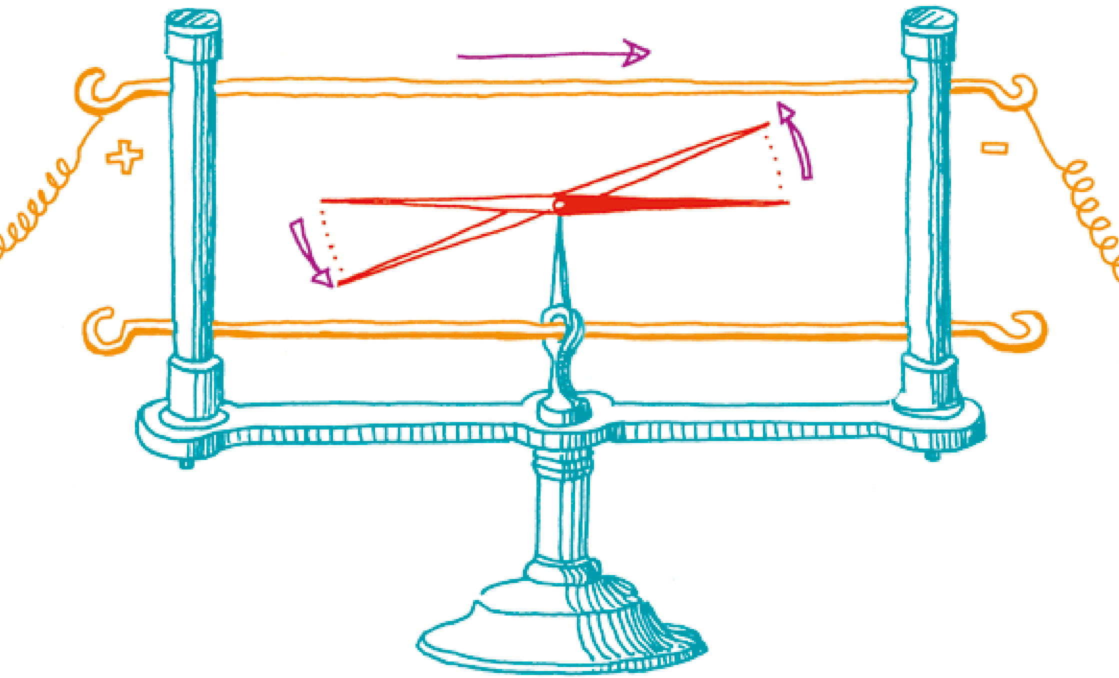
IOP Education | Stories from physics booklet 3

Electricity & Magnetism

By Richard Brock



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Introduction

The story of physics is intertwined with the stories of people. Richard has collected some amazing, amusing and enlightening stories and I am very pleased that the IOP is able to help him to share them. I'm sure that you will be inspired by the stories and their engaging retelling here. They will be of interest to any teacher and are ready to use with students to bring the discipline alive and illustrate its reliance on human ingenuity and frailty.

This booklet reveals the slightly magical phenomena associated with electricity, magnetism and the unified ideas of electromagnetism. It introduces us to more fascinating characters from the history of physics, as they try to unravel these mysteries and put the effects to (usually) good use. Interestingly, it is in this area that America becomes both a participant and a leading commercial force, as the search for physics-based answers becomes global.

Charles Tracy

IOP Head of Education

Message from the author

Electromagnetism is an appealing topic to teach as electrical currents can seem otherworldly and carry a hint of danger. The domain contains a rich seam of stories that highlight both the power and hazards of electricity. In this booklet you can read about how Donald Trump's uncle worked with Robert Van De Graaff (known for his static generator) to build an X-ray barbecue that saved many lives. On the theme of US presidents, you will learn about Benjamin Franklin's shocking experiment with a turkey and his ideas for electrical pranks.

Franklin's turkey is not the only animal to appear in the booklet. You will find out why Henry Cavendish built an artificial torpedo fish from pieces of leather and how to make a voltmeter from a frog (not recommended). The animal stories also touch on magnetism and you will discover how you might use a cow magnet.

The stories describe some of the great characters in the history of physics. You will be introduced to the extraordinary French physicist, François Arago, who tried to repel invading troops with a lance at the age of seven, was punched by an archbishop and acted as a courier for two lions for Napoleon. You will read about Ritter, his 'marriage' to a large Voltaic pile and his subsequent self-experimentation. This booklet will allow you to find out what Georg Ohm was doing at university to make his father force him to withdraw from his course.

I have greatly enjoyed collecting these stories about electricity and magnetism.

Thanks as ever to Caroline Davis at the Institute of Physics for championing the project and her editing, and to Stuart Redfern for his brilliant illustrations.

So, let me tell you some stories about physics…

Richard Brock

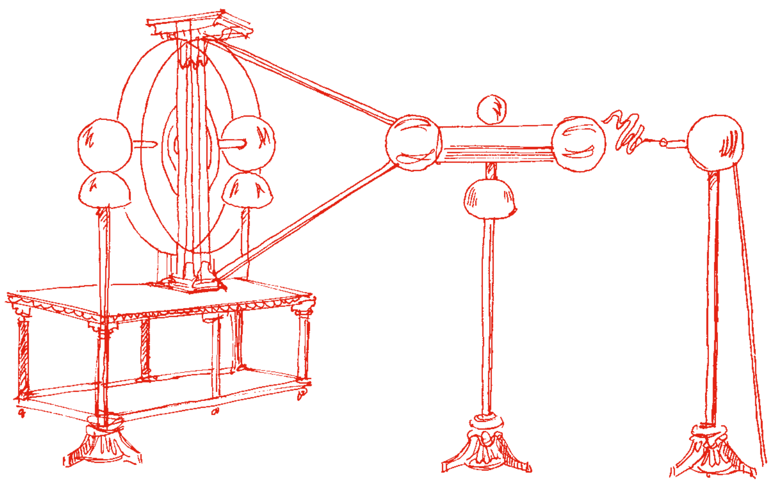
Electromagnetism

Martinus van Marum's machine

Martinus van Marum, a Dutch physician, developed an interest in the physical sciences and was appointed director and curator of the cabinet of curiosities of the Dutch Society of Science. Van Marum gave public demonstrations of chemical and electrical phenomena and, in the 1780s, had a large static generator built which can be seen today in the Teylers Museum in Haarlem.

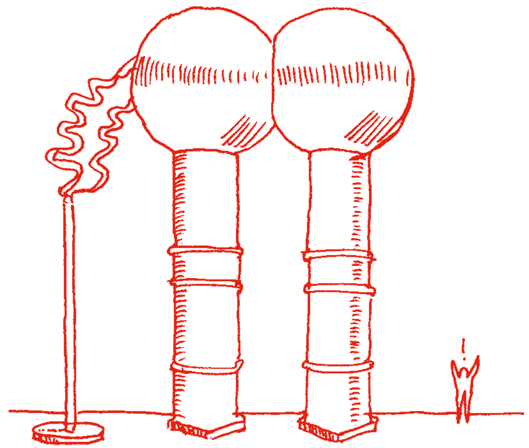
The machine consists of two glass discs, 1.5 m in diameter, that can generate a potential of 300-500 kV and produce sparks over distances of 7 m. The effects of the machine on different objects were impressive: a 10 cm by 10 cm piece of box-wood was "rent in pieces", metal objects were melted and "dispersed in all directions" and a piece of tin was vaporised.

Van Marum developed other demonstrations of static electrical effects, including artificial clouds formed of two bladders filled with hydrogen gas and given opposite charges. The bladders gradually rose to the ceiling, were attracted to each other, and, when they were close enough, a spark jumped between them causing an explosion. To make the demonstration more like a storm, Van Marum added a third balloon, filled with a mixture of hydrogen and air, between the two balloons. This exploded with a loud bang when the artificial lightning was triggered.



Giant Van de Graaff

The world's largest Van de Graaff generator is housed in Boston's Museum of Science and has two 4.5 m diameter spheres mounted on 7.6 m poles. The device is capable of generating a potential of 7 MV, over thirty times the output of a typical classroom Van de Graaff generator that can reach 200 kV.



Trump's X-ray barbecue

John Trump, the uncle of US president Donald J. Trump, worked as one of Van de Graaff's assistants. Van de Graaff was known for his impeccable manners and his colleagues joked that it was impossible to go through a door after the physicist.

Van de Graaff and Trump became interested in the medical uses of high-energy accelerators and Trump met with a radiologist who wanted to construct a device that could exceed 400 keV. Trump is reported to have declared: "Make it 1 MV and we might be interested." Trump went on to develop a 2 MV radiotherapy device in which a patient was rotated in front of an X-ray source which *Life* magazine described as an "X-ray Barbecue". Trump's contributions to radiotherapy were acknowledged in his obituary in the *New York Times* which reported that his inventions had "provided additional years of life to cancer patients throughout the world".

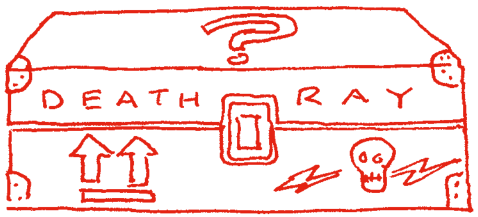
Tesla's mysterious box

Towards the end of his life, the prolific American-Serbian inventor Nikola Tesla claimed to have invented a particle beam or "death ray" weapon. Short of money and facing a $400 bill from the Governor Clinton Hotel in New York, he offered a working model of the weapon as collateral for the debt. He delivered the model in a locked case and cautioned that the box would explode if opened by an unauthorised person. Intimidated by the eccentric scientist's warning, the hotel staff stored the unopened box in the hotel vault.

In 1943, when Tesla was found dead in his hotel room, the FBI asked John Trump (see above) to analyse his papers. Finding nothing of value in Tesla's writing, the investigators' interest turned to the mysterious box in the hotel vault.

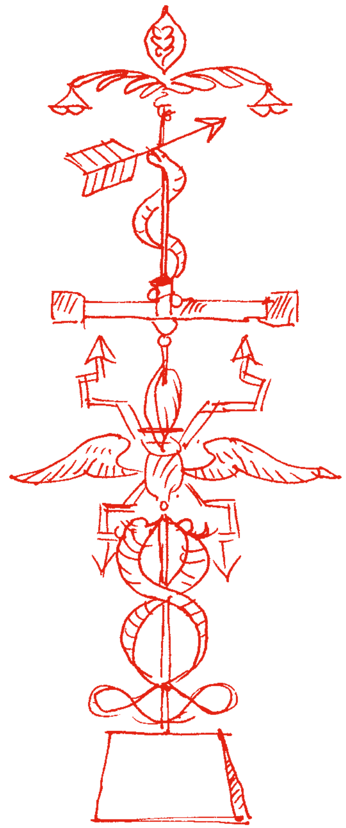
After the disappointment of Tesla's papers, the possibility that a previously unknown death ray was hidden in the storage vault of a New York hotel was startling. As Trump went to cut the brown paper wrapping the mysterious box, the FBI agents accompanying him withdrew from the vault...

Anticlimactically, the box contained a wooden chest with a brass-hinged lid that held only a Wheatstone bridge.



When lightning conductors were political

A curious dispute between Benjamin Franklin and King George III over the shape of lightning conductors demonstrates the dangers of political interference in scientific investigation.



Franklin, a founding father of the United States and polymath, was also the inventor of the lightning rod and recommended that pointed conductors were most effective at preventing damage.

In the late 1770s, a powder magazine in Purfleet, Essex, protected by pointed rods, suffered minor damage following a lightning strike. In response, Benjamin Wilson, a British painter and natural philosopher, proposed that rounded rather than pointed conductors would offer more effective protection. In 1777, Wilson constructed a 47 m long device from foil and pasteboard for generating electrical discharges. He suspended it by silk threads from the ceiling of London's Pantheon.

