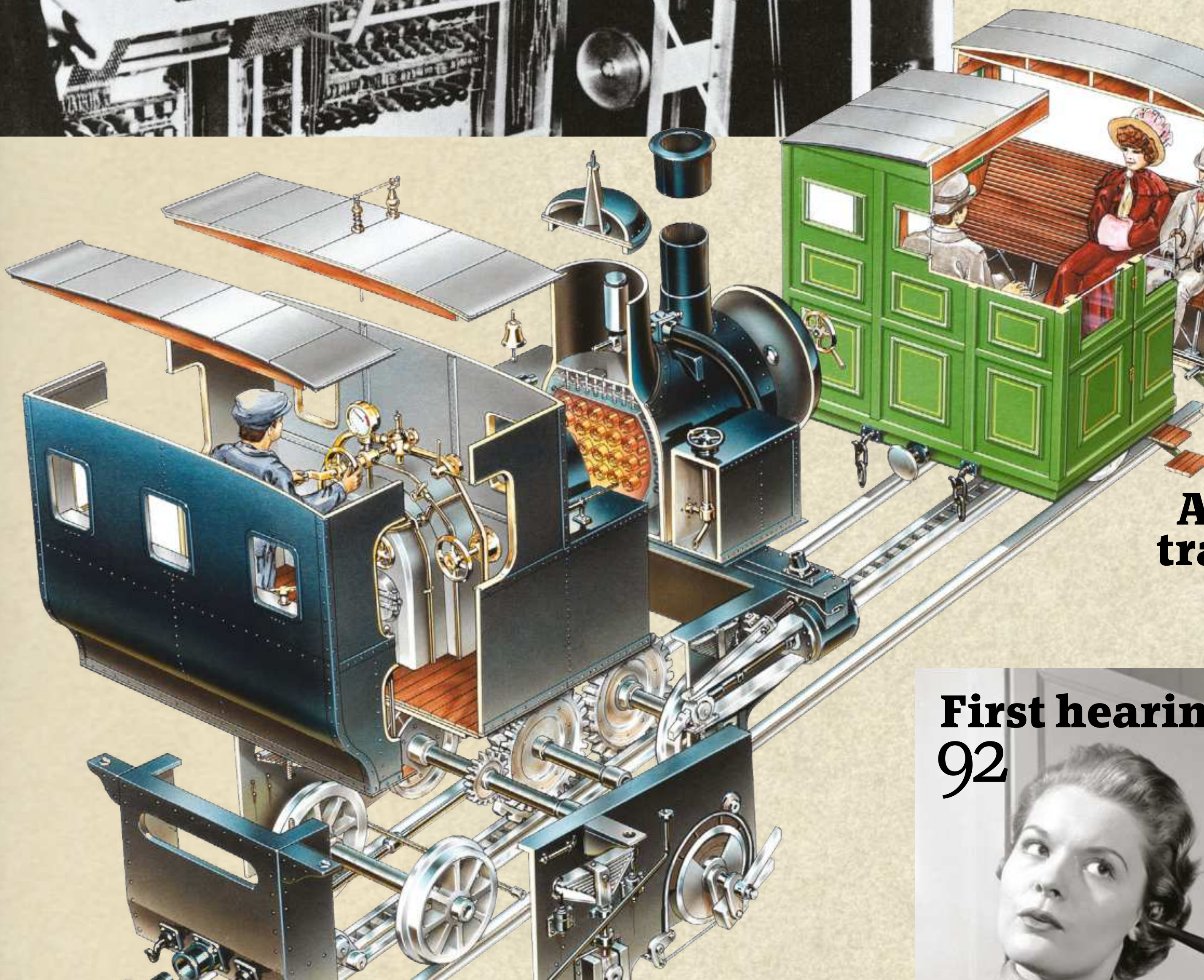
INDUSTRY & INVENTION







History's most gruesome inventions

From brutal torture devices to bizarre medical treatments, these terrifying contraptions reveal a darker side of innovation

From the wheel to the World Wide Web, we have invented some truly ground-breaking things during our time on Earth. Yet throughout history, inventors have also been known to put their skills to use in horrifying ways, creating contraptions that have caused unimaginable suffering.

In the past, if you committed a terrible crime, a punishment much worse than a long prison sentence often awaited you. From boiling people alive to sawing them in half, execution methods were often developed to be as cruel as possible. These gruesome events were usually carried out in public to deter others from committing the same crime.

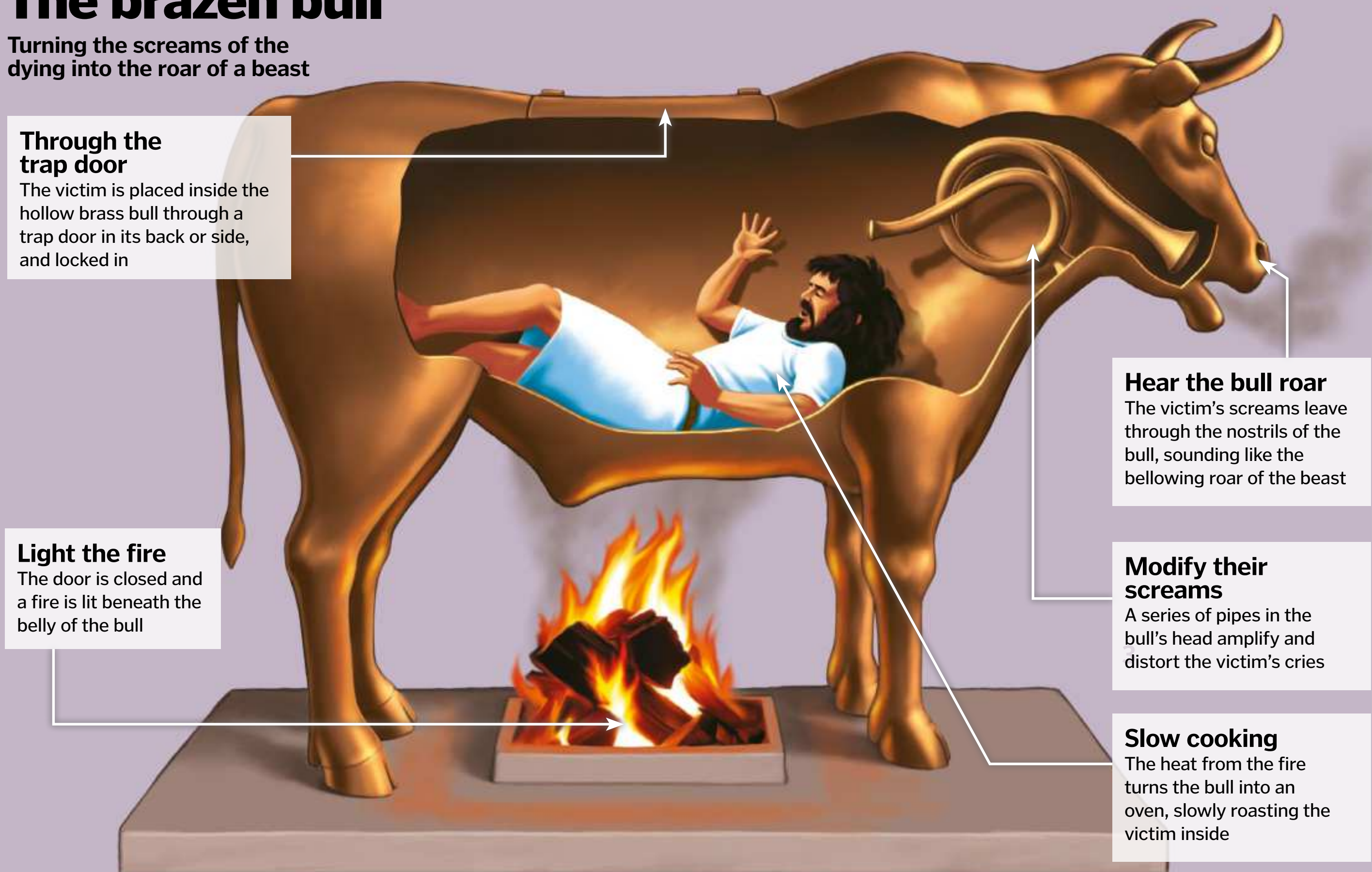
But even if you weren't sentenced to death, there were plenty of ghastly implements that could be used to torture you instead. Typically used to extract a confession or information about accomplices, torture was popular in medieval times, with the screams of victims echoing from castle dungeons across Europe.

War has also inspired a selection of horrific innovations. While guns and bombs killed instantly, chemical weapons could draw out death for several agonising days – thankfully, this form of warfare is now prohibited.

We are also lucky that some medical devices from history are no longer used. Despite being designed with good intentions, many medieval procedures were truly stomach-churning, making a trip to the doctor quite the ordeal. So be grateful these inventions are before your time…

The brazen bull

Turning the screams of the dying into the roar of a beast

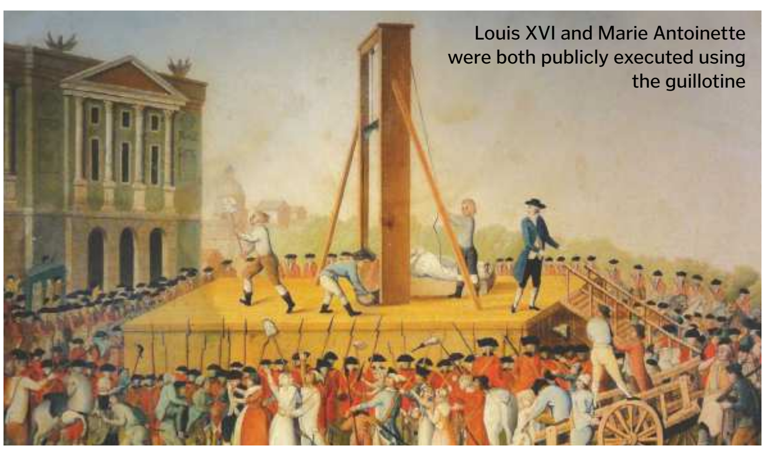


One of the most brutal methods of execution ever created took the form of a hollow bull statue. Invented in Ancient Greece by Perillus, a bronze worker in Athens, it was given as a gift to a cruel tyrant named Phalaris of Agrigentum. As well as roasting criminals alive, the device doubled as a musical instrument, converting the victim's desperate cries into what Perillus described as "the tenderest, most pathetic, most melodious of bellowings". Distrustful of the inventor's claims, Phalaris ordered Perillus to climb inside and prove the device's musical capabilities. As soon as he was inside, Phalaris shut the door and lit a fire beneath. However, rather then letting him die at the hands of his own creation, Phalaris had him removed and thrown off a cliff instead.

Crucifixion

Devised over 2,500 years ago as punishment for the most serious crimes, crucifixion would kill victims in a horribly drawn-out and painful way. With their wrists and feet nailed or tightly bound to a cross, and their legs broken by the executioners to speed up death, the victim's weight would be transferred to their arms. This would gradually pull the shoulders and elbows out of their sockets, leaving the chest to bear the weight. Although inhaling would still be possible, exhaling would be difficult and the victim would eventually suffocate due to a lack of oxygen. This excruciating process could take 24 hours.

Crucifixion would lead to suffocation and multiple organ failure



Louis XVI and Marie Antoinette were both publicly executed using the guillotine

Guillotine

Although beheading methods had already been around for centuries, in 1789 French physician Dr Joseph Guillotin proposed a much more efficient and humane device for decapitation. When the executioner released the rope holding the guillotine's weighted blade in place, it would drop onto the victim's neck, killing them in a fraction of a second. This helped to eliminate the human error that was common with axe and sword beheadings, sometimes requiring multiple swings to fully remove the head. Although quick, guillotine executions were popular spectator events during the French Revolution and the guillotine operators became national celebrities.

Electric chair

Electrocution was adopted as a quicker and supposedly less painful method of execution than hanging in the 1880s. The victim has their head and one calf shaved to reduce resistance to electricity before being strapped in across their waist, arms and legs. A moistened sponge is placed on their head and an electrode in the shape of a metal skullcap is secured on top. Another electrode is attached to their shaved leg before the power is switched on. 2,000 volts pass through their body, paralysing the respiratory system and causing cardiac arrest.

Electrocution is still used as a method of execution in some US states

Inside a torture chamber

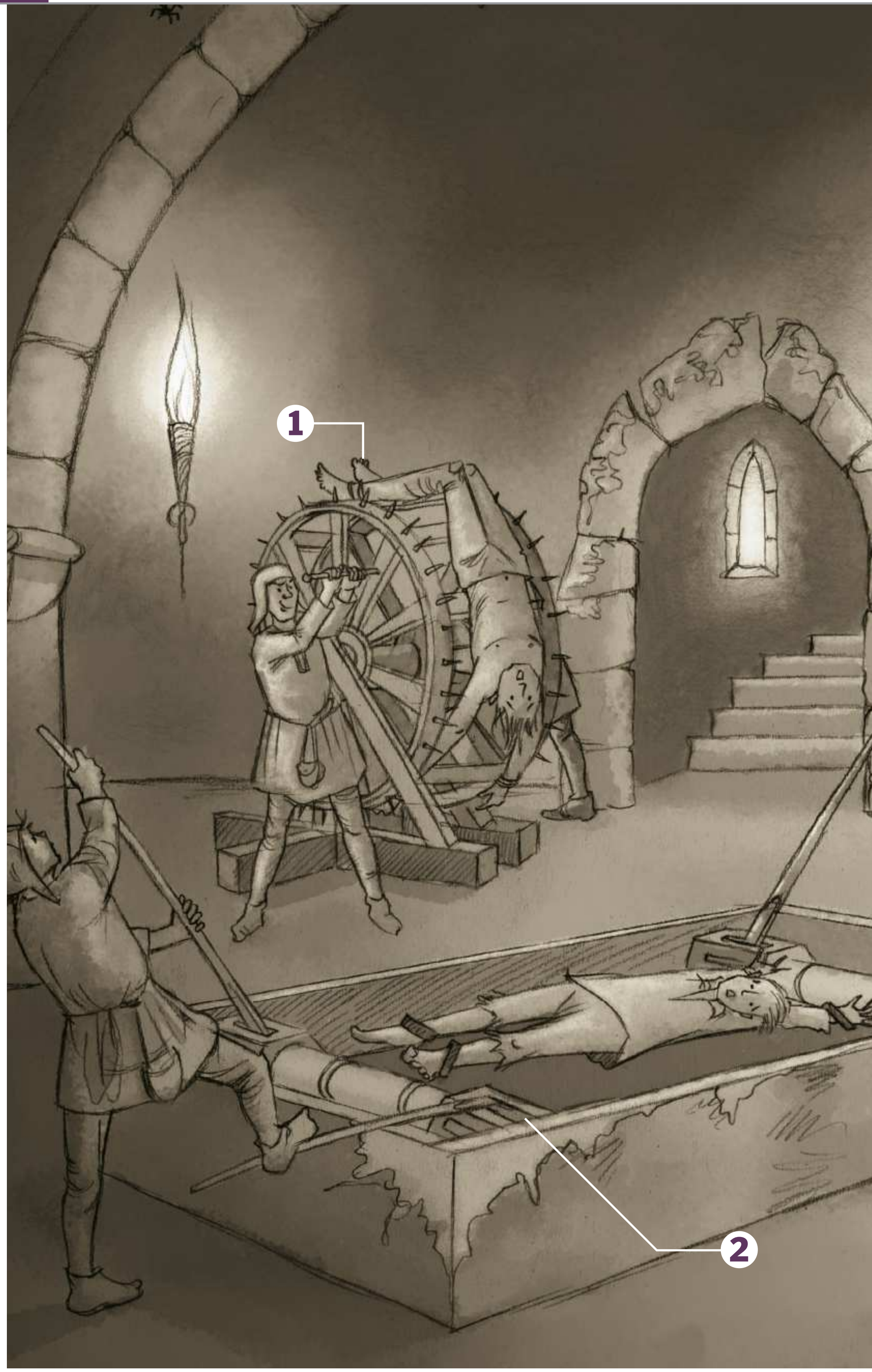
The terrifying devices that inflicted intense pain

Torture has been used as a method of punishment and interrogation for centuries, with the Ancient Greeks and Romans regularly torturing criminals as part of their justice system. However, by the Middle Ages torture had become particularly prevalent, especially in response to crimes of treason. If you had been disloyal to the sovereign and your country, a whole plethora of horrifying torture devices awaited you.

Torture was usually conducted in secret, with most medieval castles featuring an underground dungeon in which these diabolical deeds took place. A great deal of ingenuity and artistic skill went into developing instruments that would inflict the maximum amount of pain. Often simply threatening to use one on a person was enough to get them to confess, while others would quickly give in after seeing it used on a fellow prisoner. Some torture devices were designed to only inflict pain, but others would result in a slow, drawn-out death that prolonged suffering until the victim drew their last breath.

> "Often simply threatening to use torture on a person was enough to get them to confess"

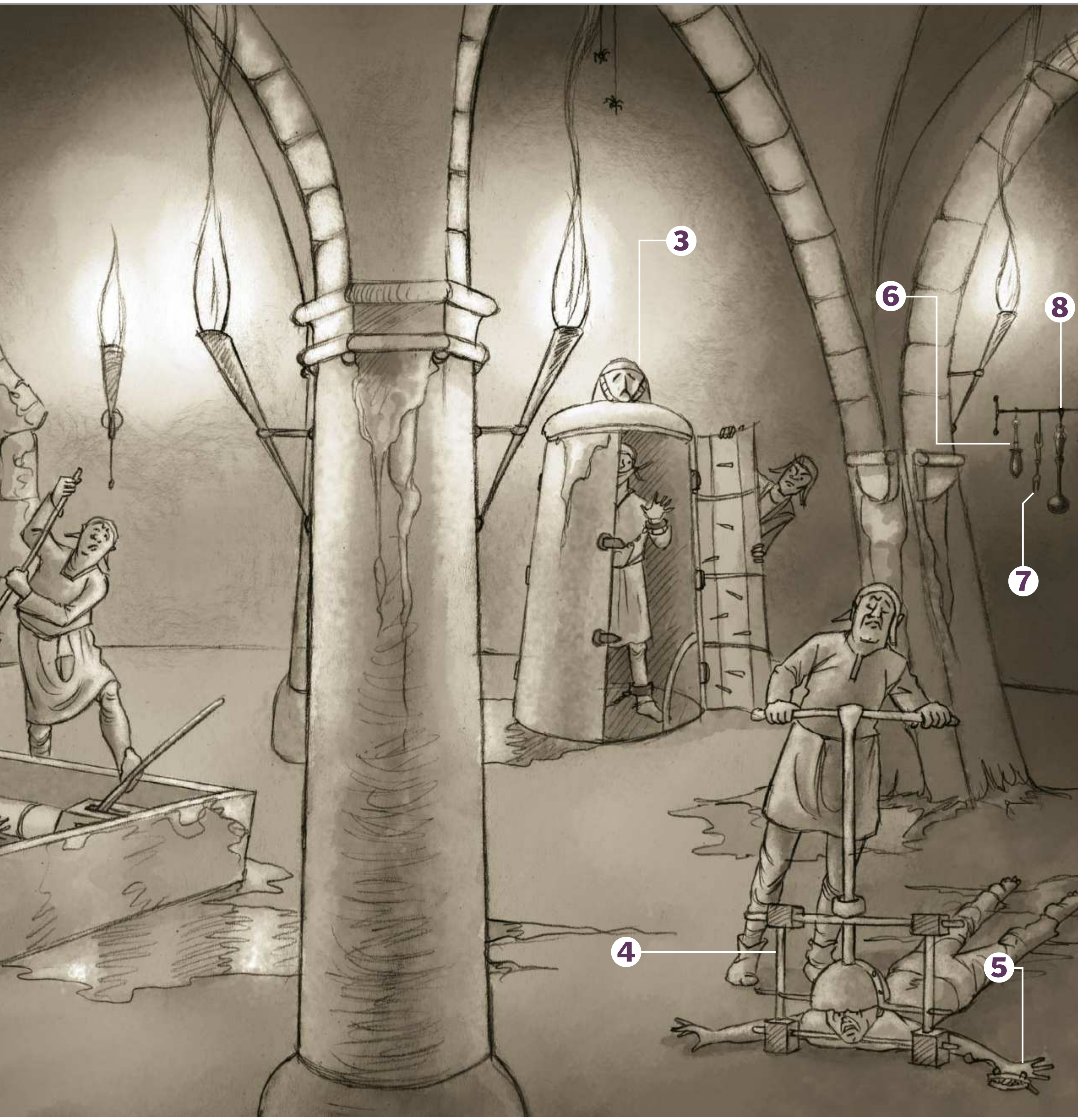
However, even if a prisoner was lucky enough to survive the torture, they were usually left severely disfigured and often had to be to be carried to their resulting trial as they could no longer walk on their own. From the mid-17th century onwards, torture became much less common as there was much speculation about its effectiveness. Many prisoners would say anything to end their suffering, so it often produced inaccurate information or false confessions. It wasn't until 1948 that the United Nations General Assembly adopted the Universal Declaration of Human Rights, banning the use of torture.



1 Breaking wheel
With the victim's limbs tied to the spokes of this large wooden wheel, it would be slowly revolved. As it spun, the executioner would bludgeon the victim's arms and legs with an iron hammer, shattering their bones one by one. If the victim survived this, they were placed on top of a large pole so birds could peck at their body until they eventually died of dehydration, which could take several days.

2 The rack
With their hands and feet tied to rollers at each end of the wooden frame, the victim would be subjected to brutal interrogation. If they failed to confess or give up the information the torturer was looking for, a crank would be turned to rotate the rollers. This would pull on the ropes, gradually and painfully stretching the victim's body, eventually dislocating their limbs.

3 Iron maiden
A series of menacing spikes protruded from the interior of this iron chamber. With the victim inside, the door was closed slowly, causing the strategically placed spikes to pierce the body. However, the spikes were not long enough to be instantly fatal. Instead, the victim would be left to slowly bleed to death.



4 Head crusher
With the victim's chin placed over the bottom bar and their head beneath the metal cap, the executioner would slowly turn the screw to bring the two together, only stopping if the victim gave the right answers. As the victim's head was crushed, their teeth would shatter into their jaw and their eyes would pop out from their sockets.

5 Thumb-screws
Used as punishment or a method of extracting information, the victim's fingers, thumbs or toes were placed between two horizontal metal bars. When the screw was turned, the two bars were pressed together, crushing the digits inside. Some thumbscrews even featured metal spikes on the bars to increase the pain.

6 Choke pear
Also known as the 'pear of anguish', this device was inserted into one of the victim's orifices, such as their mouth. When the key or crank was turned, the 'petals' of the pear-shaped end would slowly open up, painfully mutilating the victim's insides, but not causing death.

7 Heretic's fork
Usually reserved for blasphemers, this metal rod with two prongs at either end was attached to a leather strap around the victim's neck. One end would pierce their chin, while the other dug into their sternum, causing immense pain if they attempted to move their jaw or neck, making it more or less impossible to talk.

8 Lead sprinkler
Deceptively designed to look like a holy water sprinkler, this device was actually filled with molten lead, acid or boiling hot oil or water. The long handle was shaken to shower the victim's body with the substance inside. This caused horrific burns and was potentially lethal.

Miserable medicine

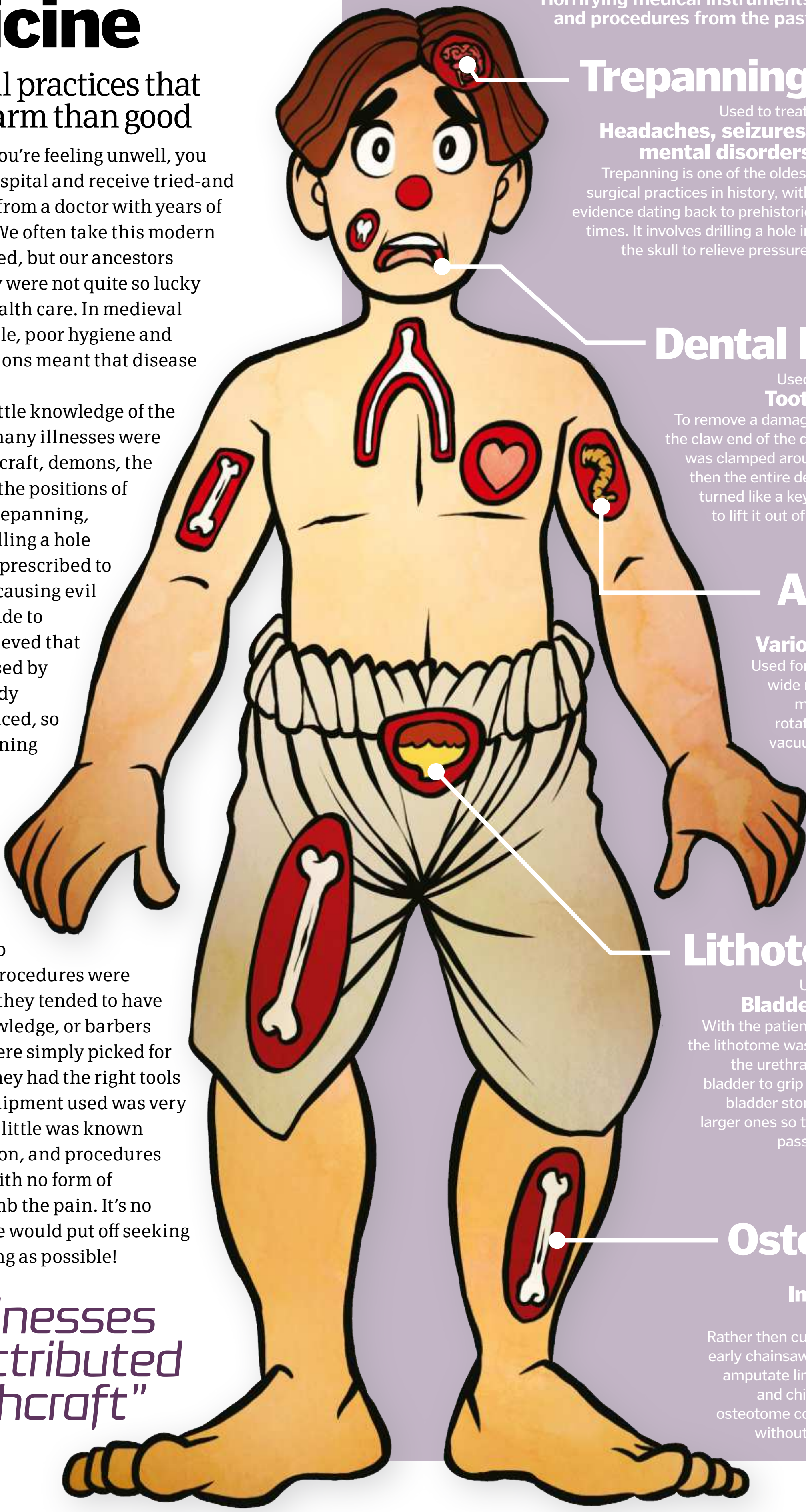
The medical practices that did more harm than good

Nowadays, when you're feeling unwell, you can visit a clean hospital and receive tried-and tested-treatments from a doctor with years of medical training. We often take this modern medicine for granted, but our ancestors throughout history were not quite so lucky when it came to health care. In medieval England for example, poor hygiene and filthy living conditions meant that disease was very common.

However, with little knowledge of the human anatomy, many illnesses were attributed to witchcraft, demons, the will of god or even the positions of celestial bodies. Trepanning, which involves drilling a hole into the skull, was prescribed to allow the disease-causing evil spirits trapped inside to escape. Others believed that diseases were caused by the fluids in the body becoming unbalanced, so bloodletting – draining the blood from a particular part of the body – was thought to restore that balance to normal levels.

The 'doctors' who carried out these procedures were usually monks, as they tended to have basic medical knowledge, or barbers or butchers who were simply picked for the task because they had the right tools for the job. The equipment used was very rarely sterilised as little was known about contamination, and procedures were carried out with no form of anaesthesia to numb the pain. It's no wonder that people would put off seeking treatment for as long as possible!

"Many illnesses were attributed to witchcraft"



Terrifying treatments

Horrifying medical instruments and procedures from the past

Trepanning

Used to treat:
Headaches, seizures, mental disorders

Trepanning is one of the oldest surgical practices in history, with evidence dating back to prehistoric times. It involves drilling a hole in the skull to relieve pressure.

Dental key

Used to treat:
Toothache

To remove a damaged tooth, the claw end of the dental key was clamped around it and then the entire device was turned like a key in a lock to lift it out of the gum.

Artificial leech

Used to treat:
Various infections and diseases

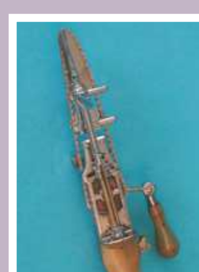
Used for bloodletting, a popular treatment for a wide range of medical conditions, this device mimicked the action of reel leeches, with rotating blades that cut into the skin while a vacuum in the cylinder sucked out the blood.

Lithotome

Used to treat:
Bladder stones

With the patient still awake, the lithotome was inserted up the urethra and into the bladder to grip onto smaller bladder stones or cut up larger ones so they could be passed naturally.