The machine was demonstrated to King George III using a model of the Purfleet arsenal, with Wilson presenting his argument that domed conductors were more effective than pointed ones. In reality, the shape of the conductors has little impact on the effectiveness of the protection offered, but, perhaps for political reasons, George III gave his to support to Wilson rather than the American scientist.

One version of the story suggests that the king ordered the President of the Royal Society to implement the use of rounded conductors. The President is said to have replied: "Sire, the prerogatives of the President of the Royal Society do not extend to altering the laws of … nature", and resigned.

Electrical entertainments

During the eighteenth century, a craze for electrical demonstrations sprang up and itinerant lecturers toured fashionable salons showing off novel entertainments. Some of the strangest of these included:

- **Stephen Gray's Flying Boy** – a young boy was suspended by silk threads from a wooden frame and charged. When the boy held out his hands, pieces of paper and chaff flew up from the floor.
- **The Electrifying Venus** – a female member of the audience stood on an insulated stool and was charged. When a male volunteer attempted to kiss her, he received a shock.
- **The Thunder House** – a doll's house which demonstrated the effects of lightning strikes and the protection offered by lightning conductors. Some houses were rigged with gunpowder to dramatise the effect of a strike on an ungrounded house.

Electrical Bovril

Bovril has an unexpected electrical connection. In 1871, Edward Bulwer-Lytton published a novel, *The Coming Race*, which featured a subterranean race with a mysterious power, *vril*, linked with magnetism and galvanism. When the manufactures of a new beef extract were looking for a catchy name, they combined the words *bovine* and *vril* to create the portmanteau, *Bovril*.

Static gravity

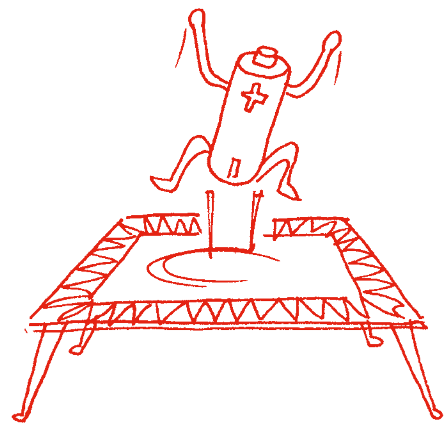
Otto von Guericke proposed that the attractive force of the Earth was not gravitational in origin, but electrical. In the 1600s, he argued that the electrostatic attraction was caused by friction between the air and the surface of the Earth. He developed a demonstration to make his case: he formed a sulphur ball, the size of a child's head, and mounted it on a rod through its diameter. He then placed it in a frame. Rotating the sulphur ball, which represented the Earth, against his hand, he showed it would attract small leaves and pieces of paper and gold.

Guericke was elected as mayor of Magdeburg (now in Germany) and, in order to impress the visiting Holy Roman Emperor, carried out the experiment now known as the Magdeburg hemispheres. Two copper hemispheres were joined to form a sphere which was evacuated and each hemisphere was harnessed to a team of eight horses. The horses were only sometimes able to separate the hemispheres but Guericke could release them simply by opening a stopcock.

Battery bounce

The anecdotal observation that alkaline batteries that are low on charge bounce higher than fully charged ones has been supported by the work of a team of American researchers.

When an alkaline battery is fully charged, the anode consists of zinc particles in an electrolyte matrix that allows the particles to move freely. As the battery loses charge, the zinc particles become encased in zinc oxide shells, restricting their movement. Connections between zinc particles grow, displacing water, allowing pressure waves to pass through more easily and increasing the height of bounce.

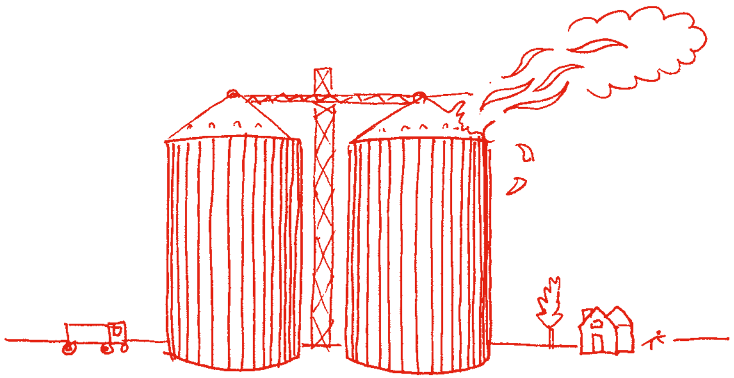


Electric extinguishers

It is not uncommon for a user to receive a small shock when they touch a grounded conductor after discharging a carbon dioxide fire extinguisher. This is because charge can be transferred by the motion of the dry ice particles through the nozzle. As an extinguisher is likely to be used in a potentially explosive environment, it is recommended that discharge nozzles are grounded before use as an extinguisher can develop a potential of up to 30 kV during discharge.

Grain explosions

In the 1970s, electrostatically generated sparks caused a number of explosions at grain elevators, large facilities designed to store grain. An article in *New Scientist* in 1978 reported that grain elevator explosions had killed 50 people in the United States and that researchers at the University of Southampton had constructed two laboratory-sized silos to investigate the build-up of charge.



The phenomenon arises because fine powders, such as flour, can acquire a charge as they pass along a pipe. They then discharge to the walls of the silo, causing a spark. A charge as low as 10^{-3} C may be sufficient to create a spark that can transfer 1 mJ. This is enough to have a devastating effect in a highly flammable atmosphere of air rich in flour particles.

The risk can be mitigated by using dischargers: either passive needles placed along a pipe to allow excess charge to flow off, or active dischargers which use a power supply to deliver an appropriate current to eliminate undesirable charge.

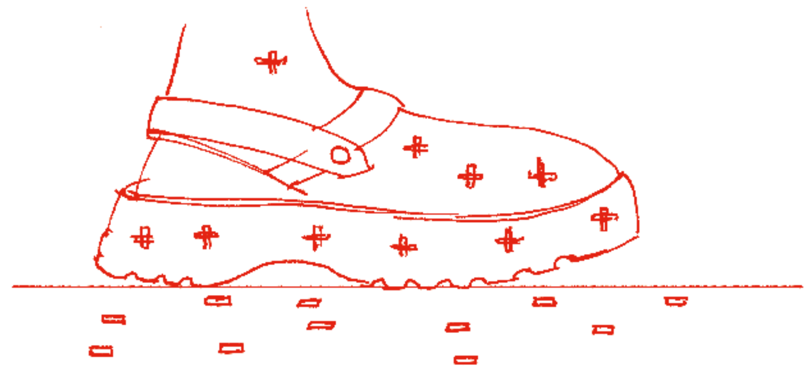
Sparking surgery

A 1966 report in *The Journal of the American Society of Anesthesiologists* described a case of an explosion caused by an electrostatic spark during an operation to remove a patient's tonsils. After the tonsil snare was tightened, a loud explosion was heard and a fire broke out on the anaesthetist's cart and tray. The patient was carried from the room and suffered burns to the head.

Tests on the anaesthetist's gas transmission system indicated that a potential difference of 6 kV might have built up between a portable vaporiser and the anaesthesia machine. This could be retained for six to ten seconds before discharging.

Precautions are normally in place to prevent static sparks during surgery. Anaesthetists are required to wear conductive shoes to prevent the build-up of charge on their bodies but, in this case, the conductive plugs inserted into the anaesthetist's shoes had lost their conductivity. In addition, a band of adhesive material had been stuck across the top of the anaesthetist's metal chair, insulating half of the surface.

The report concludes that the anaesthetist was negligent in allowing his footwear to become non-conductive and in failing to remove the insulating strip stuck to his seat.



Current

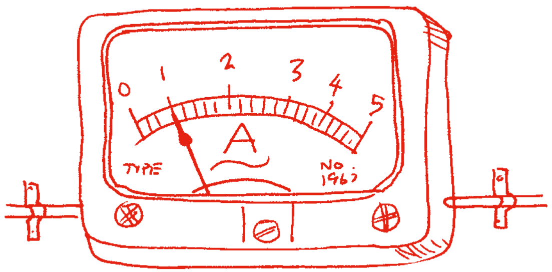
Why I?

The use of the symbol "*I*" for current might seem counterintuitive but the label arises from a historical French term. In the 1820s, André-Marie Ampère showed that two parallel, current-carrying wires will attract or repel each other depending on the direction of the currents flowing through them. From this observation, he developed the eponymous Ampère's law, which relates the size of the force between two conductors to the length of the wires and the magnitude of the current. He labelled the flow of charge "*intensité de courant*", meaning current intensity, and gave it the symbol "*I*".

Ampère's early achievements

Ampère's father was a follower of Jean-Jacques Rosseau's model of education whereby students learn from nature rather than from direct teaching. Instead of securing tutors for his son, Ampère's father left the young scientist to educate himself within a well-stocked library. This approach seemed to work – by the age of 12, Ampère was studying advanced mathematics.

Among Ampère's many contributions to science are an early version of the periodic table and a description of bonding based on the geometrical shapes of molecules. In addition, Ampère developed a model of magnetism as the circulation of electric currents within molecules, arguing, "One can consider each molecule as a small voltaic pile in which the currents, entering by one extremity of the molecule and leaving by the opposite end, come together across the space around the first of these two extremities, thus forming a closed solenoid." It was not until 1915 that his model of magnetism finally received experimental support from a paper co-authored by Einstein.



Ampère's final happiness

Ampère's life was marred by tragedy – his father was guillotined for being on the wrong side of the French Revolution and his first wife died while she was young. These events explain the epitaph chosen for Ampère's tombstone: *Tandem felix* (happy at last). Ampère's many achievements were celebrated after his death: he is one of 72 scientists, engineers and mathematicians whose names were honoured by being engraved on the Eiffel Tower.

Electric monks

One of the first estimates of the speed of travel of electrical currents was made from a bizarre experiment carried out by the French clergyman and physicist, Jean-Antoine Nollet.

In 1746, Nollet arranged for 200 Carthusian monks to form a circle. The monks held 7.5 m brass poles in each hand, creating a circular chain with a circumference of about a 1.6 km. When he connected a Leyden jar (an early charge storage device) into the circuit, the unfortunate monks' muscles contracted as they experienced an electric shock.

Nollet had intended to measure the speed with which the current travelled, but he observed that the monks at different places in the circle reacted at the same moment, leading him to the conclude that conduction occurs with "unlimited rapidity". Nollet also discharged a Leyden jar through 180 Royal Guards in the presence of King Louis XV.

Nollet's work has a modern application. He observed that, when a person was connected to a high voltage supply, and cut, rather than bleeding normally, blood would spray from the wound. The rather gruesome discovery, known as *electrostatic spraying*, is now applied to the more prosaic process of electrostatic painting.