Osteotome



Used to treat:
Infections in the arms or legs

Rather then cutting down trees, this early chainsaw was actually used to amputate limbs. Unlike a hammer and chisel, the hand-cranked osteotome could cut through bone without causing it to splinter.

Weapons of war

The chemical arms race changed warfare forever

Chemical weapons

On 22 April 1915, Germany shocked the world by launching the first large-scale gas attack in war. After waiting several weeks for the wind to blow in the right direction, German soldiers released clouds of chlorine gas near the enemy trenches in Ypres, suffocating the unprepared Allied troops. Although The Hague Convention of 1899 prohibited the use of poisonous weapons, Germany justified its actions by claiming that France had already broken the ban by deploying tear gas grenades in 1914. The chlorine gas attack kick-started a chemical arms race, and by the end of World War I around 50 different chemicals had been used on the battlefield. The most prevalent were chlorine, phosgene and mustard gas, which would result in slow and painful deaths if soldiers were exposed to large enough quantities. Eventually, gas masks were developed for protection, but chemicals such as mustard gas could still cause horrific blisters if they came into contact with the skin. Among the most devastating chemical weapons are nerve agents, such as sarin, which attack the nervous system. Even small concentrations can be lethal, killing in mere minutes.

Cl_2

Chlorine

Appearing as a pale green cloud with a strong bleach-like odour, chlorine gas reacts with water in the lungs to form hydrochloric acid. This damages the lung tissue, causing coughing, vomiting and eventually death.

$COCl_2$

Phosgene

This colourless gas with a musty odour reacts with proteins in the alveoli, tiny air sacs found in the lungs. This leads to fluid in the lungs and eventually suffocation, but the symptoms can take up to 48 hours to manifest.

$C_4H_8Cl_2S$

Mustard gas

With the odour of garlic, horseradish or sulphur, yellow-brown clouds of mustard gas cause chemical burns on the skin, eyes and respiratory tract, leading to large blisters, temporary blindness and shortness of breath.

$C_4H_{10}FO_2P$

Sarin

Colourless, tasteless and odourless, this gas blocks normal communication between nerves. The nerve signals become stuck 'on', and muscles are unable to relax. This can lead to spasms, paralysis and asphyxiation.

The Geneva Protocol

By the end of World War I, over 125,000 tons of poison gas had been deployed in battle. Although it was only responsible for less than one per cent of the war's total fatalities, the psychological terror it had inflicted on soldiers was immense. On 17 June 1925, seven years after the war had ended, the Geneva Protocol was introduced, prohibiting the use of chemical and biological weapons. 138 states have now signed the treaty.

38 states originally signed the Geneva Protocol to ban the use of chemical weapons

Napalm

Napalm is a flammable liquid with a gel-like consistency, allowing it to stick to surfaces easily. In a bomb, it is combined with gasoline or jet fuel to explode upon impact, burning at over 2,760 degrees Celsius. Contact with skin can result in severe burns and even death by asphyxiation. When ignited, napalm generates carbon monoxide and removes oxygen from the air, suffocating those in the vicinity. Some of the greatest atrocities of war were caused by napalm.

Napalm fires combust oxygen in the air, turning carbon dioxide into carbon monoxide

Greek fire

Developed by the Byzantine Greeks in the 7th century, Greek fire was a flammable liquid that could burn on water, making it particularly effective for naval warfare. It was sprayed at the enemy using early flamethrower devices, or thrown in primitive hand grenades. The resulting fire could only be extinguished with sand, vinegar or urine. The true ingredients are a mystery, but scientists believe it could have contained petroleum, sulphur and pine tar.

Greek fire was the napalm of its day, but its ingredients are a mystery

Medieval writing equipment

Why we used quills for over 1,300 years

Before the invention of the pen, most people used quills to write with. These were stripped bird feathers, usually from geese. In particular, swan feathers were very sought after but geese, crow, owl and turkey feathers were simpler to obtain.

Quills were easy to supply, comfortable to hold and tapered down to a point so the writer could create all the subtle curves and lines of fine handwriting.

The first record of their use was around the 6th century by European monks, replacing the reeds they had been using up until then. Feathers were stripped, buried in hot sand to harden, hollowed out and then filled with ink. They were time-consuming to make and had to be refilled and reshaped regularly, but continued to be the main writing implement until the metal pen became popular in the mid-19th century.

How to make a quill

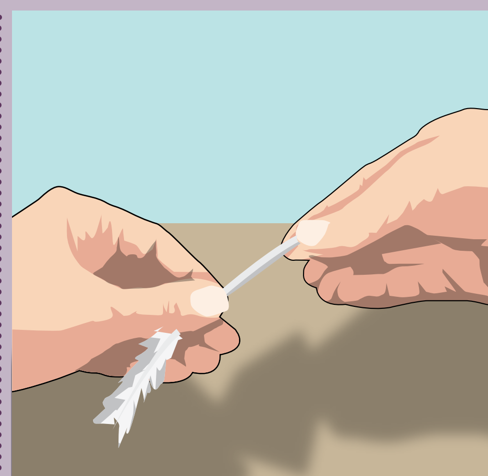
Travel back through time to the Middle Ages and write with feathers

Prime your feather

Scout around near a river or lake for a feather that has been dropped by a swan or goose. Ideally it should be around 15cm long and intact. Using a Stanley knife, very carefully shave off the fluffy feathers at the pointy end. You should be able to grip the quill without touching any feathers. Then place the feather in a bowl of water and leave it overnight to soak.

Toughen and shape

Heat sand in the oven at 175°C and bury the feather, using oven gloves to avoid burns. Wait until the sand has cooled and remove the hardened feather. From about 2.5cm above the tip, slice down at an angle of around 45 degrees to the tip of the feather. Make a small, flat cut on the opposite side of the tip. There should now be two spikes on the tip that you need to pinch together.



Finishing off

Shave the pinched end so it is nice and smooth and you should have a feather tapering nicely to a point. Dip your quill in the ink where it should soak up the writing fluid. There should be enough to write a fair few lines, depending on how tightly you've pinched it together. The tighter you've pinched it, the more ink it should retain. Take it out and begin writing like a medieval scribe!

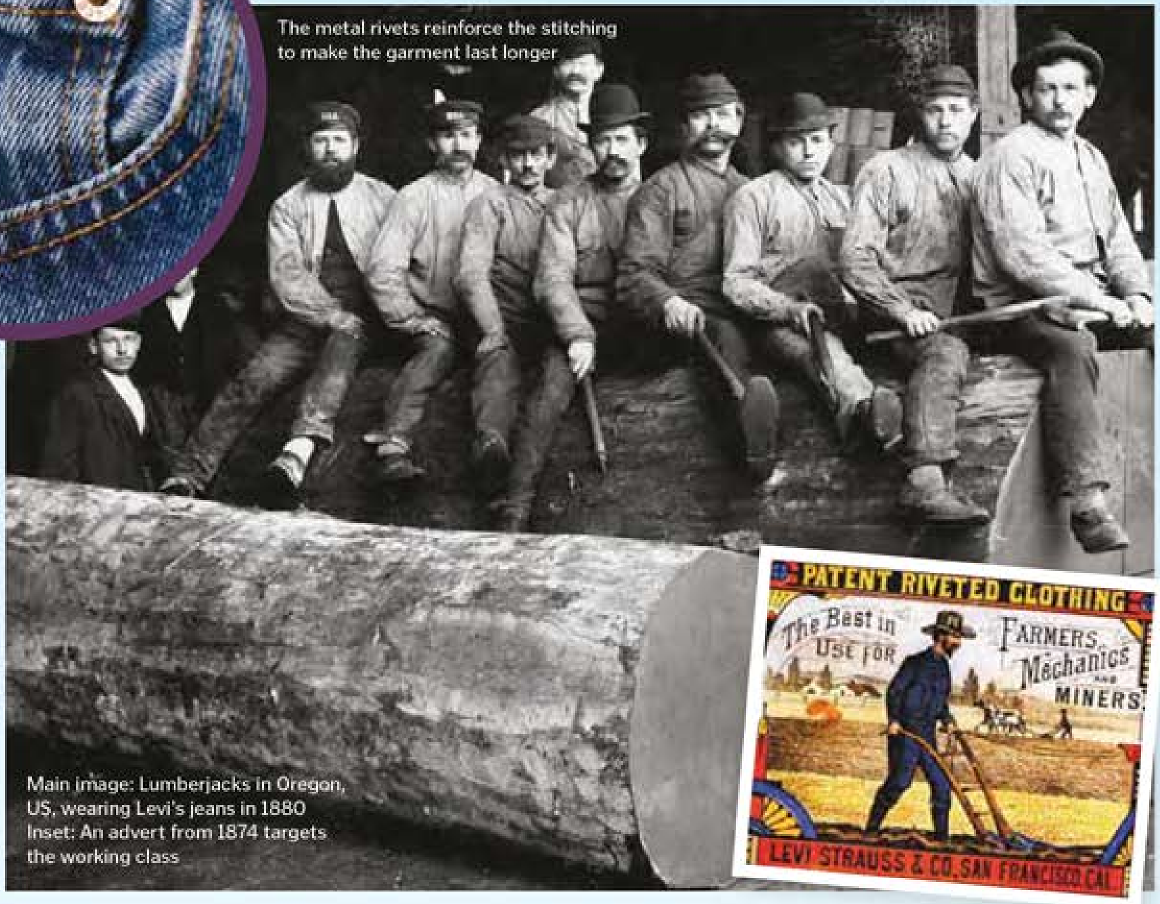
The first hearing aids

From 19th-century ear trumpets to microchips

Although they may look like something out of a cartoon, ear trumpets were used frequently throughout the early-19th century. The first type of hearing aid had a large surface area that amplified sound that was directed toward the ear. They were made of metal, silver, wood or animal horns and were incredibly bulky. However, as their use became more widespread, they featured a collapsible design so the ear trumpet could be carried in pockets and removed when necessary. Horns were so popular that even midwives would use a similar instrument to the ear trumpet for listening to pregnant ladies' wombs.

Early hearing aids could hardly be described as 'inconspicuous'

The metal rivets reinforce the stitching to make the garment last longer



Main image: Lumberjacks in Oregon, US, wearing Levi's jeans in 1880
Inset: An advert from 1874 targets the working class

The birth of blue jeans

The 'riveting' story of how two visionary immigrants created an American classic

Denim jeans are a fashion essential around the world, but their origins are much more humble. During the late 1800s, America was in the full throes of the Gold Rush, and Jacob Davis, a Latvian immigrant, was working as a tailor in Nevada. Jacob sold clothing to local miners and workmen, who required strong and hard-wearing material for their work. It was here that Jacob struck gold.

By fixing small copper rivets to the most strained areas of the garment, such as the pockets, he created a much more durable design. This new, robust clothing caught public attention and Jacob's 'waist overalls', as they were known, became so popular that he sought a patent to protect his idea. But a patent required money, so he asked his fabric supplier, Levi Strauss, for help.

Bavarian-born Strauss had also travelled to the States to seek his fortune and saw potential in Jacob's product. The pair were granted a patent in 1873 and before long the modern denim jean was being worn in factories, farms and mines across the country. Indigo was chosen to dye the jeans because it was dark enough to hide stains, it didn't penetrate the woven fabric and, crucially, it was cheap.

When the patent expired in 1908 dozens of imitations flooded the market and in the decades to come were worn by men and women of all classes. Teenagers began calling them 'jeans' instead of 'overalls' and manufacturers officially adopted the term in the 1960s. Today their popularity is as durable as the original riveted design.

Denim by the decades

How have jean styles changed over the years?

5 jean-ius facts

Denim jeans is a misnomer

In the late 1700s, two cotton fabrics were produced: denim and jean. Denim, originally made in de Nîmes, France, was more durable and thicker than jean, used to make workers' trousers in Genoa, Italy.

They were almost banned

Jeans gained a 'bad boy' image after featuring in movies like *Rebel Without A Cause*. Schools began banning them, so Levi's ran a campaign starring a clean-cut, denim-clad kid with the slogan 'Right for school'.

Levi wasn't his real name

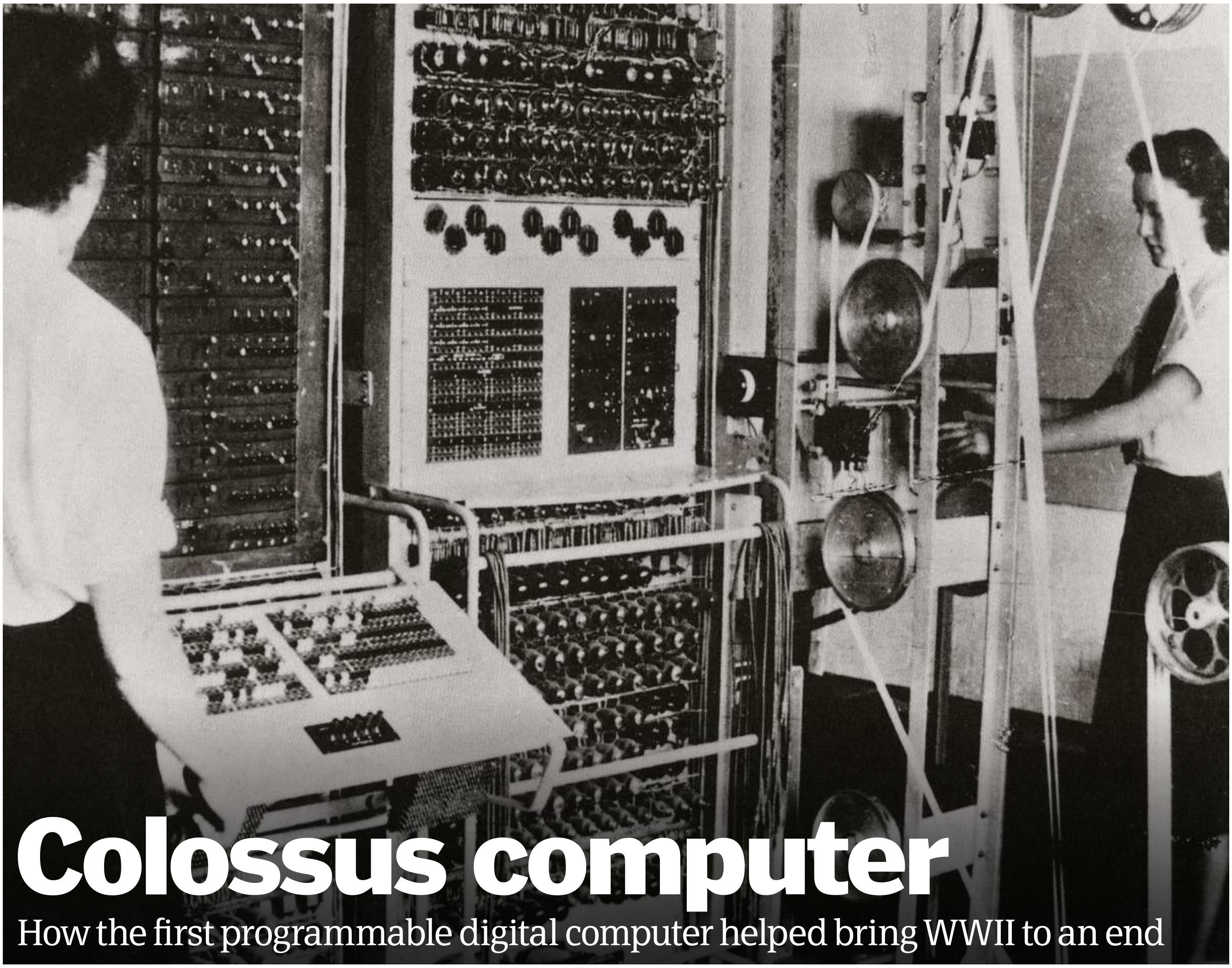
He was born Loeb Strauss, but like his future business partner, Jacob Davis, he changed his name after immigrating to the US. Eventually Levi set up a wholesale dry goods business in San Francisco.

Duck or denim?

When Levi and Jacob began mass-producing their waist overalls, they manufactured two kinds. One was from blue denim and the other from brown cotton duck — a tough canvas material that was used to cover wagons.

Built to last

In the Levi Strauss & Co archives lies two pairs of jeans dating from the late 1870s or early 1880s, which are thought to be the oldest in existence. Only two people know the combination to the fireproof safe that protects them.



Colossus computer

How the first programmable digital computer helped bring WWII to an end

The Colossus computer was a machine used by the British intelligence service during World War II to analyse and decrypt teleprinter orders and messages enciphered with a Lorenz SZ40/42 encryption machine by the Nazi Germany High Command. The contents of the messages were of incredible value to the Allies, as they often contained key orders for German generals, including troop movements and tactics.

Prior to the German use of the Lorenz cipher, the Allies had successfully cracked their Enigma code and had for years held the ability to decode messages thanks to Alan Turing's electromechanical Bombe machine. The Lorenz cipher was much more complex, however, with the SZ40/42 enciphering a message by combining its characters with a keystream of characters generated by 12 mechanical pinwheels. As such, without knowing the key characters – ie the position of the pinwheels – no decryption could take place.

The Colossus solved this issue by finding the Lorenz key settings, rather than actually decoding the message – the latter part done manually by cryptologists. The computerised process involved the Colossus analysing the inputted encoded message's characters and then counting a statistic based on a programmable logic function (such as whether an individual character is true or false). By analysing a cipher text in this way a number of times, the initial position of the Lorenz machine's 12 pinwheels could be determined and the keystream established.

Historically, the Colossus proved to be a colossal success, with the Allies decoding many war-changing messages throughout 1944 and 1945 and the generated intelligence used to counter the Nazis' movements in Europe. In addition, after the war, the technological advancements in computing brought about by Colossus led to Britain becoming a pioneering centre for computer science.

A colossal reconstruction

As part of the transformation of Bletchley Park into a museum, a fully functional replica of the Mark 2 Colossus was completed in 2007 by a team of engineers led by electrical engineer Tony Sale. Unfortunately, this was nowhere near as simple as six decades' worth of technological advancement since the war might make you think, with many blueprints and original hardware being destroyed after WWII, leaving those responsible for its reconstruction severely lacking in workable information.

Luckily though, after a dedicated research campaign, many of the Bletchley team's original notebooks were acquired, which when collated delivered a surprising amount of information. As such, by using the notebooks and consulting several original members of the Bletchley team, including the designer of the Colossus's optical tape reader – Dr Arnold Lynch – the reconstruction was completed successfully and is today situated in exactly the same position of the original Colossus at Bletchley Park, where it can be used to crack codes once more.

A sculpture to commemorate Flowers, with his son (left)

Flowers in focus

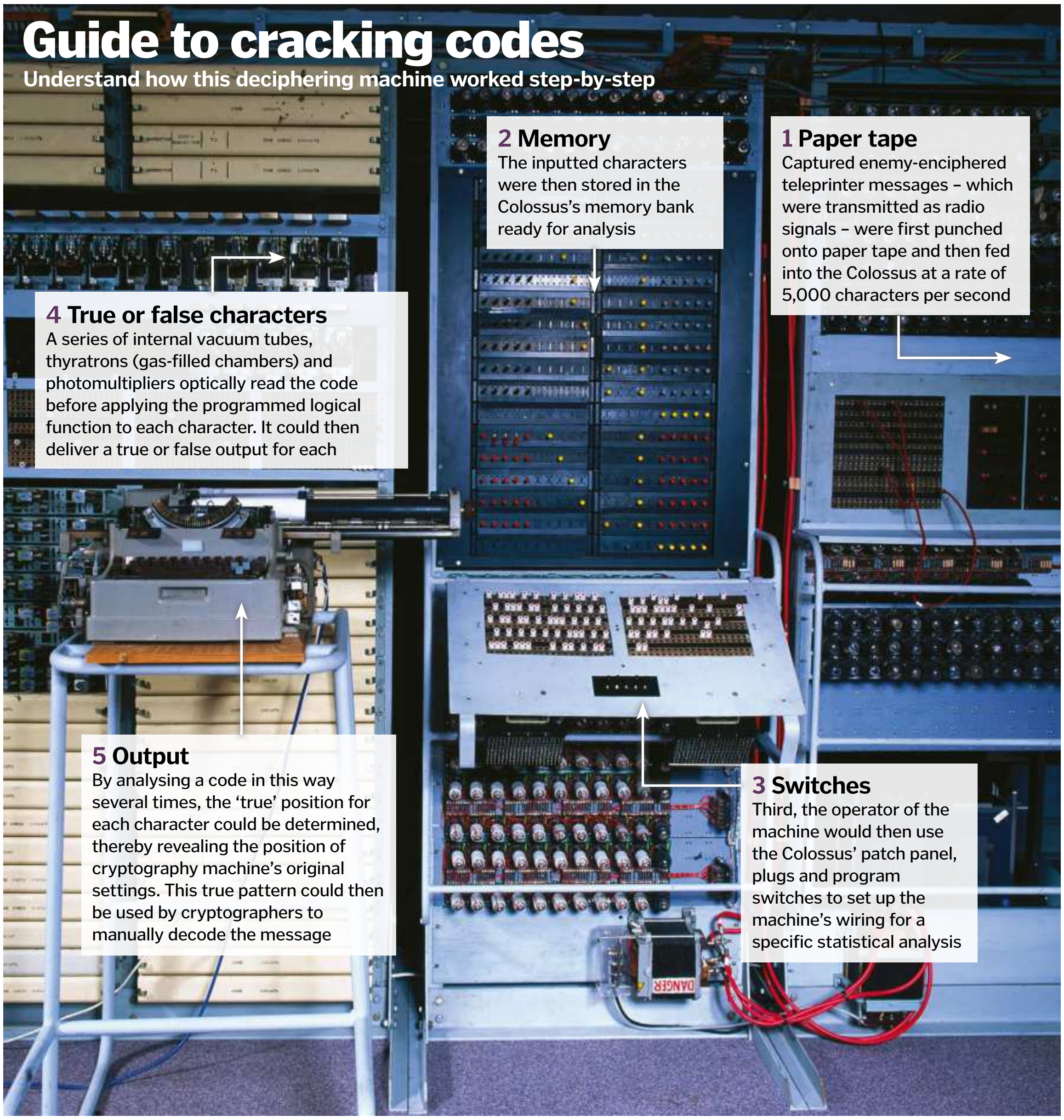
Thomas (Tommy) Flowers was the British engineer behind the revolutionary design and construction of the Colossus computer. After graduating from the University of London with a degree in electrical engineering, Flowers went on to join the telecommunications branch of the General Post Office, where he explored the use of electronics for telephone exchanges.

Off the back of this work, Flowers was invited to help code-breaking expert Alan Turing to build a machine that could help automate part of the cryptanalysis of Nazi Germany's Lorenz cipher – a high-level cipher used to communicate important orders from the high command.

By 1943 Flowers had built the Colossus, and soon after received funding to create a second improved variant, which went into active service in June 1944. Despite his key role in helping the Allies to victory, Flowers could not talk about his work for decades after the war as he was sworn to secrecy.

Guide to cracking codes

Understand how this deciphering machine worked step-by-step



In 1993 Bletchley Park was re-opened as a museum devoted to code breakers

Bletchley's role in WWII

Bletchley Park was the British government's main decryption headquarters throughout World War II. Located in Milton Keynes, Buckinghamshire, England, Bletchley was a top-secret facility for Allied communications, with a diverse team of engineers, electricians and mathematicians working manually – and later with the help of decryption machines – to break the various enemy codes used to disguise orders and private communiqués.

Among the many decoders – also known as cryptanalysts – working at Bletchley, Alan Turing became by far the most famous, with his work in breaking the Enigma and then Lorenz codes earning him the nickname the 'Father of Computer Science'. Indeed, between them Turing, Flowers and the rest of the Bletchley team's efforts arguably were crucial to the Allies' eventual victory in 1945, with the intelligence gathered by them – intel which was code-named 'Ultra' – speculated by some to have shortened the war by up to four years.

Today Bletchley Park is run by the Bletchley Park Trust, which maintains the estate as a museum and tourist attraction, with thousands of people visiting the site every year. Among the Trust's many activities is the reconstruction of many of the machines that helped to break the Axis codes – as discussed in more detail in 'A colossal reconstruction' opposite.

After WWII Alan Turing went on to advance our knowledge of computers and artificial intelligence even further

"Bletchley Park was the main decryption headquarters throughout World War II"

Rack-and-pinion railways

How did these unique transit systems help hefty locomotives scale steeper mountain slopes than ever before?

A rack-and-pinion railway (also known as a cog railway) was one that employed a toothed track. The addition of the toothed rail – which was usually located centrally between the two running rails – enabled locomotives to traverse steep gradients over 7 per cent, which remains to this day the maximum limit for standard adhesion-based railways.

Core to the operation of each rack-and-pinion system was the engagement of the locomotive's circular gears onto the linear rack. The rack and pinion therefore was essentially a means of converting the rotational energy generated by the train's powerplant into linear motion on the rack. As both the rack-and-pinion gears had teeth, the system also acted as an additional form of adhesion to the track, with the inter-meshing teeth holding the vehicle in place when not in motion.

Due to the primary form of power traditionally being steam, for rack-and-pinion systems to work the trains needed to be considerably adjusted. This modification stretched from the undercarriage of the train (so pinions could be installed) to the tilting of its boiler, cab and superstructure.

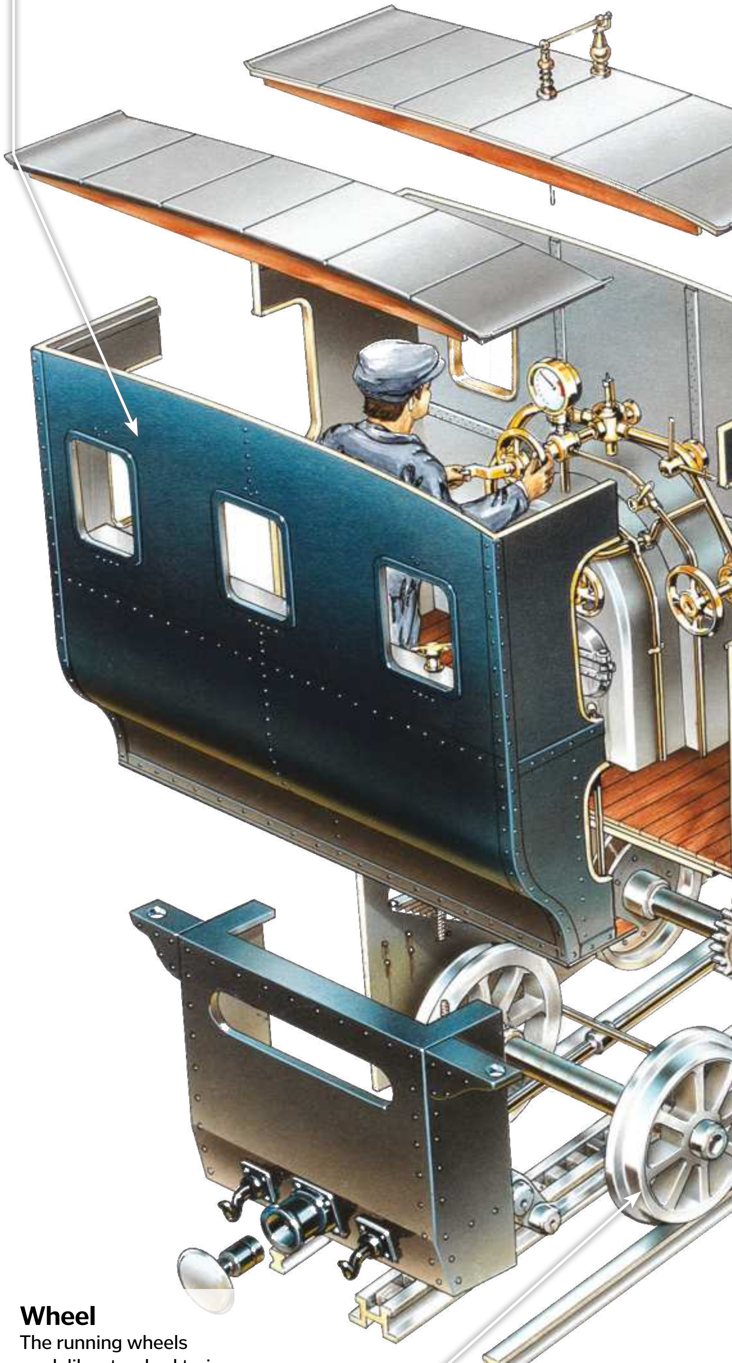
Tilting was necessary as steam engine boilers require water to cover the boiler tubes and firebox at all times to maintain stability – something that is nigh-on impossible to achieve if the train isn't level. As such, cog railway locomotives would lean in towards the track to counter the terrain's gradient.

Today, while rare, rack-and-pinion systems are still in operation worldwide, albeit with a mix of steam engines and diesel/electric locomotives. One of the most famous is the Mount Washington Cog Railway, which we look at more closely in the boxout opposite.