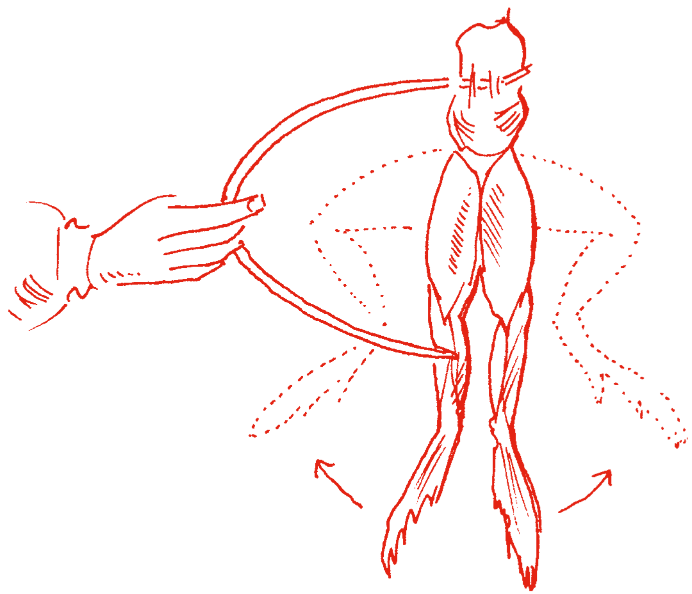
From frogs to corpses

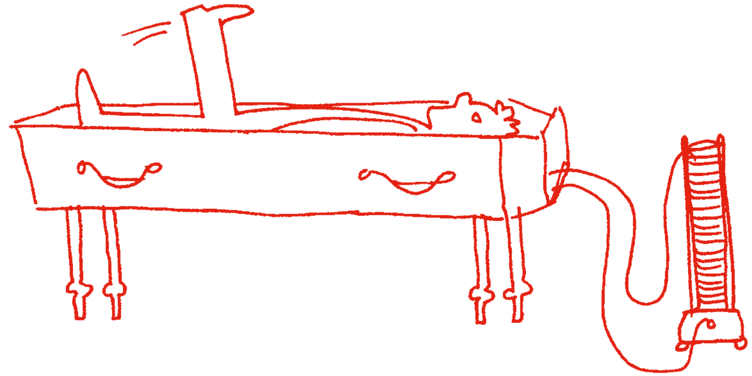
Italian physicist Luigi Galvani's experiments with frogs' legs, which demonstrated the link between electrical current and the action of nerves, are well known. But there are some interesting footnotes to the story.

It is reported that, following Galvani's experiments in 1780, the supply of live frogs diminished due to scientists' eagerness to replicate his work. One researcher, Eusebio Valli, wrote an impassioned plea to a colleague:

> Sir,
> I want frogs. You must find them.
> I will never pardon you, Sir, if you fail to do so.
> I am without Ceremonies, Your most humble servant,
> Valli

Galvani's experiments may also have spurred on his rivals. Alessandro Volta is reported to have developed the first Voltaic pile, an early form of battery, in order to contradict Galvani's belief that the current animating the frogs' legs was due to some form of innate vital force.





Galvani's nephew, Giovanni Aldini, followed in his uncle's footsteps by touring a gruesome demonstration of the action of electrical current on tissues. In front of audiences, Aldini applied currents to the bodies of recently executed criminals, including a decapitated corpse. The corpses were seen to clench their jaws, raise an arm or open an eye as if to stare at the audience, among other effects.

On a visit to London, Aldini acquired the body of a recently executed murderer, George Foster, and applied electrical stimulation that caused the body to seem reanimated. A local newspaper reported that this apparent resurrection was so troubling that one member of the audience died of fright after returning home.

Aldini's work may have been an inspiration for Mary Shelley's *Frankenstein*.

Shocking!

- **Surviving the shock** – different magnitudes of 60 Hz alternating current have different effects on the human body:

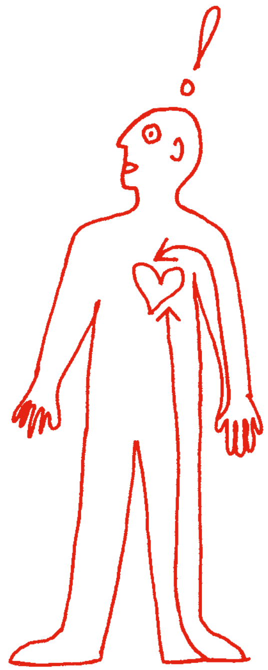
Current	Typical effect
1 mA	Barely perceptible
5-10 mA	Painful shock
100 mA	Minimum current that will cause ventricular fibrillation
2 A	Causes cardiac standstill and damage to internal organs

While currents of between 100 mA and 200 mA can be lethal, victims who experience currents in the range of 200 mA to 1 A have a good chance of survival as the current causes the heart muscle to contract so fibrillation cannot occur.

- **Wet and dry resistance** – a large proportion of the body's resistance occurs due to the outer layer of dead skin. For example, a calloused, dry hand may have a resistance as high as 100,000 Ω. By contrast, the resistance of the internal body, where tissues are wetter, is only around 300 Ω. Cuts and abrasions on skin can, therefore, reduce the resistance of the injured part of the body. When experiencing a shock, sweating and the formation of blisters may reduce body resistance, increasing the current that flows in a positive feedback loop. At potential differences greater than around 500 V, the high resistance of the outer layer of skin may break down, allowing current to flow into the body. Current can enter the body through a pinhead-sized wound and such shocks may lead to significant deep tissue damage with minimal burning to the skin.

- **Pins, needles and buzzes** – in direct current shocks, the victim experiences a shock only when contact is made or broken, but with alternating current, a continuous feeling of shock is reported. The experience of a shock may be more severe in someone who has tensed their muscles, or if the site of the shock is close to a nerve. The sensations induced by electric shocks are subjective. Victims encountering the same low-level electrical shock, have variously reported buzzing, tingling (pins and needles), a jolt or a burning sensation.

- **A shock to the heart** – the two most dangerous paths for current to take through the human body are from hand-to-hand and from hand-to-foot (in particular left hand to left foot) since the current will travel through the chest and, possibly, the heart.



- **Letting it go** – when receiving a shock above a certain magnitude of alternating current, known as the *let-go threshold*, the person experiencing the shock may struggle to release a conductor they have grasped because of contractions to their muscles. Exposure to currents above the let-go threshold may not be harmful if the person only experiences the shock for a short period of time. However, prolonged exposure may lead to breathing difficulties and asphyxiation. The let-go thresholds are different for men and women: the maximum reasonably safe current is 9 mA for men and 6 mA for women because of differences in the average strength of muscles in their hands.

Ritter and his "marriage"

Johann Ritter is perhaps best known for his discovery, in 1801, of the rays that subsequently became known as ultraviolet radiation. However, his experiments with Voltaic piles (an early form of battery) are particularly curious.

A visitor to Ritter's flat described "...a vile and dismal room in which everything possible: books, instruments, wine bottles – lay indiscriminately about". Ritter "...was in an indescribably agitated state, full of sullen hostility. One after another he guzzled wine, coffee, beer, and every sort of drink." The events that led to the scientist's dishevelled state are a warning of the dangers of scientific obsession.

Before constructing a large Voltaic pile, Ritter wrote in a letter to his publisher that: "Tomorrow I marry i.e., my battery." The comment was a warning of Ritter's unhealthy dedication to research.

Ritter began to experiment with the effects of the Voltaic pile on his body and discovered it could produce sounds in his ears, colours in his eyes, sensations of hot and cold in his fingers and sneezing fits. Subsequently, he reported that he tested the effects of current on his "organs of reproduction" and "organs of evacuation". His experiments became more extreme. Ritter studied the effects of remaining connected to a pile for an hour and noted a "dullness in all his limbs" that lasted over a week.

In addition to these experiments, Ritter described the effects of pinning back an eyelid and staring at the Sun: "I have in each eye a place which has no more sense for black and white, and which sees colours reversed: red, blue and blue, yellow or red."

Ritter died aged just 33. It is impossible to know whether his death resulted directly from his experiments or from the alcohol and opium he took to mitigate the symptoms caused by his dangerous research.

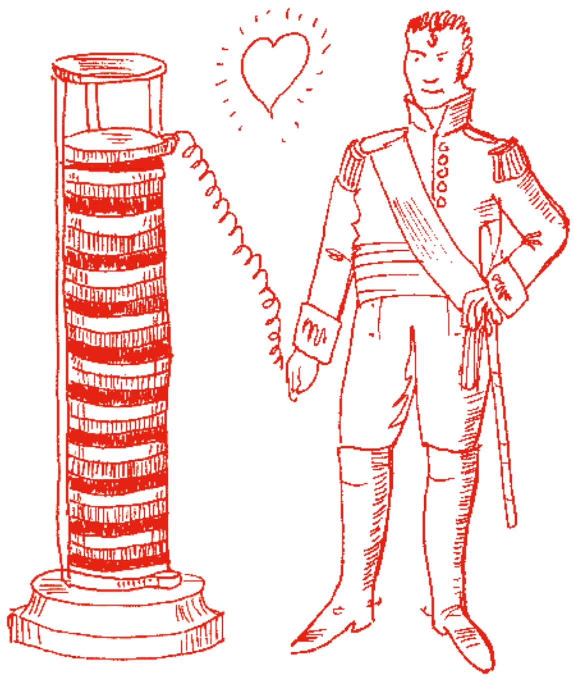
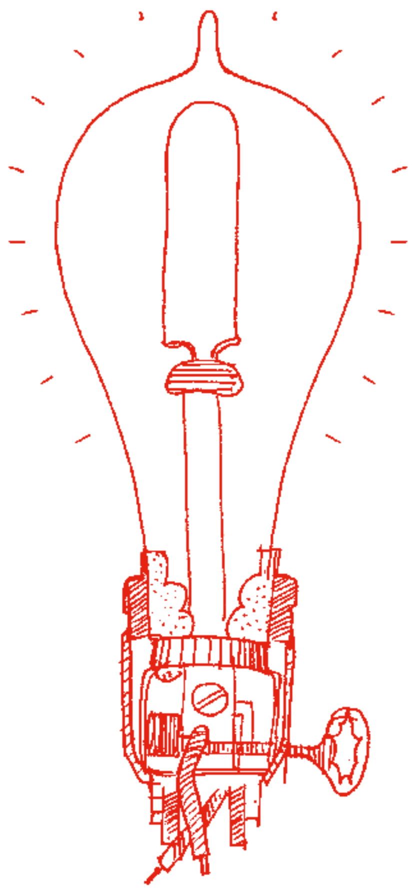


Fig. 283 – Pile de Volta.

The war of the currents

At the end of the 19th century in the United States, two systems of power transmission competed for business – a battle that became known as the *war of the currents*.



Thomas Edison developed a low voltage (110 V) direct current system to deliver power to high resistance incandescent lights. Although he initially gave electricity away for free, he later developed the first electricity meter to monitor his customers' usage. The meter consisted of two zinc plates immersed in a solution of zinc sulphate. Once a month, the plates were removed, taken to a laboratory, washed and weighed in order to estimate the current used. Edison's direct current system had the drawback that it could only deliver current to locations less than a mile from the power plant.

George Westinghouse initially set up a rival direct current system but, when he learned of the advantages of the systems in Europe, he opened the first alternating current plant in Buffalo, New York.

As Westinghouse's system gained customers, Edison began to lose business, and the president of the Edison Electric Company, Edward Johnson, issued a pamphlet containing newspaper stories of electrocutions caused by alternating current. Edison reportedly paid children to bring him stray dogs and cats, which he would 'Westinghouse' with alternating current to demonstrate the danger of his rival's system.

It has been suggested that Edison colluded with another opponent of alternating current, Harold Brown, to recommend that the soon-to-be-introduced electric chair should use alternating, rather than direct current. Brown organised an experiment in front of the chairman of the death penalty commission and members of the press in which he killed dogs, calves and a lame horse using alternating current. Perhaps as result of these demonstrations, alternating current was chosen to power the electric chair, and the first execution went ahead in August 1890.

However, despite Edison's efforts, the numerous advantages of the alternating current system meant it was eventually adopted as the standard method of transmitting electricity.

The two electric fluids

Charles François de Cisternay du Fay, an 18th century French nobleman, soldier and scientist, was interested in the attraction and repulsion of objects that occurred after they had been rubbed.