A rack-and-pinion railway built with a Strub system in rural Italy, 1920

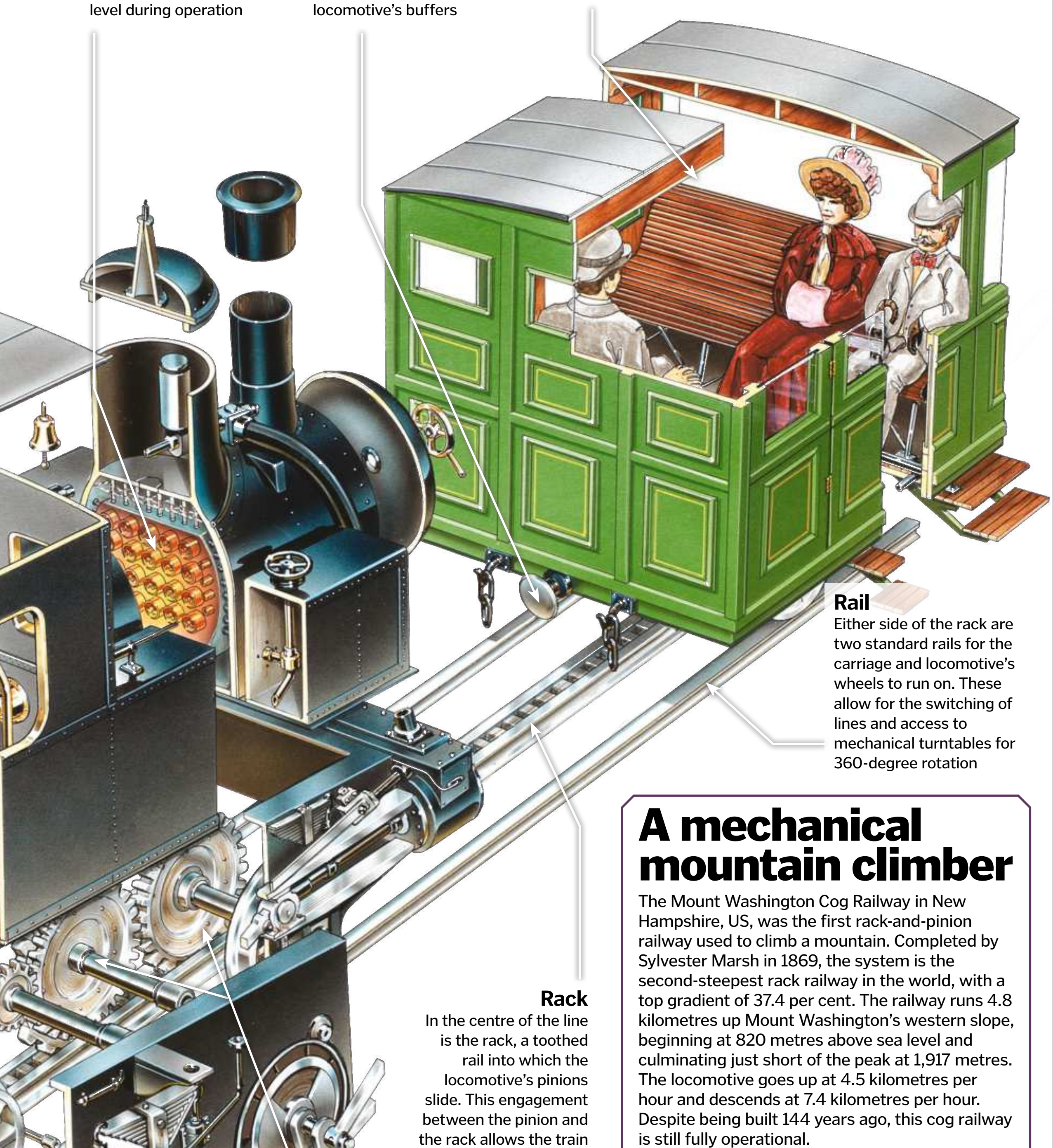
Rack and roll

Understand the anatomy of a rack-and-pinion locomotive now with our cutaway illustration



Cabin
To the rear of the engine and carriage is the cabin. From here the driver controls the steam boiler and the engagement of the pinion gears

Wheel
The running wheels work like standard train wheels, running along the rails either side of the central rack



A mechanical mountain climber

The Mount Washington Cog Railway in New Hampshire, US, was the first rack-and-pinion railway used to climb a mountain. Completed by Sylvester Marsh in 1869, the system is the second-steepest rack railway in the world, with a top gradient of 37.4 per cent. The railway runs 4.8 kilometres up Mount Washington's western slope, beginning at 820 metres above sea level and culminating just short of the peak at 1,917 metres. The locomotive goes up at 4.5 kilometres per hour and descends at 7.4 kilometres per hour. Despite being built 144 years ago, this cog railway is still fully operational.

Cog railway evolution

1 Marsh
Made famous by the Mount Washington Cog Railway, the Marsh system – invented by Sylvester Marsh in 1861 – used the locomotive's gear teeth like rollers, arranged in rungs between two 'L'-shaped wrought-iron rails.

2 Riggenbach
The 1863-made system created by inventor Niklaus Riggenbach used a ladder rack made from steel plates connected by regularly spaced rods. While effective, the fixed ladder rack was fairly complicated and expensive to build, so very few examples survive.

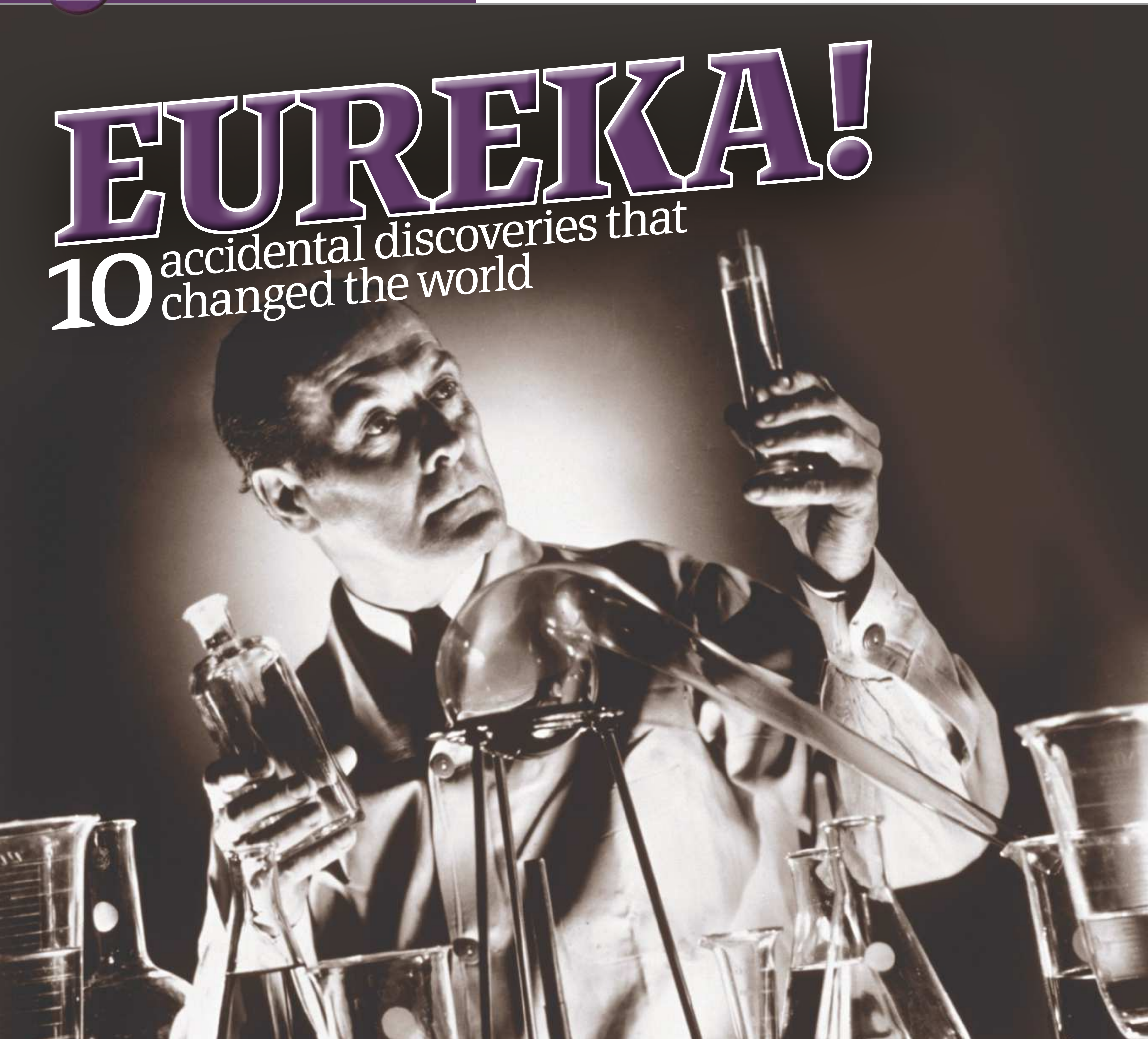
3 Abt
Carl Roman Abt improved the Riggenbach system in 1882 by using multiple solid bars with vertical teeth machined into them that were mounted centrally between the rails. This ensured the pinions on the wheels were in constant contact with the rack.

4 Locher
Eduard Locher's system designed in 1889 had gear teeth cut into the sides of the rails rather than the top, which were engaged by two cog wheels on the locomotive. This new system could work on steeper track gradients than anything prior.

5 Strub
Invented by Emil Strub in 1896, the Strub system utilised a rolled flat-bottom rail with rack teeth machined into the head 100mm (4in) apart. The safety jaws installed on the locomotive gripped the underside of the head in order to prevent dangerous derailments.

EUREKA!

10 accidental discoveries that changed the world



It's no secret that the best ideas often come to us when we least expect them to. For some it may be on the drive home from work or in the middle of the night, while others may have their lightbulb moments while taking 'time out' in the bathroom. The ancient Greek mathematician Archimedes was in the latter group, having famously realised how to measure the volume of irregular objects while taking a bath. When he climbed in, the water level rose, and it occurred to him that the volume of water displaced must be equal to his own. How he maintained his reputation after running naked through the streets screaming 'Eureka', we're not sure!

It's not just ideas that can come to us by chance; sometimes it's a physical invention. While it's true that most of history's greatest discoveries were made after years of painstaking research, others happened completely by accident. Take the humble ice lolly, for example. Arguably a lifesaving invention during the hot summer months, it was initially the result of a failed attempt at making soda. In 1905, an 11-year-old boy called Frank Epperson had been trying to make himself a sugary beverage, but left his concoction outside overnight with the stirrer still in the cup. Being the middle of winter, the liquid froze, and in the morning Frank enjoyed a frozen treat on a stick. Eighteen years later, he realised the commercial possibilities his accidental invention could have, and he began selling them on California beaches.

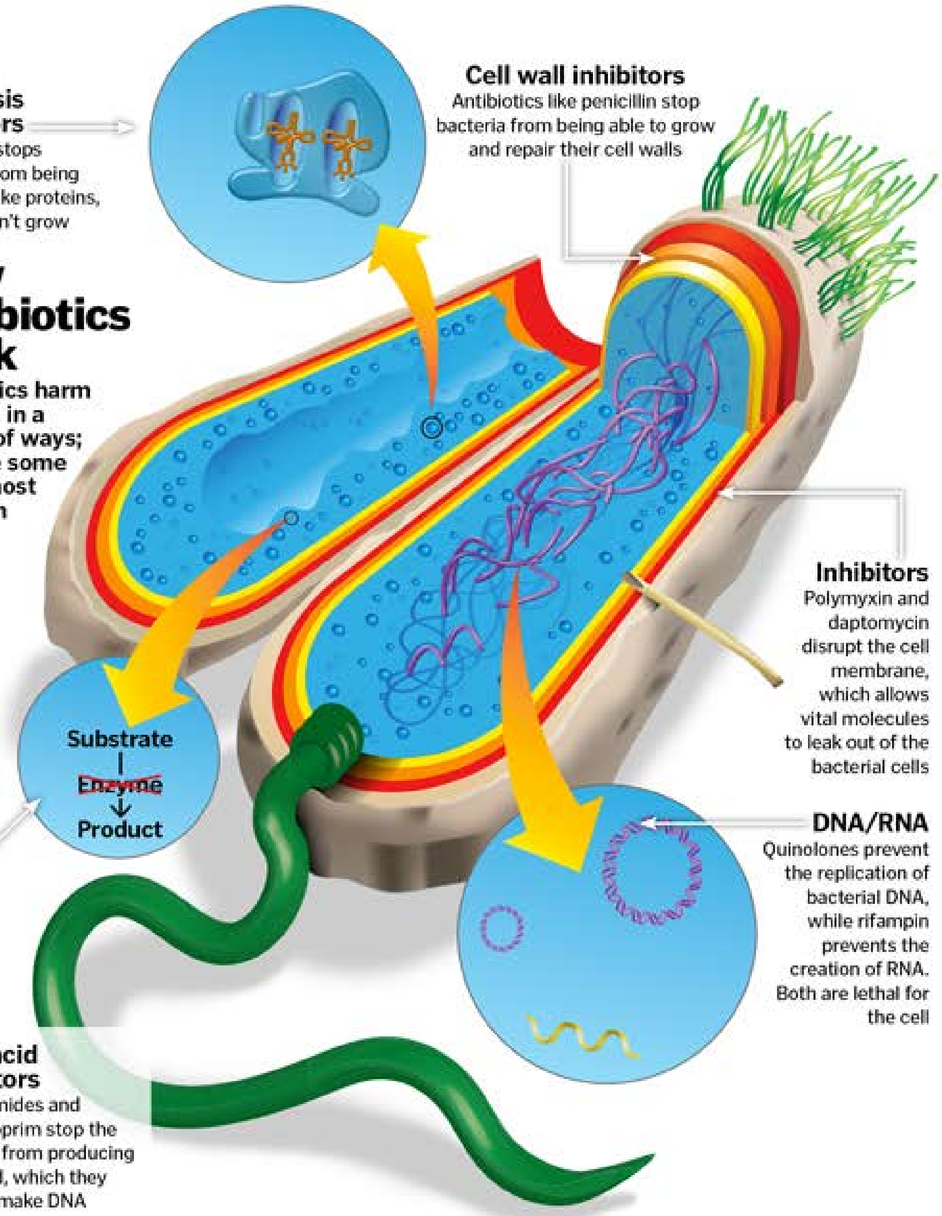
So whether it's the result of a clumsy spill or a contaminated laboratory, accidental inventions are just a slapdash scientist away, as long as they are able to realise the potential. Naked celebrations are, of course, optional.

Penicillin

1 A contaminated experiment is any scientist's worst nightmare, but in the case of biologist Alexander Fleming, it would be his making. While studying the influenza virus, he accidentally left a petri dish out of the incubator while he was away on holiday. Upon returning, he discovered that the petri dish, in which he had been growing staphylococcus bacteria, had also begun to grow mould. When Fleming examined the dishes more closely he noticed that there was a ring around the mould where the bacteria had not grown. The 'mould juice' was actually penicillin, produced by the Penicillium mould that had contaminated the dish. Fleming later found that it was able to kill many different types of bacteria. It was two other scientists, Howard Florey and Ernst Chain, who turned penicillin into a drug, but without Fleming, antibiotics may never have been invented.

How antibiotics work

Antibiotics harm bacteria in a variety of ways; here are some of the most common



DISCOVERER CASE FILE

Sir Alexander Fleming

Born in Scotland in 1881, Fleming went on to study at St Mary's Hospital, London, where he completed a bachelor's degree in medicine. His accidental discovery of penicillin earned him a Nobel Prize, which he shared with Florey and Chain.

Plastics (Bakelite)

2 Throughout the 19th century, scientists tried desperately to solve the mystery of polymers – very large molecules that can be expanded and moulded. In 1870 an American inventor modified a naturally occurring polymer called cellulose to create an incredible new material called celluloid, which could be moulded or rolled when heated. But it would be another 40 years before the first wholly synthetic plastic was made. The discoverer, Leo Baekeland, had been experimenting with synthetic resins. After heating the liquid, he found that it produced a solidified matter, which was insoluble in solvents and did not soften when heated. He called it 'Bakelite', and it was soon used in the production of everything from electricals to jewellery.

DISCOVERER CASE FILE

Leo Baekeland

A Belgian chemist born in 1863, Baekeland left his homeland for New York aged 23. Here he invented Velox photographic paper, which allowed developments under artificial light, before turning to plastics.

Bakelite was used to make telephone casings because it was electrically nonconductive and heat-resistant

Microwave

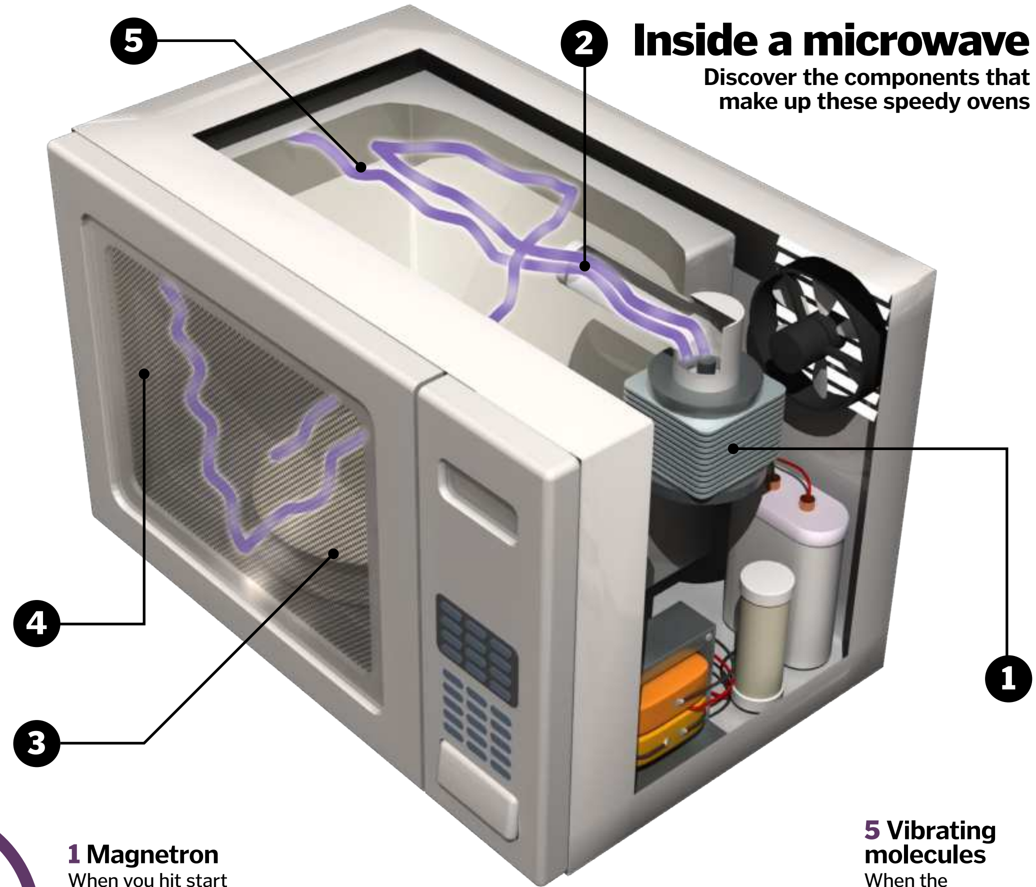
3 Not only was the microwave discovered by accident, it was also discovered by a man who had not even completed high school. At the age of 12, Percy Spencer left education to work in a spool mill and was later hired to install electricity in a nearby paper mill. In the 1920s, Spencer began working as an engineer for Raytheon, a company that went on to improve radar technology for Allied forces in World War II. One day, he was stood in front of an active radar magnetron when he noticed the chocolate bar in his pocket had melted. He began testing the effects of magnetrons on other foods, and invented the first true microwave oven by attaching a high-density electromagnetic field generator to an enclosed metal box. The oven was a success, and in 1945 the company filed a patent for the first commercial microwave.

DISCOVERER CASE FILE
Percy Spencer

Born in 1893, at eighteen months old Spencer's father died and his mother left him in the care of his aunt and uncle. Despite his difficult start, he would become one of the world's most famed physicists.

Inside a microwave

Discover the components that make up these speedy ovens



1 Magnetron
When you hit start on a microwave, the magnetron takes electricity from the power outlet and converts it into high energy microwaves

2 Wave guide
These waves are blasted into the food compartment through a channel called a wave guide

3 Turntable
The food spins around on a turntable, allowing it to be cooked evenly

4 Metal walls
The microwaves bounce off the reflective metal walls to hit the food from different angles

5 Vibrating molecules
When the microwaves penetrate the food, they cause the molecules inside it to vibrate faster. This quickly heats the food up

Artificial sweetener

4 The first artificial sweetener, saccharin, was discovered by a Russian chemist called Constantin Fahlberg. He had been experimenting with preservatives in his work, and while eating a bread roll, he noticed that it had been sweetened by the substance left on his hands. He went back to the lab and retraced his steps, until he was able to synthesise the sweetener in bulk.

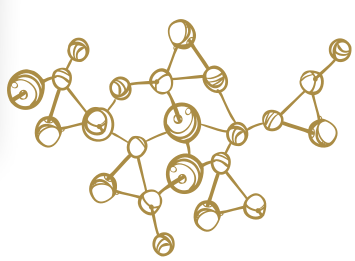
DISCOVERER CASE FILE
Constantin Fahlberg
Fahlberg was initially hired to analyse the purity of sugar.

Saccharin rose to popularity during World War II, when sugar became scarce

Superglue

5 This super-sticky substance was discovered by accident – twice! Chemist Harry Coover had been attempting to make clear plastic gun sights for the Second World War, and one formulation he tested produced an extremely quick bonding adhesive. It was useless for his gun sights, though, and he forgot about it until almost ten years later, when he stumbled across it again while developing heat-resistant canopies for jet airplanes. This time he realised its potential, and the product was put on the market.

DISCOVERER CASE FILE
Harry Coover
Coover worked as a chemist for Eastman Kodak.



Coca-Cola

6 After being wounded in the American Civil War, pharmacist John Pemberton became addicted to morphine. Seeking an alternative, in 1886 he began experimenting with coca – the plant from which cocaine is derived. He eventually stirred up a fragrant, caramel-coloured liquid that he combined with carbonated water and put on sale for five cents a glass. The soda, named Coca-Cola, would become the world's fourth most valuable brand.

DISCOVERER CASE FILE
John Pemberton
Pemberton established a wholesale drug business.

Stainless steel

7 Steel has been forged for millennia, but it wasn't until 1913 that a metallurgist called Harry Brearley discovered a way to stop it rusting. He had been tasked with finding an erosion-resistant metal to prolong the life of gun barrels. Legend has it that as attempt after attempt failed, his pile of scrap metal grew bigger, and he later noticed that one of the scraps hadn't rusted like the others. He had invented stainless steel, and quickly saw its potential in the cutlery industry.

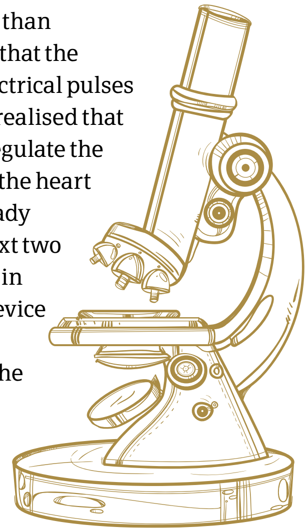
DISCOVERER CASE FILE
Harry Brearley
Brearley was lead researcher at Brown Firth in 1908.

The pinnacle of New York's Chrysler Building is clad with non-rusting stainless steel

DID YOU KNOW? *It wasn't until Thomas Edison's assistant died of skin cancer in 1904 that concerns were raised about X-rays*

Pacemaker

8 Pacemakers have existed in a very rudimentary form since the 19th century, when it was discovered that electrical impulses could be used to provoke a heartbeat. However, the devices that followed were large and bulky and had to be plugged into a mains current, putting the patient at risk of electrocution. It wasn't until 1960 that battery-powered implantable pacemakers came into use, having been invented four years previously. Electrical engineer Wilson Greatbatch was working on a heart-rhythm recorder when he added the wrong size of resistor to the circuitry. Rather than recording, he found that the device produced electrical pulses instead. He quickly realised that it could be used to regulate the electrical activity of the heart and guarantee a steady rhythm. Over the next two years, he succeeded in miniaturising the device and making it safe from bodily fluids. The first patient, a 77-year-old man, went on to live for a further 18 months.



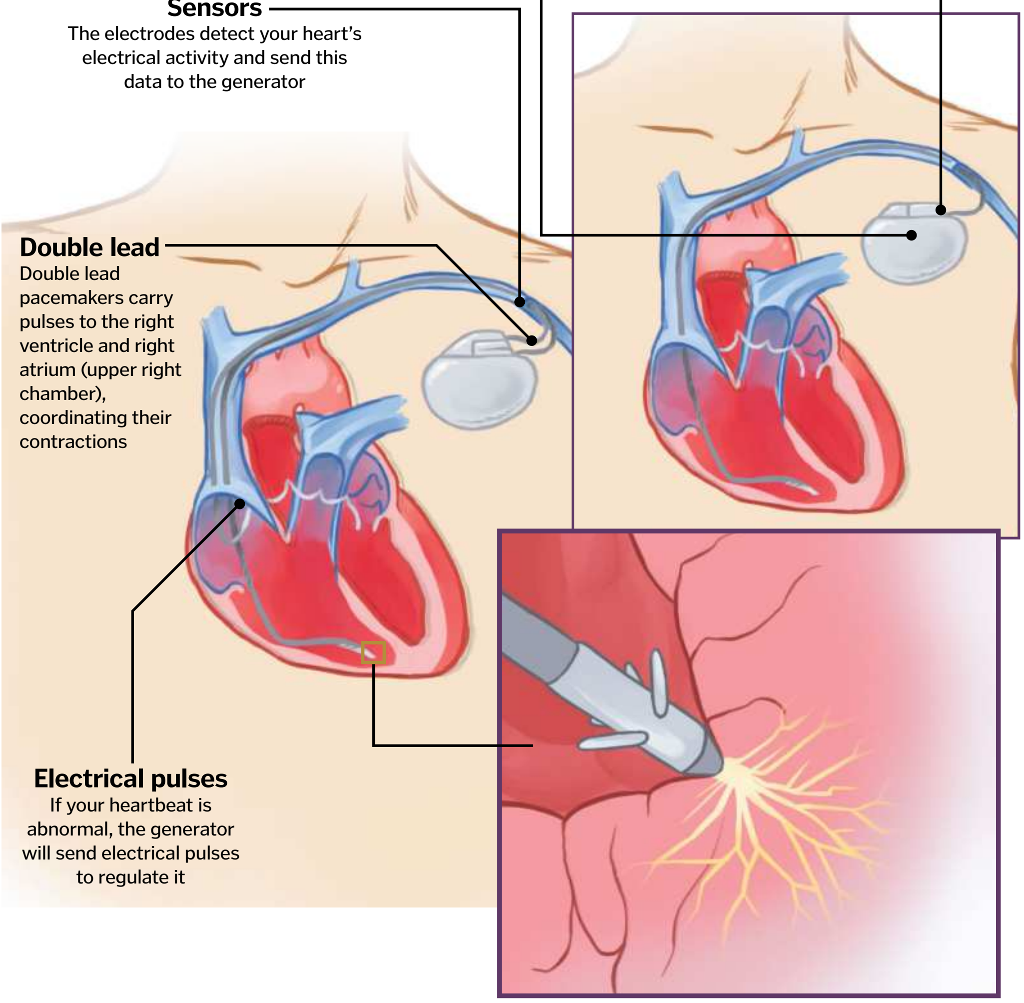
DISCOVERER CASE FILE

Wilson Greatbatch

The American engineer and inventor was born in New York in 1919, and served in World War II before completing a degree in electrical engineering. By the time of his death in 2011, he held over 325 patents.

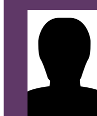
How a pacemaker works

Discover how these amazing pieces of tech can keep our hearts beating



Teflon

9 The non-stick substance found on frying pans was inadvertently invented by a man called Dr Roy Plunkett. He had been trying to synthesise a non-toxic alternative to refrigerants like sulphur dioxide and ammonia, and was experimenting with tetrafluoroethylene (TFE). After storing the gas in cylinders, he opened one to discover that it had polymerised into a waxy white powder that was extremely sticky and had a very high melting point. Three years later, the substance, which was named Teflon, was patented.



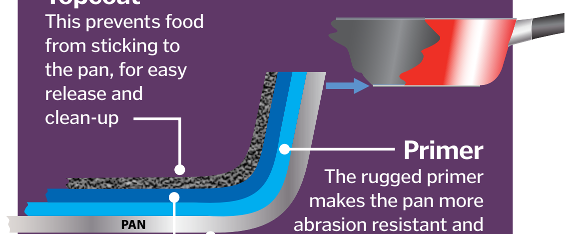
DISCOVERER CASE FILE

Roy Plunkett

Plunkett received the John Scott Medal for the "comfort of humankind".