He experimented with small pieces of foil and discovered that, if one piece were charged by glass rubbed with silk, it would be attracted to another charged with amber rubbed with wool. By contrast, two pieces of metal charged from the same source would repel. From these observations, Du Fay concluded that there were two electric fluids: *vitreous* (from glass rubbed with silk) and *resinous* (from amber rubbed with wool). He hypothesised that the fluids were separated by frictional forces and neutralised when they recombined.

While many scientists accepted Du Fay's two fluid model of electricity, Benjamin Franklin was one of the first scientists to propose a single fluid theory. He noted that when objects become charged, for example when glass is rubbed with a cloth, the two bodies gain equal but opposite charges. Franklin therefore hypothesised that all bodies contain a single fluid, or *electric fire*, which exists in a neutral state unless frictional forces act to cause an imbalance.

Franklin gave Du Fay's vitreous fluid the label *positive* and called the resinous fluid *negative*, leading to the mismatch between conventional current and the direction of flow of electrons that exists today. Franklin also coined the terms *conductor* and *non-conductor*.

Benjamin Franklin's turkey shocker ...

Though his experiment with a kite in a thunderstorm is well known, Benjamin Franklin (see page 7) put electricity to some other strange uses.

He describes an attempt to electrocute a turkey with a shock from a Leyden jar, resulting in the unfortunate scientist inadvertently shocking himself. He reports that those with him observed: "...that the flash was very great, and the crack as loud as a pistol", but that "his senses being gone", he didn't see or hear anything. He described a "universal blow throughout my whole body from head to foot, which seemed within as well as without."

... and shocking pranks

Franklin proposed a number of electrical pranks:

- Drinking glasses were covered in a tin coating to give an unsuspecting drinker a shock.
- A gentleman and a lady were asked to stand on wax insulators. One of the two would be passed an electric phial (or Leyden jar), while the other grasped a wire attached to the phial. The two protagonists would then be asked to move their lips together in order to experience an "electric kiss".
- A fake spider, constructed from cork, thread and pieces of lead, was animated by being charged so that it appeared "perfectly alive to persons unacquainted".

Lichtenberg figures

In 1778, the German physicist Georg Christoph Lichtenberg built a large *electrophorus*, a capacitor-like device charged by rubbing with fur or cloth. When he first tested the instrument, it had not been cleaned, and was covered in powder left over from polishing.

In a paper, Lichtenberg described:

> Much to my great joy, it [the powder] gathered to form little stars, dim and pale at first, but as the dust was more abundantly and energetically scattered, there were very beautiful and definite figures, not unlike an engraved design. Sometimes there appeared almost innumerable stars, milky ways and great suns.

The branching patterns generated by electrical discharges became known as Lichtenberg figures. Lichtenberg figures are observed on the skin of some victims of lightning strikes.

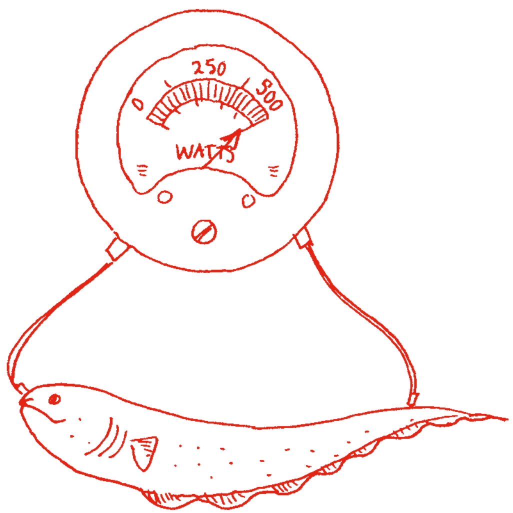
A very public discovery

The first demonstration of the relationship between electricity and magnetism occurred in a public lecture. Hans Christian Ørsted is said to have developed an interest in science while working in his father's pharmacy as a boy. While traveling in Europe, he met the German physicist Johann Ritter (see page 18) and began to research magnetism and electricity. As he was preparing to give a public demonstration of the heating effects of currents, it occurred to Ørsted that currents might also affect a compass. Not having time to test his hypothesis, he decided to try it out in his demonstration – it turned out that his hypothesis was correct.

Electrical animals

A number of animals, including sharks, platypuses, echidnas, sturgeon and catfish are sensitive to electrical stimuli, a sense known as *electroreception*.

- **Eel vs torpedo** – The electric eel, which lives in fresh water, can generate a current of 1 A with a power output of 500 W. By contrast, the torpedo fish is found in saltwater habitats, and the ions dissolved in sea water mean the magnitude of the torpedo's current diminishes less than the electric eel's output. This allows the torpedo to produce currents of up to 50 A with a peak power output of nearly a kilowatt.



- **Poking fun with fish** – One of the first scientists to experiment with the electrical behaviour of animals was John Walsh, who was awarded the Copley Medal by the Royal Society in 1773, for a paper on the torpedo fish. He describes his incredulity on first experiencing a shock from a torpedo fish (also known as the electric ray). The list of his subsequent experiments reveals a dedication to research undiminished by pain.

  Walsh reports poking the electric fish with a number of different materials and records his experiences:

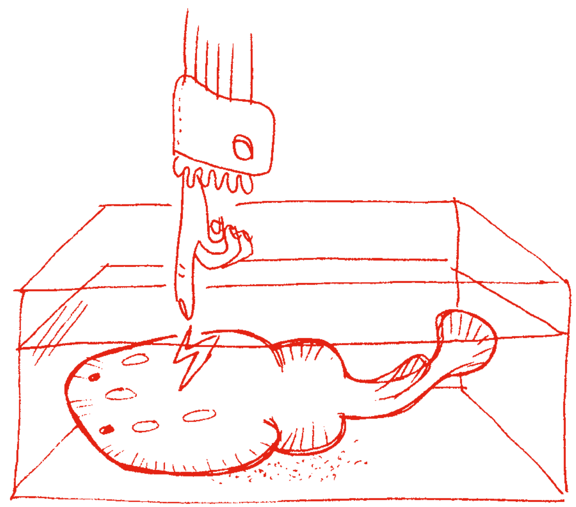
  > Touched the upper and lower sides of the same flank with Spoons; Shock, twice.
  > Repeated it with Spoons; a Shock.
  > With Sealing Wax; nothing.
  > Repeated with spoons; Six times.
  > With sealing wax, twice; nothing.

Despite the similarity of the sensation of shocks from the torpedo fish to other electric shocks, critics doubted that the effect was electrical as the spark and crackling sound characteristic of electrical discharge were absent. Walsh attempted in vain to reproduce these phenomena by poking a patient torpedo fish with a piece of tin foil attached to a stick of sealing wax.

The debate about the missing spark led Henry Cavendish to construct, and demonstrate in public, an artificial torpedo that produced shocks without sound or sparks. The first model torpedo was made of a piece of wood, cut to the shape of the fish, and connected to several Leyden jars. The wooden version, however, did not conduct well and Cavendish built a second version out of pieces of leather with thin pewter plates attached to each side, connected to the Leyden jars by glass-insulated wires. The device was then placed inside a sheep's skin soaked in brine.

In a paper on the artificial torpedo, Cavendish argued that both the "degree of electrification" (equivalent to electrical potential) and "quantity of electric fluid" (a measure of current) determined the nature of electrical phenomena, pre-empting Volta's discussion of tension and charge in capacitors.

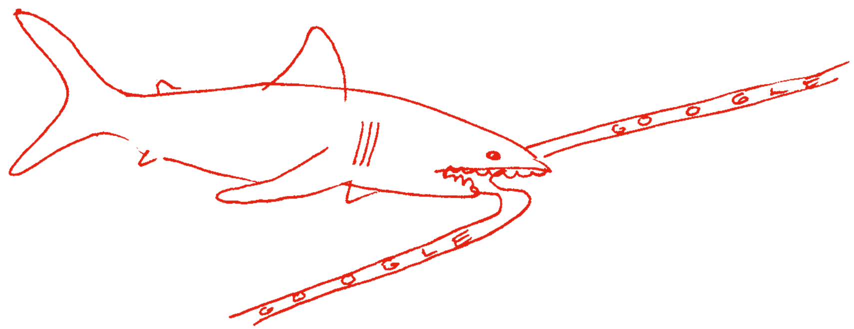
In 1775, in his London home, Walsh finally succeeded in eliciting an elusive spark from a torpedo fish by holding a piece of tin foil pasted onto glass near a fish held in the air.



- **Grasping the eel by the tail –** Between 1776 and 1777, George Baker, a ship's captain, exhibited five electric eels in an apartment on Piccadilly, opposite St. James's Street in London. Visitors could experience a mild shock by placing their fingers in the eels' tank but were told that the best way to experience the eels' abilities was to grasp the animal firmly by its head and tail. Some visitors reported that their limbs were numbed for several hours, while others were brought to tears or fell to the floor. When an interested physician attempted to purchase a single eel, Baker set the price at 50 guineas (over £53 at a time when the average annual wage of a female domestic servant was £16).

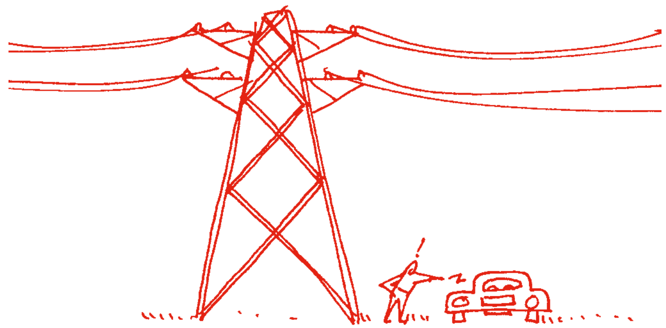
- **Electric shark attacks –** The heads of sharks, skates and rays are studded with tiny pores, known as *ampullae of Lorenzini*, which help the animals sense electric fields. Researchers have discovered that the pores contain a jelly which is the most highly proton conductive substance in the natural world.

  Early submarine fibre optic cables suffered several insulation failures that were believed to have been caused by shark bites. It is speculated that either acoustic vibrations or the relatively high magnetic field around the cable (the voltage lines to power the optical repeaters required three times the current of previous coaxial telephone cables) attracted the sharks. Subsequent cables were protected with fish bite tape.



Contact currents

When someone stands close to a power line or a substation, the alternating fields present can induce currents in their body. A person standing directly below a transmission line may have currents of around 1 nA induced in the periphery of their body by the 60 Hz magnetic field.

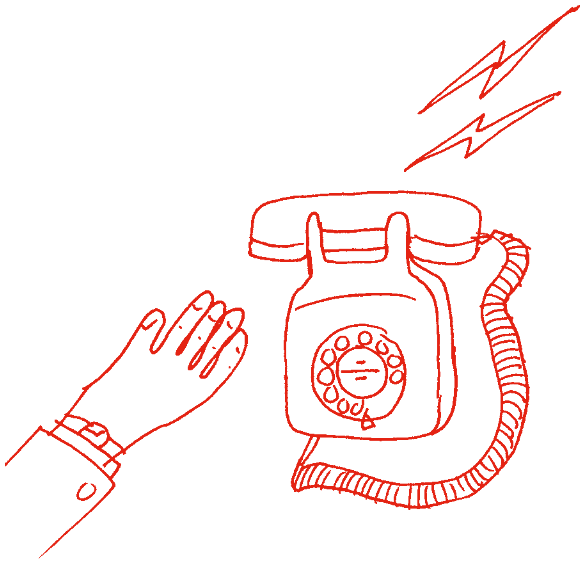


When they touch a grounded conductor, such as a car, the person might experience a shock – an effect known as a *contact current*. Well-grounded individuals who touch large objects under power lines will draw the largest contact currents. Generally, contact currents are imperceptible, but, under the right circumstances, can be annoying or even painful.