Protecting a pan

Peel back the layers to find out what makes modern frying pans so practical



X-Rays

10 It was while German physicist Wilhelm Röntgen was investigating the effects of cathode ray tubes that he made a curious discovery. During an 1895 experiment, he evacuated the tube of all air and filled it with gas before passing an electric current through it. Despite it being covered with black paper, he noticed that a screen several feet away was illuminated by the invisible rays, which he named 'X' to indicate the unknown. They were later found to pass through human tissue, allowing for the imaging of bones.

DISCOVERER CASE FILE

Wilhelm Röntgen

Born the only child of a cloth merchant in 1845, Röntgen studied mechanical engineering.

Röntgen took this radiograph of his wife's left hand

The Antikythera mechanism

An ancient scientific device that accurately calculated the locations of stars and planets

The Antikythera mechanism was the most advanced astronomical instrument of the ancient period. Assembled by the ancient Greeks, or perhaps the Babylonians, it was lost for 2,000 years before being discovered among artefacts taken from a shipwreck off the Greek island of Antikythera in 1901.

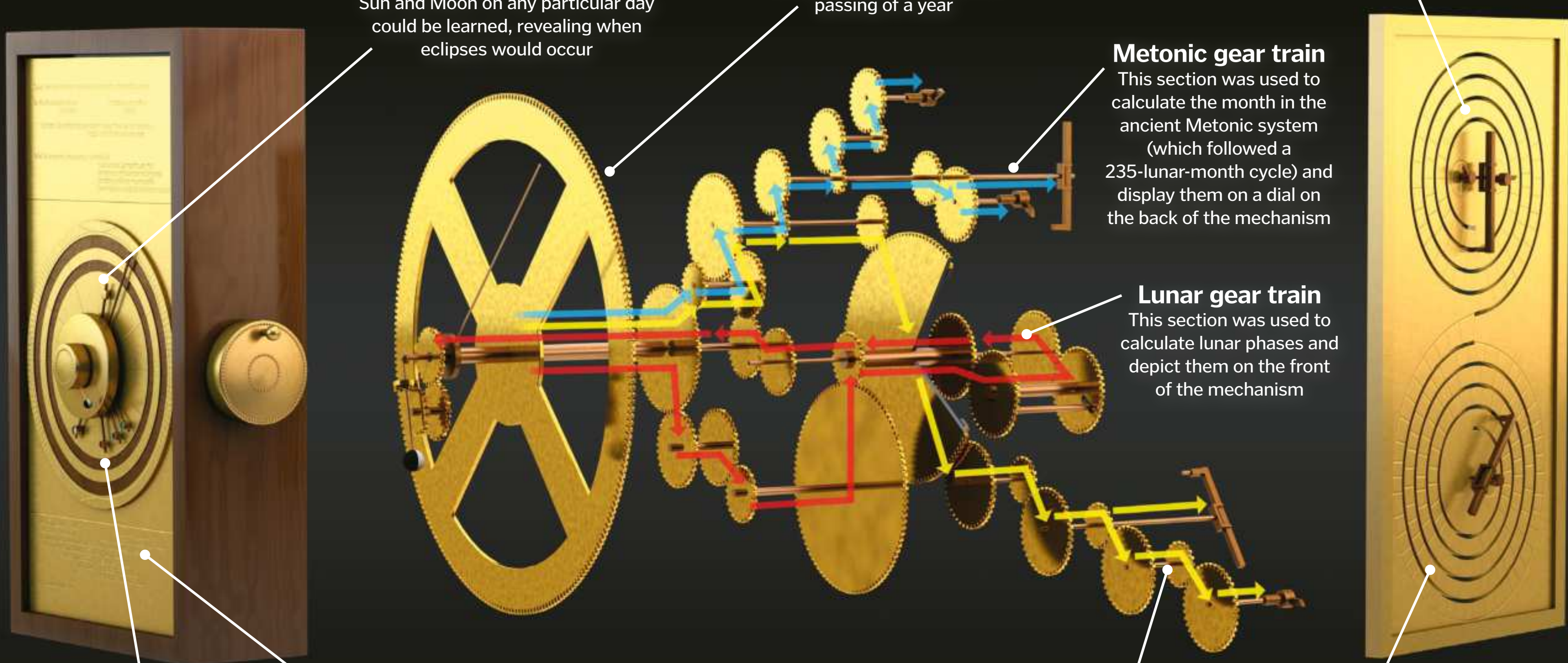
After meticulous study, scientists and historians declared the distorted mass of bronze to be an analogue computer, able to determine the positions of planets and the timing of eclipses. It accurately displays the phases of the Moon as well as the location of the five known planets in antiquity (Mercury, Venus, Mars, Jupiter and Saturn) in the sky.

Initially contained in a wooden case, only around 40 per cent of the original remains survive, and it is too delicate to examine by hand, so X-ray imaging and CT scans have been used to reveal how it worked. Inside, interlinking bronze gears are precisely arranged and cut exactly to size to turn rotating dials and pointers. The mechanism is evidence of the Greek's impressive astronomical knowledge and dates back to 205 BCE, the earliest date listed in the inscriptions on the device. It's the first invention we know of designed to show the layout of all the known celestial bodies in the sky at any given time, and was likely used for both educational and scientific purposes.

The 82 remaining fragments are kept at the National Archaeological Museum in Athens, Greece

How it could have worked

Based on the gears discovered, scientists can predict the mechansm's inner workings



The corvus

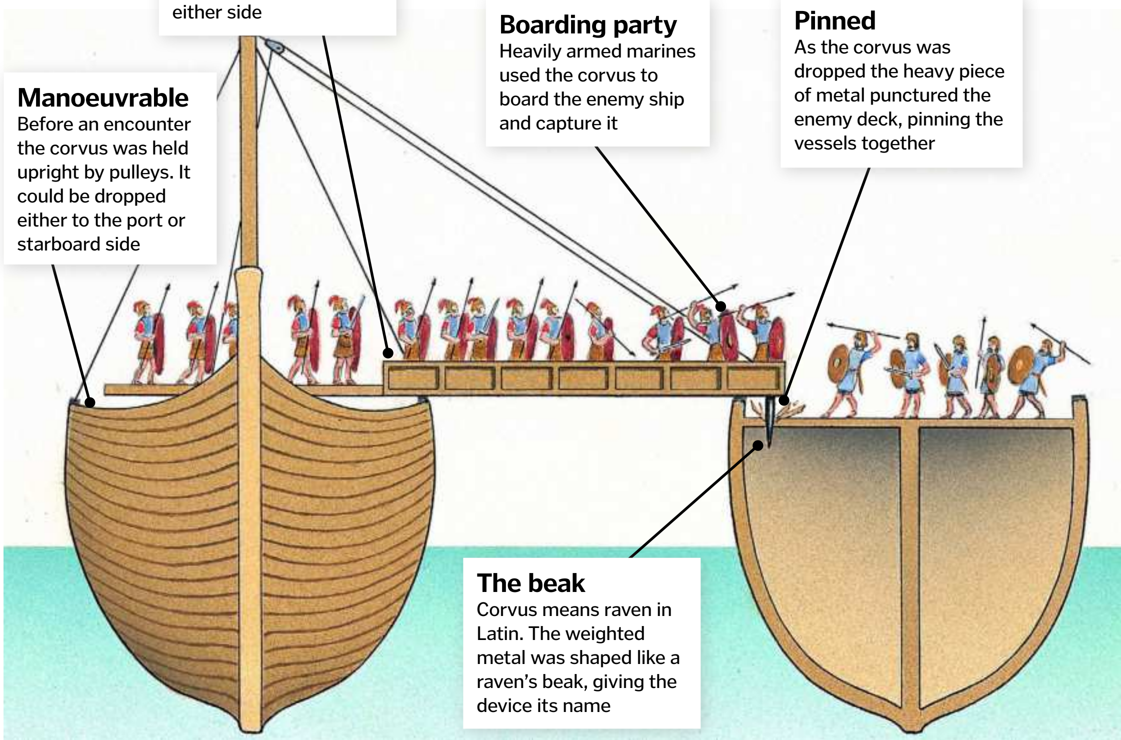
The invention that turned the tide for the Romans during their first war at sea

As the Carthaginians approached the Roman fleet near Mylae in 260 BCE, they saw an unfamiliar object affixed to the prow of the opposing ships. The marines were startled, but as their ships were both faster and better constructed they continued their advance full of confidence. What followed would be remembered as a great victory for the Romans and a disaster for their adversaries.

A common tactic in ancient naval warfare was ramming and sinking enemy ships, but the Romans knew they were outclassed in a typical sea battle. Instead, they favoured boarding the enemy ships with their superior soldiers, and so they designed the corvus. They put the new invention into practice at Mylae. When their opponent's vessel neared they dropped their new boarding bridge onto their decks, pinning them and enabling Roman marines to swarm aboard and take the enemy ship.

All aboard

How the Romans brought hand-to-hand combat to naval battles



Automatic doors of the ancient world

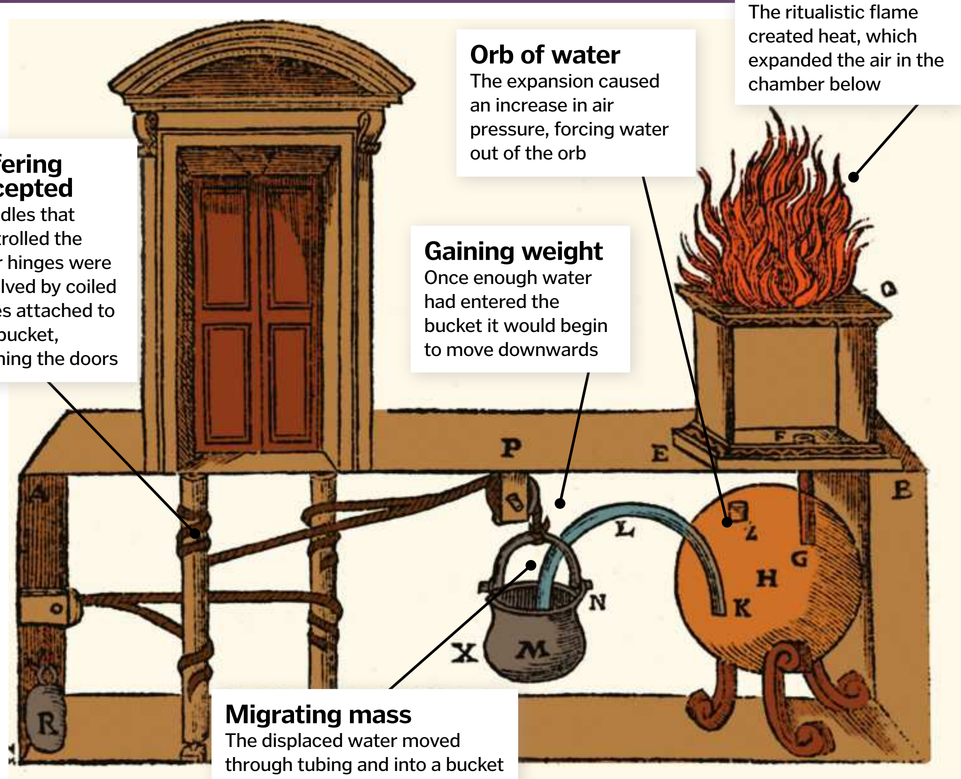
A bright spark called Hero of Alexandria designed the world's first self-opening temple doors

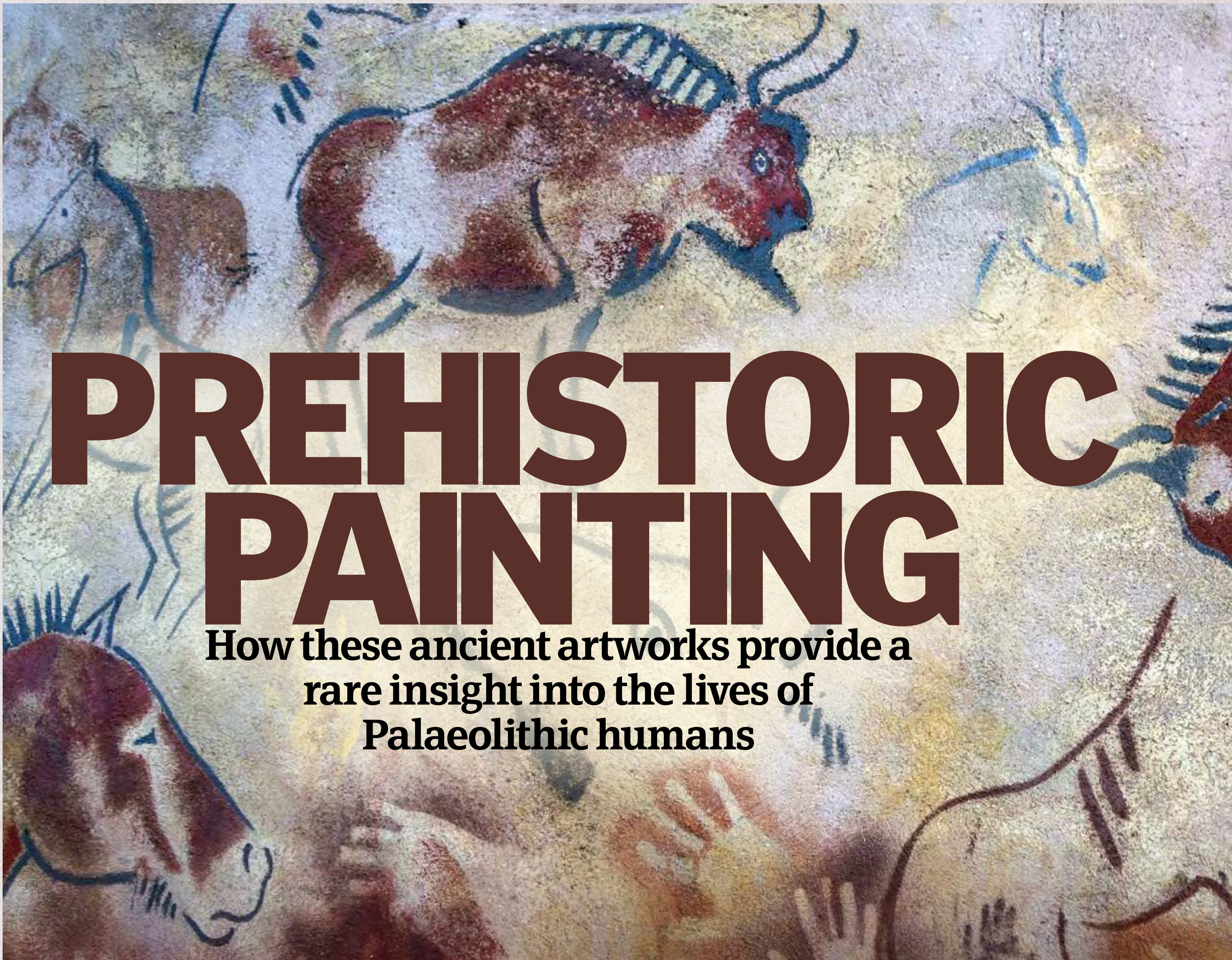
As worshippers gathered around a temple of the ancient world they were treated to a sight so spectacular that it appeared to prove the existence of the gods. The congregation would watch as a temple priest stood beside a set of grand entrance doors and lit a large fire to begin his ritual. He would then make an offering over the flames, and after some time the doors would open wide, seemingly by the gods themselves.