Telephone-induced lightning injuries

Towards the end of the 1980s, in Australia, a survey reported that around 60 people a year were injured as a result of using landline telephones during thunderstorms. A 1998 report from the UK describes the case of a nine-year-old boy who used a landline during a thunderstorm: the phone was blown off the wall and the boy lost consciousness, suffered superficial burns and later developed a cataract.

Lightning strikes can cause current surges of between 3 and 5 kA in telephone lines, either by a direct strike or by induction from surges in power lines that run close to phone cables. When lightning strikes, the local Earth potential may increase. As telephones are held at a zero of potential relative to a remote Earth, the potential difference caused by a rise in local Earth potential can cause a current to flow, causing telephone users to experience a shock.



Currents in the Earth and under the sea

Telluric currents are natural or artificial currents that flow through the Earth or the sea. They have many causes including changes to the Earth's geomagnetic field.

Michael Faraday unsuccessfully attempted to measure telluric currents from Waterloo Bridge using suspended electrodes. Undeterred, he obtained permission from the king to place electrodes into the lake in the gardens of Kensington Palace. He initially detected a small current, but concluded this was due to the thermoelectric effect.

In addition to the intended signals, currents are induced in undersea cables by a number of mechanisms. Some of the currents fluctuate over the solar day because of variations in the ionosphere caused by changes in solar radiation. Others are induced by the tidal motion of the oceans which results in a movement of ions in the Earth's magnetic field. In addition, currents may be driven in long cables that run north-to-south by a thermoelectric effect due to temperature differences along the cables. Finally, the detonation of a high-altitude nuclear bomb is reported to have caused disturbances in the Earth's radiation belts and geomagnetic field that induced detectable currents in undersea cables.

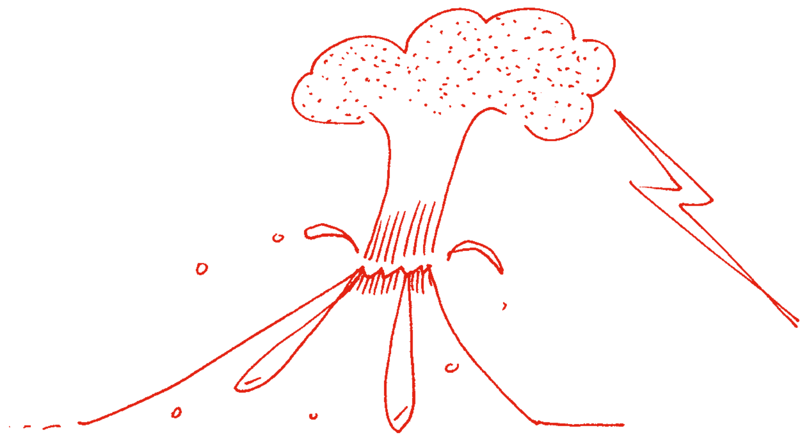
The 'everlasting' storm

Typically, there are between 1,500 and 2,000 thunderclouds active at any given time around the world, producing a global positive current of around 1.25 kA flowing from the tops of thunderclouds to the ionosphere.

Even so, lightning is typically not a common occurrence. But visitors to one part of Venezuela stand a very good chance of encountering a storm. At the entry point of the Catatumbo River into Lake Maracaibo, a microclimate is created in which 10-hour-long lightning storms are observed around 150 nights of the year. The storms produce an average of 1.2 million lightning flashes a year, contributing 0.2 A to the global total lightning current.

En-lightning!

- The most common kind of lightning, around 75% of activity, is cloud-to-cloud lightning which is seen as a diffuse light within clouds. Of lightning that travels from sky to ground, 90% is negatively-charged downward lightning. Upward travelling lightning, distinguishable by rising branching lines, is rarer and is thought to arise from objects taller than 100 m. Positively-charged lightning accounts for some of the largest recorded strikes, including some in the range 200-300 kA. Discharges involving both positive and negative charge may occur.



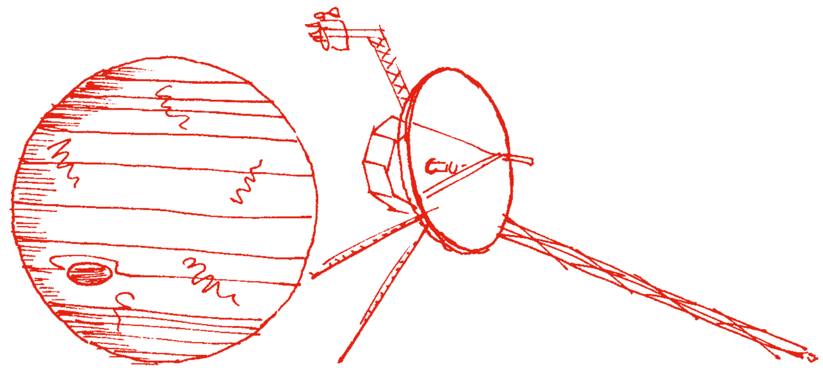
- Around 60 volcanic eruptions are reported to have caused lightning-like phenomena. The motion of dust and ash particles can lead to the build of electrostatic charge.

- Flashes of lightning have been reported after the detonation of thermonuclear bombs.

- Various forms of discharge in the sky were reported before the Kobe earthquake in Japan in 1995, including flashes, domes of light and luminous funnels. An orange arc-like phenomenon was described as 100 times brighter than moonlight.

- Researchers have triggered lightning by firing rockets with trailing ground wires into clouds.

- Lightning is not only found on the Earth – the phenomenon has been observed on Jupiter. The *Voyager* spacecraft recorded 20 lightning events in 192 seconds. It is thought Jovian lightning originates from a band of water and ice cloud 30 km thick around the planet.



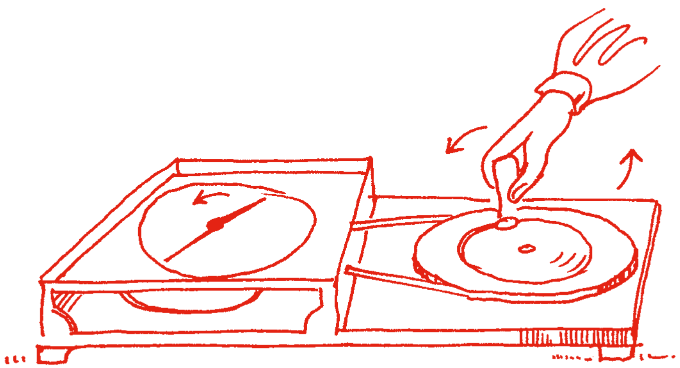
- Though the typical energy of a cloud to ground lightning strike is 10^9-10^{10} J, most of the energy is transferred to heat in the air, sound, light and radio waves. Nevertheless, a strike can heat sand to 30,000 K, much higher than the melting temperature of silica. When lightning strikes rocks or sand, the passage of large currents can heat the sand so that it forms hollow or branching mineral structures called *fulgurites*, or *petrified lightning*. The longest recorded fulgurite is over 5 m long.

The adventures of Arago

One of the first scientists to study eddy currents, François Arago, also served as the 25th Prime Minister of France in 1848 (a provisional position, Arago held the post for just over a month) and campaigned for the abolition of slavery. Arago noted that when a copper disc was placed beneath a compass, the oscillations of the needle were damped. His name is commemorated in a piece of apparatus, Arago's disc, which consists of a copper disc, rotated with a hand crank, situated beneath a compass needle. The motion of the disc relative to the needle induces eddy currents in the copper, which in turn, cause the needle to move. Arago was unable to account for the motion, and the explanation of the phenomenon was later supplied by Michael Faraday.

In addition to his scientific and political work, Arago lived an adventure-filled life which he described in vivid detail in his autobiography. He grew up close to the Pyrenees and reported an early encounter with Spanish soldiers:

> The Spanish troops in their retreat had partly mistaken their road… I ran immediately to the house to arm myself with a lance which had been left there by a soldier of the *levée en masse*, and placing myself in ambush at the corner of a street, I struck with a blow of this weapon the brigadier placed at the head of the party. The wound was not dangerous; a cut of the sabre, however, was descending to punish my hardihood, when some countrymen came to my aid, and, armed with forks, overturned the five cavaliers from their saddles, and made them prisoners. I was then seven years old.



With fellow French physicist Jean-Baptiste Biot, Arago was commissioned to carry out a survey of the meridian line, and, on a visit to Valencia, he met the city's archbishop. For some reason the meeting soured, and the archbishop hit Arago with a "movement, which was very near breaking my teeth, a gesture which I might justly call a blow of the fist".

Elsewhere, Arago and Biot were attacked by two men in an argument over a woman and, while fleeing in his carriage, Arago accidentally killed one of his assailants.

During the peninsula war between Spain and France, Arago was captured by locals in Majorca who assumed that his triangulation equipment was evidence of espionage activities. He was imprisoned but escaped by boat to Algeria, from where he returned to France bearing two lions as a gift from the ruler of Algiers to Napoleon.

Just as Marseilles was in sight, his boat was captured by a Spanish vessel and he was returned to Spain where he was imprisoned: first in a windmill, then a fortress and finally a prison ship. Arago wrote to the Dey of Algiers, to inform him that one of his lions had died during the Spanish attacks. In response, the Dey threatened Spain with war unless the Frenchman was released.

Liberated, Arago took a boat to Marseilles, but a storm damaged his ship, driving it to Sardinia and then onto Algeria. Arago set out over land, again hoping to seek help from the Dey of Algiers. However, in the interim, the Dey had been beheaded and the new ruler imprisoned Arago as a slave and demanded a ransom for his release.

Fortunately for Arago, the new Dey was himself deposed and hanged, enabling Arago to set out for France. Again in sight of Marseilles, the hapless physicist's ship was intercepted by a British vessel blockading the port. But this time, happily, Arago was allowed to proceed to Paris where he received a hero's welcome.

Arago became friends with Jules Verne who used the physicist's accounts of his experiences as the basis for two novels set in the Balearic Islands.

Arago and Biot's survey is commemorated by a series of 135 bronze medallions marking the Paris meridian running from Montmartre in the north to the Paris Observatory in the south (though not all of the medallions are currently visible).

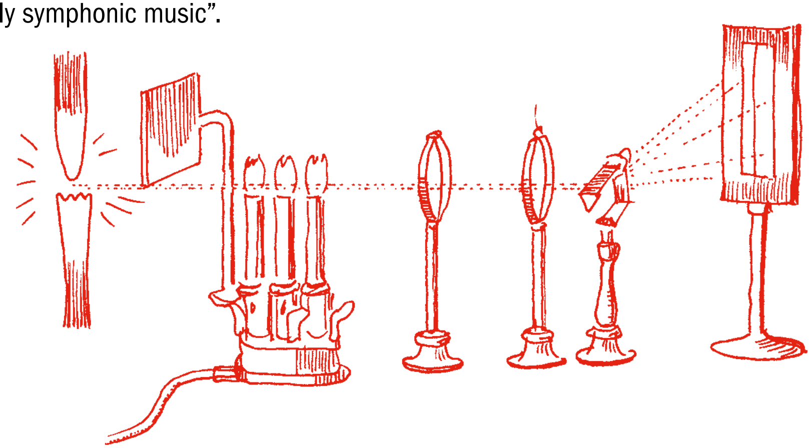
Scientific neighbours

In the 1850s, Robert Bunsen and Gustav Kirchhoff occupied neighbouring physics laboratories at Heidelberg University. One night, Kirchhoff and Bunsen were watching a fire in Mannheim from their laboratory window, and used spectral analysis to determine that barium and strontium were present in the burning material.