But what looked to the crowd as divine intervention was in fact an advanced mechanism working beneath the temple's surface. It had been designed by Hero of Alexandria, a famous inventor whose knowledge of physics far exceeded that of his contemporaries. Hero understood that air could be pushed and pulled, and it was by exploiting this knowledge that he designed one of the greatest illusions of power in the ancient world.

Hero's automata

Explore the mechanics that created an illusion of magic





PREHISTORIC PAINTING

How these ancient artworks provide a rare insight into the lives of Palaeolithic humans

Prehistoric cave paintings are believed to be among the first examples of human art. The remnants of images found in caves today provide archaeologists with a fascinating insight into the world of our Stone Age ancestors.

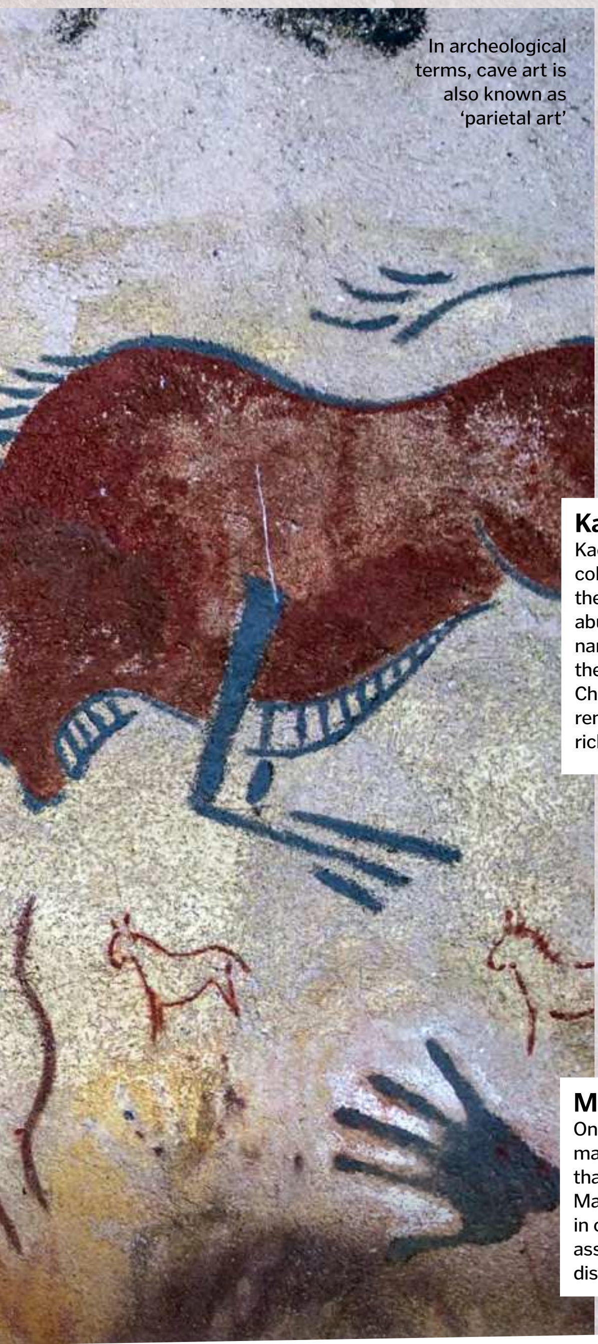
So how did they make the paint? Black paints could be made from a simple mixture of charcoal and a binder, such as saliva or animal fat. The earliest coloured paints were made from naturally occurring minerals (known as pigments) such as iron oxides, which were ground into a powder before being mixed with a binder. These pigments were in high demand, and some prehistoric artists may have travelled 40 kilometres or more to gather them.

To make a typical cave painting, an outline was scored on the wall with a sharp stone, then marked out with charcoal. The image could then be filled in with a coloured pigment paint, and shaded to make it three-dimensional.

The majority of cave paintings are illustrations of animals that roamed the land nearby, including lions, rhinos, bears and even sabre-toothed cats. Images of the humans themselves are much less common. One theory for this is that it was believed that the artwork was a link to a spirit world, and the depictions would increase luck when hunting. Campfires in the caves helped to give the impression that the painted creatures were alive, with the illustrations dancing on the walls. Outlines of human hands, also known as hand stencils, are a common sight among cave paintings, thought to be a sort of artist's signature.

Scientists can estimate when a cave painting was made using radiometric dating, either using the rate of decay of the isotope carbon-14 in the pigments, or the rate of uranium decay in the surrounding rocks. Some paintings in Europe are thought to date back as far back as the Upper Paleolithic period, making them up to 40,000 years old. The European examples are perhaps the most well-known, but prehistoric cave art has also been found in Africa, Asia and Australia, with (relatively) more recent examples in the Americas dating back nearly 10,000 years. Based on the discoveries so far, cave art seems to have become less popular as warmer climates allowed humans to begin settling outside of caves.

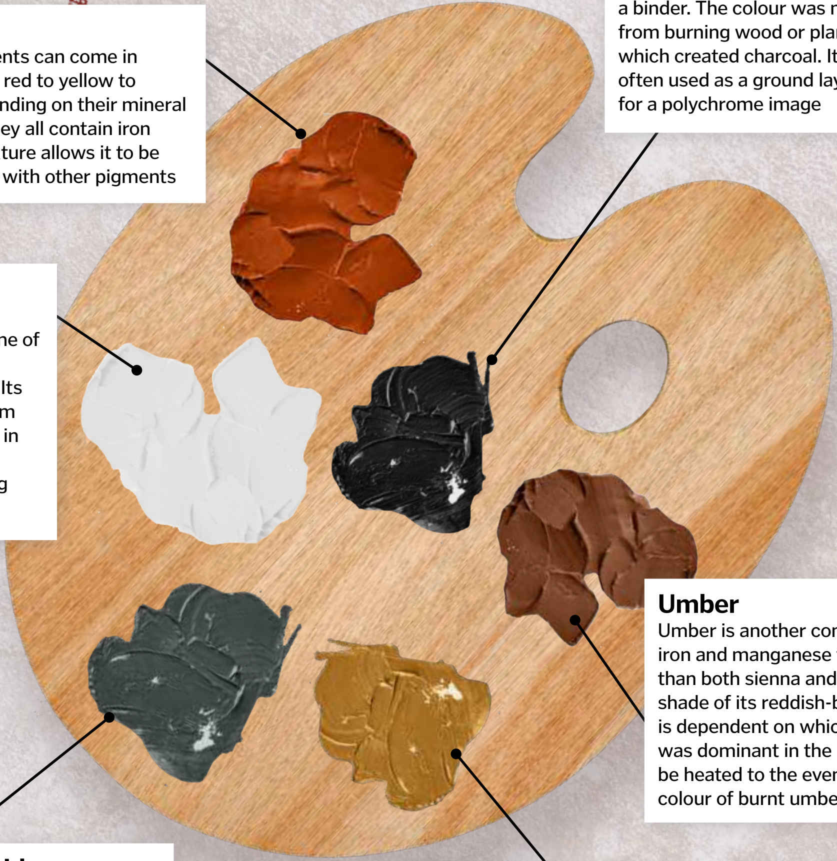
Discoveries of prehistoric art continue to fascinate us today and provide a unique insight into the culture of our distant ancestors.



In archeological terms, cave art is also known as 'parietal art'

The prehistoric palette

The colours and shades used to illustrate the Stone Age world



Ochre
Ochre pigments can come in shades from red to yellow to brown, depending on their mineral blend, but they all contain iron oxide. Its texture allows it to be easily mixed with other pigments

Carbon black
Monochrome paintings were a simple mix of carbon black and a binder. The colour was made from burning wood or plants, which created charcoal. It was often used as a ground layer for a polychrome image

Kaolin
Kaolin is a white-coloured clay and one of the Earth's most abundant minerals. Its name originates from the town of Gaoling in China, which is renowned for having rich kaolin deposits

Umber
Umber is another combination of iron and manganese that is darker than both sienna and ochre. The shade of its reddish-brown colour is dependent on which mineral was dominant in the mix. It could be heated to the even darker colour of burnt umber

Manganese oxides
One of the darkest colours used, manganese oxide could create shades that were brown, grey or black. Manganese deposits weren't common in caves adorned with artwork, so it's assumed painters would trek long distances to find a source

Sienna
A mixture of iron oxide and manganese oxide, raw sienna is a pigment with a yellow-brown colour. When heated, it turned into burnt sienna, which is darker in tone and redder in colour

Green and blue

Cave art typically features red, brown, yellow and black, but none of the paintings, it seems, included blue or green. This can be explained in part by the lack of natural pigment sources for these shades. In the Palaeolithic period, obtainable blue-coloured minerals were rare, especially in Europe. Blue was used in later eras by the ancient Egyptians, who used powdered azurite to make blue-coloured jewellery. The omission of green shades is more difficult to comprehend, as green coloured minerals like malachite and terre-verte were abundant. One of the reasons given for the lack of green colour is that it may have simply not shown up as well as red or brown does under fire or torchlight.

Clay ochre could be red, yellow or brown, but not blue or green

Hand stencils

The techniques used to create the perfect prehistoric hand silhouette

1 Tools for the job

To create a hand stencil, researchers think that prehistoric humans used hollow bones or reeds to blow paint through, and a shell to hold the paint in. The pigment used to make the paint was ground into powder and could be sourced from various minerals.

2 Making the paint

The powdered pigment was mixed with a binder in the shell using the reed or bone. Researchers trying to recreate prehistoric hand prints found that to make a paint thin enough to spray, the Palaeolithic painters likely used water as a binder.

3 Creating the stencil

The artist placed one hand on the wall, held one of the reeds/bones in their mouth, and held the shell and second tube (dipped in the paint) in their other hand. Blowing through one tube across the top of the other created a cloud of colour spray on the wall.

4 Finishing touches

When the artist removed their hand from the wall, they left a silhouette with colour all around it. More colours could be added with brushes, or a charcoal outline could be drawn around the hand. Bumpy walls could also help create a 3D effect.

Whose hands were they?

Experts can determine the gender of the person who made a stencil with over 90 per cent accuracy. The technique that is used is part of a study called geometric morphometrics. Digital versions of modern male and female hand stencils were made and used as a template when measuring those of prehistoric hands. The hands were then compared based on palm shape, which has been found to be a more useful indicator of gender than just measuring finger length and hand size. The study reinforced that both genders would often produce stencils. Researchers can also make an educated guess regarding the handedness of the artists, as the hand that is on the wall would most likely be their weaker side, and the dominant hand would be the one used to hold the pigment.

Hand stencils in Cueva de las Manos (Cave of Hands) in Argentina, created between 13,000 and 9,000 years ago

The world's weirdest pigments

Our artistic ancestors were quite resourceful

Mummy brown

A hugely popular pigment during the 16th century, this was made from the remains of ancient Egyptian mummies. Mixed with myrrh and white pitch, it made a reddish-brown colour.

Tyrian purple

This pigment was made from a dye extracted from murex shellfish. A symbol of imperial authority in the Roman Empire, it was used to colour the emperor's toga.

Lead white

Long before it was known to be poisonous, lead white was used as a paint pigment and also in makeup. One theory is that it contributed to Van Gogh's deteriorating mental health.

Uranium yellow

This yellow-orange pigment was used to create coloured glass and glazes for ceramics. However, this stopped when it was found to be a radioactive and highly toxic substance.

Carmine

Carmine is a deep red colour that has long been associated with royalty and nobility. It is made from the carminic acid that oozes out of some species of crushed beetles.

Cave art across the world

The best examples of parietal paintings across the globe, from France to Australia

LASCAUX

France / 18,000 - 13,000 BCE

With hundreds of paintings and drawings and over 1,500 engravings, Lascaux is one of the best sites for prehistoric art on Earth. The caves include depictions of bison, mammoths, aurochs, lions and wolves among others.

PETTAKERE CAVE

Indonesia / 38,000 BCE

These Indonesian paintings are believed to be proof of prehistoric island-hopping in southeast Asia. The cave includes what are believed to be the oldest hand stencils on Earth.

CUEVA DE LAS MANOS

Argentina / 13,000 - 9000 BCE

The Cave of Hands plays host to some of the oldest known cave paintings in the Americas. The artwork varies from hunting scenes to hand stencils and is red or black in colour.

KIMBERLEY

Australia / 50,000 - 5000 BCE

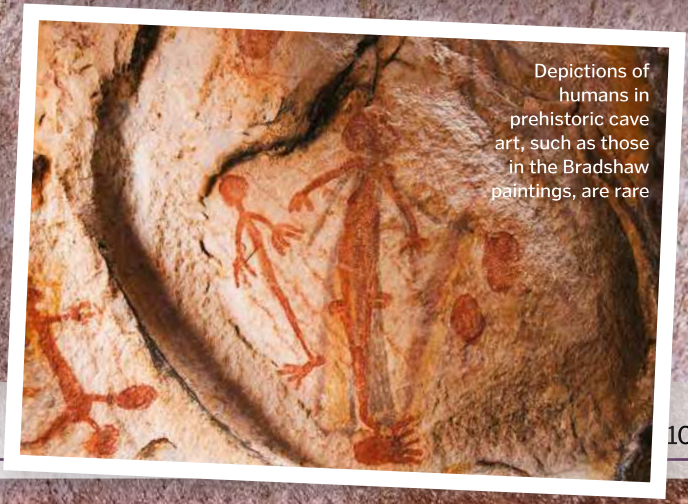
Known as the Bradshaw or Gwion Gwion paintings, the age of the art itself is difficult to determine, but it's possible that this cave is home to some of the oldest artwork of human figures in the world.

> "Some paintings in Europe are thought to be up to 40,000 years old"

BLOMBOS CAVES

South Africa / 100,000 - 70,000 BCE

Archaeologists have unearthed the remains of what appears to be a rudimentary paint workshop in these caves. They found engraved blocks of ochre (shown on the right), shell 'palettes', bone 'spatulas' and grinding equipment.



Depictions of humans in prehistoric cave art, such as those in the Bradshaw paintings, are rare