Later, while out walking, Bunsen remarked to his colleague: "If we could determine the nature of the substances burning at Mannheim, why should we not do the same with regard to the Sun? But people would say we must have gone mad to dream of such a thing." Kirchhoff replied, "Bunsen, I *have* gone mad," to which his colleague added, "So have I, Kirchhoff!"

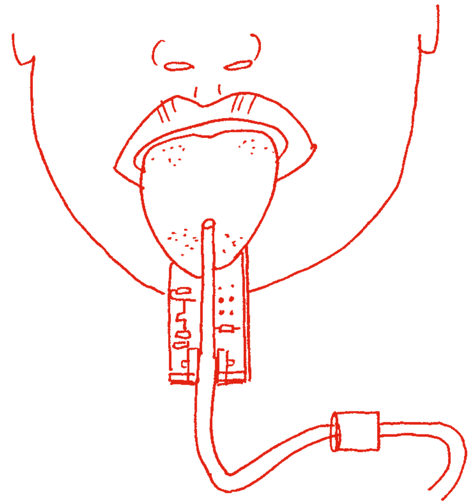
The two scientists would go on to invent a new spectroscope, the Bunsen-Kirchhoff spectroscope, which allowed them to discover the elements caesium and rubidium from their spectra.

Kirchhoff endured a number of unhappy events that occurred later in his life, including the death of his wife and an accident that left him reliant on crutches or a wheelchair. However, fellow physicist and philosopher Ludwig Boltzmann marvelled at his undented cheerful disposition. He admired Kirchhoff's style of argument, describing it as "the German Way" as it had "the sharpest precision" without "hushing up any problems". Boltzmann also described some of Kirchhoff's articles as of "uncommon beauty", in which "...every word, every letter, every hyphen, brings the mathematician closer than all other artists to the Almighty... resembling at best, only symphonic music".



The taste of electrical current

Johann Georg Sulzer, a Swiss professor born in 1720, is perhaps the first person to have reported *electrogustation*, the electrically induced sensation of taste. Sulzer described how, when pieces of lead and silver touched his tongue, they produced the taste of green vitriol (iron sulphate).



More recently, a team of researchers has developed an implement, called 'Spoon+', which applies weak current pulses to the tongue. They report that different tastes require different magnitudes of currents: sour 120 μA, salty 40 μA and bitter 120 μA, with a reversed polarity anode on the bottom of the tongue.

The team has also created a 'digital lollipop', a device that can be placed on the tongue to simulate a range of tastes through the application of different currents.

The man who was hit by a proton current

While there is ample research on the effects of electron currents on humans, there is limited evidence of how other types of charged particles might interact with the body. In 1978, a Soviet engineer, Anatoli Bugorski, was working on a synchrotron in Protvino, Russia when he was hit in the face by a beam of 76 GeV protons. He described seeing a light "brighter than a thousand suns", but reported no pain in the moment. He suffered radiation scarring to his face, hearing loss, paralysis to the left side of his face, and, subsequently, occasional seizures. However, he appears not to have suffered any mental impairment – he went on to complete his PhD and continued to work at the facility.

Though it has not been confirmed experimentally, it has been suggested that the taste of a proton current would be sour.

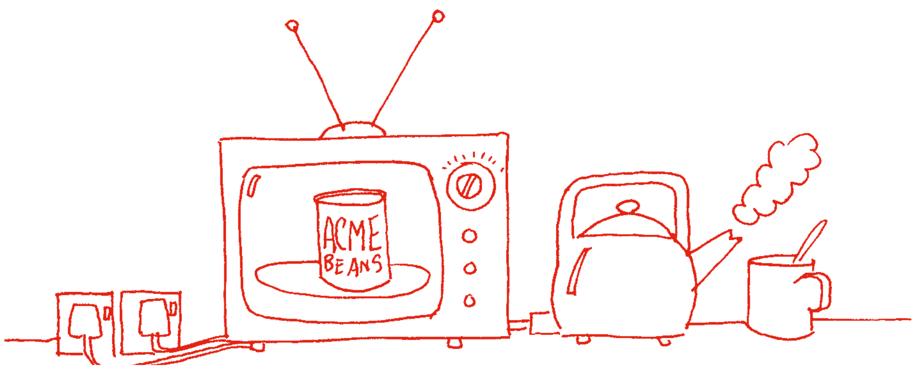
A grid of two halves

The eastern and western halves of the Japanese national grid run on different frequencies: 50 Hz and 60 Hz respectively. This difference arose as the first generators, functioning at 50 Hz, were imported to Japan from Germany and were installed in the east of the country. After the Second World War, 60 Hz generators were brought from the USA and installed in the western grid. Though it used to be the case that some electrical appliances could only be used on one grid, contemporary electronics are designed to work on both systems.

The secret hum

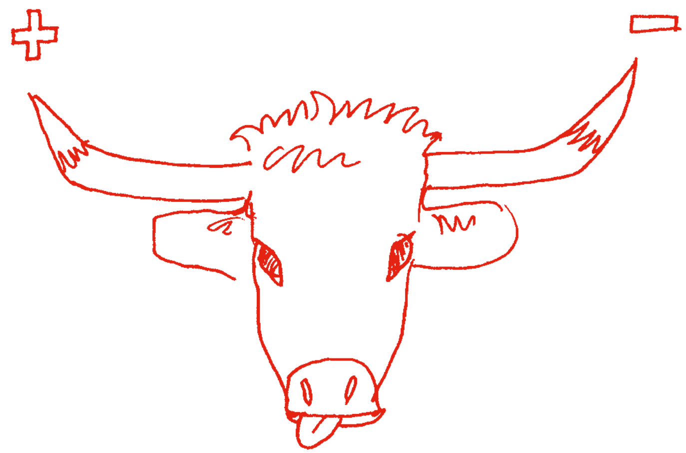
In the UK, mains electricity oscillates with a frequency of 50 Hz. This results in the emission of a signal, inaudible to people, but detectable on electronic audio recording devices. The frequency varies by the order of 0.001 Hz in response to changes in demand on the National Grid. These variations create a unique fingerprint that may become embedded in a recording. The signal acts as a timestamp which security services can use to determine the exact time at which an audio recording was made.

Electrical engineers have created models of how the grid frequency changes during big sporting events, such as the World Cup, or after an episode of a popular soap opera, in order to be able to predict times of peak demand.



The frog battery and other instruments

A number of batteries have been produced from animal parts. These gruesome creations were possible due to the existence of the *current of injury* and *demarcation potential* that occur in injured tissue and distinguish it from healthy muscle. Animal tissues have also been used in the construction of electrical instruments.



- Aldini (page 15) created a battery from an ox's head.
- Galvani (page 14) used freshly prepared frogs' legs as an early form of voltmeter.
- Chemist Robert Hare, in addition to suggesting that the experimenter's tongue may take on "the office of a galvanoscope", proposed that the limbs of a frog may be used as an "organic instrument".
- Physicist and pioneering investigator of bioelectricity Carlo Matteucci designed a frog galvanometer consisting of a frog's leg placed in a glass tube, with "a long piece of sciatic nerve protruding". The presence of current could be observed by the contraction of the leg muscles.

Fleming's happy thought

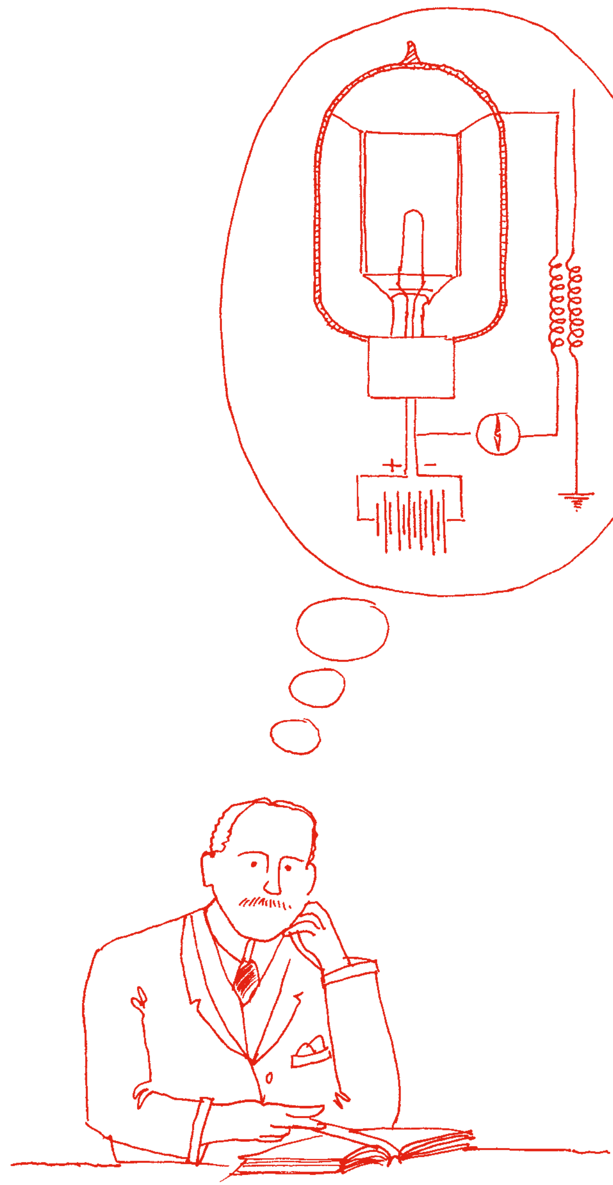
John Ambrose Fleming is best remembered for his eponymous left-hand rule. He also spurred the wireless technology revolution with his invention of the thermionic valve in 1905 and worked with John Logie Baird in the development of television. He described the idea for the valve occurring as a "sudden very happy thought". However, Fleming's route to success was far from direct.

He was forced to leave his undergraduate studies at University College London after two years to earn money working at a Dublin shipbuilder. He left that job after a couple of months to become a clerk at the stock exchange and completed a degree by studying in the evenings.

Fleming became a science teacher and developed an approach to pedagogy that emphasised practical demonstrations. While working at school, he corresponded with James Clerk Maxwell, ultimately deciding to leave teaching to study with him at Cambridge.

Fleming's transition into research was not easy and, because his mathematical knowledge was weak, he initially struggled to understand Maxwell's work on electromagnetism. Fleming overcame this inauspicious start to his academic career, ultimately becoming the first professor of electrical engineering at University College London and writing a book on the transformer that was widely read at the time.

While Fleming demanded precision of expression from his students, they complained that his lectures, though clearly explained, were difficult to follow as his delivery was so fast that they struggled to take notes. But he retained his dedication to supporting students' practical work: rather than typical laboratory classes, some of Fleming's students carried out experiments on a substation near Charing Cross.



Potential Difference

Volta, the opera singer and the electric pistol

Alessandro Volta made many contributions to science. Most famously, the unit of potential difference is named after him. Volta proposed the fundamental degree, a unit of potential difference based on the 'electric force' required to unbalance a disc kept in equilibrium by 12 grains (0.8 g) on an electrostatic balance. The unit Volta defined in this way has been calculated to be equivalent to 13,350 V. His experiments led Volta to propose the relationship that is now usually expressed as $Q=CV$ (where Q is the charge on the plates, C is the capacitance and V the potential difference).

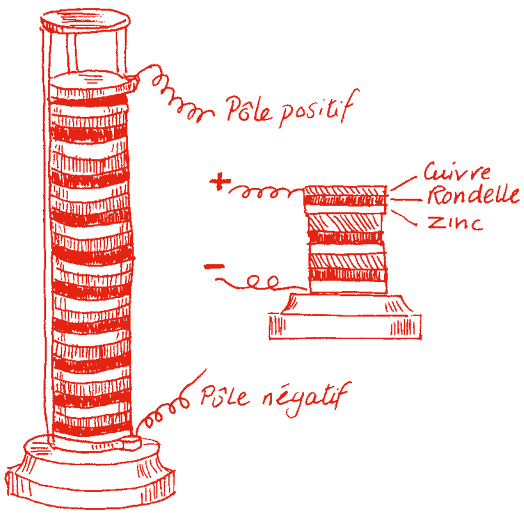


Fig. 283 – Pile de Volta.

Volta is also well-known for developing the electric pile, the first battery that could supply a continuous current. He published his research on electric piles in 1799 and it is said that he was inspired by a book which described the columns that make up the electric organ of a torpedo fish.

In addition to his electrical research, Volta is credited with the discovery of methane. Following a tip-off from a friend, he collected the gas bubbling off a swamp, found it was combustible and named the gas "inflammable air native of marshes". He combined his two major discoveries in an electric pistol, which fired projectiles through the ignition of methane with an electric spark.

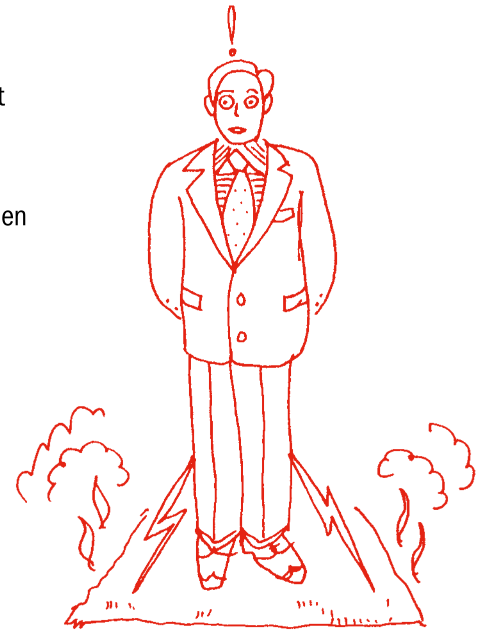
The electric pistol led Volta to a prescient proposal for communicating over a distance – he imagined, though never carried out, an experiment in which a pistol was fired in Milan by discharging a Leyden jar in Como, 50 km north.

Volta is sometimes cited as the father of the cochlea implant. He performed an experiment in which he placed electrodes in both ears, connected them to a pile (with an estimated EMF of 50 V), and reported hearing "a sound like a boiling viscid fluid". In further investigations of the effect of electrical stimuli on his senses, he wired his eye and tongue to a prepared piece of frog tissue. Completing the circuit, the frog muscles contracted and he experienced a visual stimulus and a sensation of taste.

Volta's glittering academic career hid an, at times, tumultuous personal life. In his mid-40s, he had a four-year affair with an opera singer, and proposed marriage, but the singer's low social status was unacceptable to his religious family. Though he contemplated a secret marriage and resigning his professorship, the engagement was ultimately broken off. He later married the daughter of a local government official and had three sons.

Visitors to Volta's birthplace, Como, can view a neoclassical temple erected in his honour that houses some of his instruments.

The explosive jacket



The BBC website reports the story of an Australian man, Frank Clewer, who went to a job interview wearing a nylon jacket and a woollen shirt. His clothes built up a potential difference – measured by firemen to be around 40,000 V – that caused a spark which ignited a carpet in the building. The office was evacuated and a member of the fire service reported that: "There were several scorch marks in the carpet, and we could hear a cracking noise – a bit like a whip – both inside and outside the building." The website does not record whether Mr Clewer's interview was successful.

Sensational electric learning

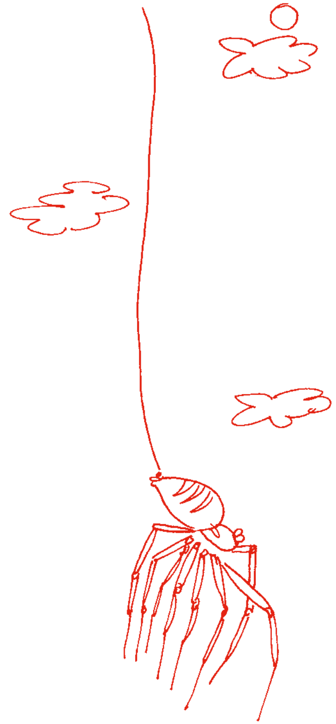
Swedish chemist Svante Arrhenius is perhaps best known for his work on the ionic disassociation of acids and bases, for which he won the Nobel prize, and the relationship between emissions of carbon dioxide and global warming.

Arrhenius also experimented with the effects of electrical currents on children. In 1911, sensational newspaper articles around the world reported that Arrhenius had embedded wires in the walls and ceiling of a classroom and compared the progress, over six months, of students taught in the electrified classroom with those who learned in normal rooms. It was claimed that the students exposed to the currents scored higher on nearly all tests and grew 50% more than a control group who were not exposed to currents. Additionally, their teachers reportedly felt "quickened" and had greater endurance as result of the trial.

Tesla (see page 6) heard of Arrhenius' work and proposed an investigation of the effects of electrical stimulation on students with learning difficulties to the superintendent of New York schools. Ever the electrical enthusiast, Tesla wrote eagerly of the prospects for electromagnetic stimulation, imagining that all future homes would have Tesla coils embedded in their walls and suggested that even adults of average intelligence would become the equals of the most brilliant minds of the pre-electric era.

Tesla was about to begin his experiment when Arrhenius responded to a request for the details of his experiment from a British psychiatrist who wished to repeat the experiment. The Swedish chemist reported that the newspaper articles had misreported his work – he had exposed new-born infants in an orphanage to high frequency currents and, though the initial results had seemed to indicate an increased growth rate for the exposed babies, Arrhenius discovered that a nurse had allocated the healthiest children to the electrical exposure group and the weakest infants to the control group. When he repeated the experiment, the effect disappeared and Tesla's plan for an electric school was never realised.

Electric spiders



Gossamer spiders, also known as ballooning spiders, may use the Earth's vertical atmospheric electric field to fly. The spiders move through the air by using gossamer threads to catch the wind in a behaviour referred to as 'ballooning'. Charles Darwin reported the phenomenon while sailing off the coast of Argentina.

Though the spiders are thought to gain buoyancy from both the wind and convection currents, surprisingly heavy spiders are capable of ballooning and have been observed taking off with unexpectedly high initial accelerations. Researchers have speculated that spiders' silk may become charged in the process of spinning or weaving and provide an additional electrostatic buoyancy force. The Earth has an average negative surface charge density of 6 nC/m^2, which may exert a repulsive force on the spiders' threads and contribute to their ability to balloon.

Saturn's shocking moon

The Cassini spacecraft received a 200 V shock from the surface of one of Saturn's moons. As Cassini made a flypast of Hyperion, approximately six minutes before its closest approach, instruments detected a flow of electrons coming from the moon. It is thought that the surface of Hyperion becomes charged both by the absorption of ultraviolet radiation and through exposure to charged particles that become trapped in Saturn's magnetic field. The build-up of charge resulted in a potential difference between the probe and moon, driving a beam of electrons over a distance of 2,000 km. There is no evidence that Cassini was damaged by the discharge but spacecraft designers have noted the effect as a potential hazard to future missions.

Resistance

Ohm overlooked

Georg Ohm's father was a locksmith, a background that may have given his son practical experience that was useful to his future electrical research. While pragmatically useful, Georg's relationship with his father was uneasy: when his father discovered that the young man spent his time at the University of Erlangen dancing, ice-skating and playing billiards, rather than studying, he forced his son to leave his studies.

In 1806, the young Ohm was sent to Switzerland, where he worked as a private mathematics tutor, before returning to university. After graduating with a doctorate, he became a lecturer but couldn't live on the meagre salary and took up school science and mathematics teaching at a challenging school in Bamberg. Ohm's experiences in the classroom inspired him to write a geometry textbook which was praised by the King of Prussia, who offered him a role in a better school, giving the scientist more time for his research. This school had excellent practical equipment and Ohm began to investigate the contemporary received opinion that current and potential difference were independent.

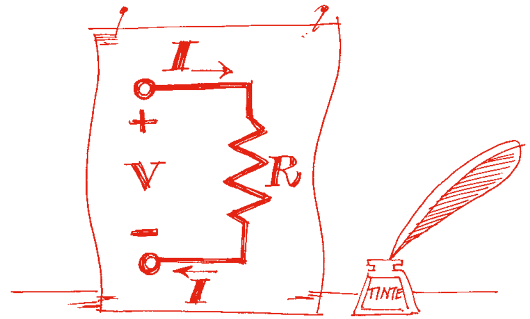
He carried out experiments on the deflection of a magnetised needle produced by different lengths of copper wire. He argued that his observations could be modelled through the relationship:

$$X=a/(b+x)$$

where X designated the deflection of the needle, x the length of copper wire and a and b were constants.

In the same year, he published another paper in which he summarised the results of his experiments in the form $S=A/L$ where S represented the strength of current, A the sum of all the tensions and L the 'Reduzirten Lange' or the resistance.

Cavendish pre-empted Ohm's statement of his eponymous law by some 70 years but his work remained unpublished and was only later rediscovered by Maxwell. Some philosophers of science categorise Ohm's law as a *ceteris paribus* law, rather than a true scientific law, as it is dependent on a condition (constant temperature) rather than being universally true.



Ohm's work did not meet with approval at the time of publication. One critic described his research as:

> ...a web of naked fancies, which can never find the semblance of support from even the most superficial observation of facts: (and) he who looks on the world with the eye of reverence must turn aside from this... as the result of an incurable delusion, whose sole effort is to detract from the dignity of nature.

As Ohm was a schoolteacher, word of his publication reached the minister of education who proclaimed, "A professor who preached such heresies was unworthy to teach science." This hostile reception led to Ohm resigning his teaching post. He spent many years seeking a university position, living in poverty while moving between poorly paid teaching jobs.

One of the reasons Ohm's work was not more readily accepted was because he used contemporary electrical terms that had ambiguous meanings. For example, he did not clearly distinguish between *force* and *electrical potential*, and confusingly drew on ideas from Fourier's theory of heat – he refers to the '*diffusion*' of electricity. The intervention of Kirchhoff, who related Ohm's concept of 'electroscopic force' with electrical potential, allowed Ohm's law to be integrated with existing electrical theory.

In the final two years of his life, Ohm's fortunes reversed and he was appointed the professor of physics at the University of Munich. In addition to his electrical law, Ohm proposed an acoustic law which proposes that musical notes may be decomposed into a number of pure tones.

What can a resistor remember?

Human skin acts like a *memristor*, a device that alters its resistance in response to the last potential difference applied. Memristors were proposed in the 1970s but the first physical device wasn't built until 2008. Researchers have found that human skin acts as memristor – it seems to 'remember' the last potential difference applied. When a negative potential difference was applied to various parts of a human arm, the area of skin displayed a low resistance; when a positive potential difference was applied before the negative, the negative potential produced a much higher resistance. This effect arises as sweat contains positively charged ions, which are drawn upwards from sweat pores by a negative potential difference, lowering skin resistance.

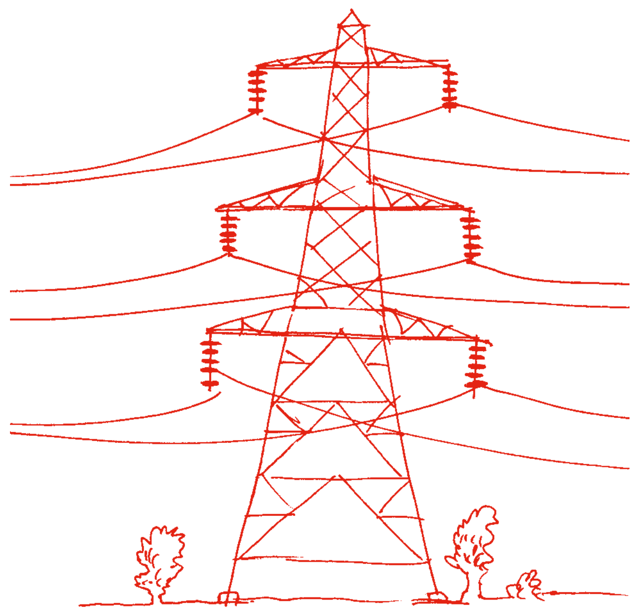
Researchers believe that memristors may, one day, replace transistors in computers. In 2012, researchers built a device using memristors which had an access time 100 times faster than the available flash solid-state memory technology used in USB drives while consuming only one percent of the energy.

Counting the discs

High voltage power lines typically use disc insulators to prevent current entering the metal pylon. Counting the number of discs can give an indication of the line voltage:

Line Voltage (kV)	34.5	45	69	92	115	138	161	196	230	287	345	360
Number of discs	3	4	5	7	8	9	11	13	15	19	22	23

When winds blow, high voltage power lines respond in three modes of oscillation: Gallop (0.1-0.5 Hz), Aeolian (8-60 Hz) and Wake-induced vibrations (0.5-2.5 Hz). Stockbridge dampers are dumbbell-shaped dampers consisting of two concrete or metal masses attached to a piece of cable or other flexible material. They reduce Aeolian vibration that can cause dangerous stresses in power lines.



Breaking bulbs

Typically, the resistance of a filament light bulb increases as the potential difference applied rises. While this is true for bulbs with metallic filaments such as tungsten-filament lamps, for other types of bulb, for example carbon-filament lamps, the reverse is true. This is because carbon has a negative temperature coefficient, which means its resistance decreases with temperature.

Extended use of tungsten-filament lamps causes some of the filament to evaporate and condense on the bulb, leading to the blackening effect sometimes observed on the inside of the glass of blown bulbs. This blackening effect can be reduced by introducing traces of halogen gas into the bulb. The halogen reacts with the tungsten vapour, preventing a build-up of material on the glass. Areas of the filament from which tungsten evaporates develop higher resistance and heat up, causing further evaporation in a positive feedback cycle that can lead to the bulb's failure.

Bulbs typically break in the first few seconds of usage because the initial current that flows after the bulb is switched on when it is still cold (the 'inrush current') is as much as 10 times the magnitude of normal operating currents. This large current creates a high magnetic field in the filament coil leading to mechanical stress as well as thermal stress, causing filament failure. Some bulb designs include an initial low-voltage preheating cycle to prevent this kind of damage.

Ayrton's lightbulb moment

In the late 19th century, arc lights were a common form of lighting. The devices produce light from a spark (or electric arc) generated in the air between two carbon rods. Among several drawbacks, they suffered from flicker and produced a hissing sound.

Hertha Ayrton, a British engineer, discovered that the cause of arc light flicker was oxygen reacting with the carbon filament. Though eager to share her findings, the Royal Society barred her from presenting the work due to her sex and a man gave her paper on her behalf. Undeterred, in 1902 she became the first woman to give a paper to the Royal Society, this time on her research on ripples.

Ayrton became active in the women's suffrage movement and formed part of a delegation with Emily Pankhurst to meet the prime minister. She was a friend of Marie Curie and tutored her daughter, Irène, in mathematics. Irène would go on to win the Nobel prize in Chemistry. Through this relationship, Ayrton persuaded Marie Curie to sign a petition protesting the imprisonment of women.

Ayrton's obituary in *Nature* argued that her husband, also a scientist, would have had a happier life if his wife had had more time to cook and bring him his slippers. It concludes: "She was a good woman, despite her being tinged with the scientific afflatus."

Magnetism

The magnetic sea

Seawater is a conductor and therefore its motion in the Earth's magnetic field leads to the induction of weak currents and low intensity magnetic fields. The magnitude of the fields induced is of the order of a few nanotesla. The fields are larger near the surface of the ocean than at greater depths due to the higher velocity of water near to the surface.

Violent magnetic storms can amplify the effect, inducing oceanic magnetic fields of around 100 nT that concentrate near coasts. Satellite observation of the magnetic fields created by the motion of seawater can be used to study the movement of tides at different depths and to understand the flow of energy through the oceans, which can provide information on climate change.

Core idea

The iron cores in solenoid magnets typically saturate at field strengths of a few tesla, limiting the strength of field they can produce. An improved design is the Bitter electromagnet which is constructed from a series of circular metal plates, drilled with a pattern of holes, and separated by insulating spaces. This design causes currents to circulate in a helical pattern. Water can be pumped through the holes to cool the metal as the high currents, of the order of 10,000 A, cause large heating effects.

While superconducting magnets can produce fields of up to 22 T, a Bitter electromagnet has been constructed that produces a field of 37.5 T and a hybrid superconducting-Bitter magnet can reach fields of 45 T.

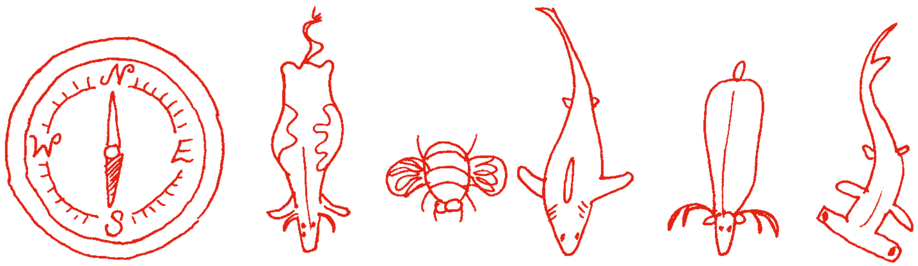
Pooing pooches point polewards

- Dedicated scientists have observed the body alignment of dogs during defecation (1,893 observations) and urination (5,582 observations) and report that the animals preferred to excrete while aligned in a north-south direction.

- Meanwhile, using images from Google Earth, a team of researchers has claimed that grazing and resting domestic cattle and red and roe deer tend to align their bodies in a roughly north-south direction. The authors report that the biological significance of the alignment is unknown. The results are controversial and other researchers have argued that there is no evidence that cattle align along magnetic field lines.

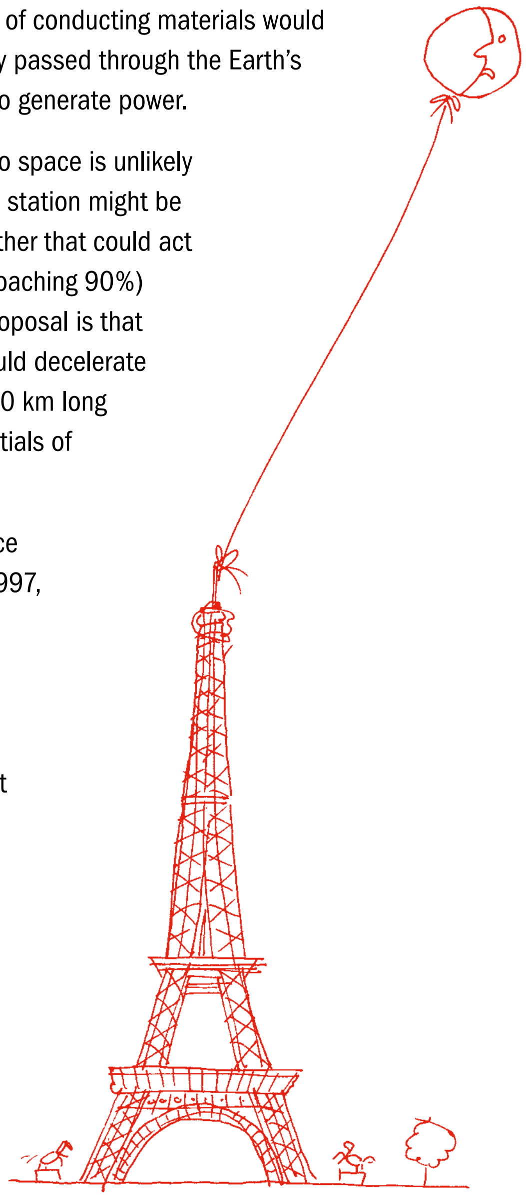
- A number of organisms including honeybees, bacteria, sharks and pigeons are capable of detecting magnetic fields. Three hypotheses exist for the nature of the mechanism that enables animals to detect magnetic fields:

  a) induction
  b) alterations in chemical reactions due to the magnetic field
  c) effects due to the presence of permanently magnetic materials in animals' bodies – for example magnetite, Fe_3O_4 has been found in the bodies of bees, pigeons and other creatures.



Celestial castles and space tethers

The concept of a space tether was first proposed in 1895 by Konstantin Tsiolkovsky who was inspired by the Eiffel Tower to imagine a “celestial castle” connected to Earth by a tower. Building on Tsiolkovsky’s idea, scientists have proposed that, since tethers made of conducting materials would experience an induced EMF as they passed through the Earth’s magnetic field, they may be used to generate power.

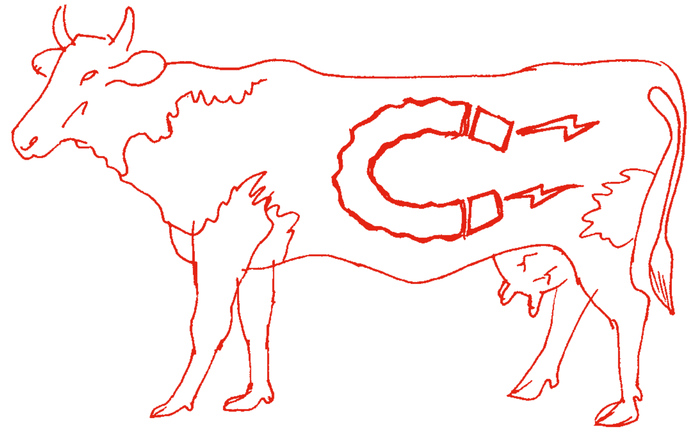


While a tether running from Earth to space is unlikely to be practical, a satellite or space station might be fitted with a shorter, deployable tether that could act as a highly efficient (perhaps approaching 90%) generator. One drawback of this proposal is that the Ampère force on the tether would decelerate the vehicle. It is estimated that a 10 km long tether might lead to induced potentials of 2-4 kV.

A number of experiments with space tethers have been attempted. In 1997, a tether deployed from the TSS1-T satellite released by the shuttle Columbia broke after 19.7 km of the cable had been deployed. Despite the break, which is thought to have been caused by an electrical discharge, the current measured in the tether was three times greater than predicted values. Further investigations of the behaviour of tethers in the upper atmosphere on shuttle missions were proposed but never flown.

The cow magnet

Cattle may suffer from a condition known as *hardware disease* caused by the ingestion of foreign bodies. The condition is often treated by encouraging the cow to swallow a cow magnet, a 7 cm rod magnet with an anti-corrosive covering. The magnet remains in the cow’s stomach and collects magnetic foreign bodies, rendering them harmless.



Dating slag

Researchers have discovered that a geomagnetic spike occurred around 1000 BCE by examining the magnetic fields in slag, a by-product of copper manufacture, smelted at the time. It is estimated that the magnitude of the Earth’s magnetic field strength doubled before falling to normal levels in the Levantine region of the Middle East. The change in field only lasted around 30 years and was confined to an area a few thousand kilometres across. The researchers speculate that the spike was caused by an intense localised equatorial patch of flux at the core-mantle boundary.

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A full set of references for this booklet is available on the Stories about Physics forum on TalkPhysics at
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