The Power of 3
Driving the future further
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Can batteries save the planet?

Overview

The original, generic meaning of the term 'battery' is 'a group of similar objects functioning together', as in an artillery battery. Benjamin Franklin, polymath and a founding father of the United States, coined the expression in 1749 in relation to articles used in his experiments with electricity [1].

Today, the name is applied to any container in which chemical energy is converted into electricity and used as a source of power.

Put simply, a battery consists of three main components: a pair of terminals, the cathode (+) and the anode (-), each made of a different chemical (usually a metal), and the electrolyte that separates them. The latter, a chemical medium, allows electrically charged atoms to flow between the two terminals, creating an electric current that powers anything connected to that battery.

In battery design, everything depends on the materials used for those components: together, they determine how many ions can be stored and how fast the battery can pump them out.

With primary (disposable) batteries, the electrode materials are irreversibly changed during discharge, meaning these batteries are used once then discarded. An example is the alkaline battery used in flashlights and many other portable devices.

In secondary (rechargeable) batteries, the electrochemical reaction is reversible and the original chemical compounds can be reconstituted, allowing the battery to be discharged and recharged multiple times. Examples include the relatively inexpensive lead-acid batteries used in most motor vehicles, and the much more expensive lithium-ion (Li-ion) batteries that power, for example, portable electronics and electric vehicles.

Oft taken for granted but amazing nevertheless, batteries have become intrinsic to modern living.

Battery evolution (a potted history)

Battery evolution has long been an international affair *(see table below)*.

Year	Inventor	Activity
1600	William Gilbert (UK)	Establishment of electrochemistry study
1745	Ewald Georg von Kleist (NL)	Invention of Leyden jar, stores static electricity
1791	Luigi Galvani (Italy)	Discovery of 'animal electricity'
1800	Alessandro Volta (Italy)	Invention of the voltaic cell (zinc, copper disks)
1802	William Cruickshank (UK)	First electric battery capable of mass production
1820	André-Marie Ampère (France)	Electricity through magnetism
1833	Michael Faraday (UK)	Announcement of Faraday's law
1836	John F Daniell (UK)	Invention of the Daniell cell
1839	William Robert Grove (UK)	Invention of the fuel cell (H_2/O_2)
1859	Gaston Planté (France)	Invention of the lead acid battery
1868	Georges Leclanché (France)	Invention of the Leclanché cell (carbon-zinc)
1899	Waldemar Jungner (Sweden)	Invention of the nickel-cadmium battery
1901	Thomas A Edison (USA)	Invention of the nickel-iron battery
1932	Schlecht & Ackermann (Germany)	Invention of the sintered pole plate
1947	Georg Neumann (Germany)	Successfully sealed the nickel-cadmium battery
1949	Lewis Urry, Eveready Battery	Invention of the alkaline-manganese battery
1970s	Group effort	Development of valve-regulated lead acid battery
1990	Group effort	Commercialisation of nickel-metal-hydride battery
1991	Sony (Japan)	Commercialisation of lithium-ion battery
1994	Bellcore (USA)	Commercialisation of lithium-ion polymer
1996	Moli Energy (Canada)	Introduction of Li-ion with manganese cathode
1996	University of Texas (USA)	Identification of Li-phosphate ($LiFePO_4$)
2002	University of Montreal, Quebec Hydro, MIT, others	Improvement of Li-phosphate, nanotechnology, commercialisation

History of modern battery development. Source: BU-102: Battery Developments, *Battery University*

NB: no major new battery system has entered the commercial market since the invention of the Li-phosphate battery in 1996.

Although primitive batteries may have existed in Babylonian times (the evidence is disputed), it wasn't until the 1550s that English scientist William Gilbert made the distinction between magnetism and static electricity (then called the 'amber effect'). Known as the 'Father of Magnetism', Gilbert is credited with establishing the study of electrochemistry.

William Gilbert, the 'Father of Magentism'.
Source: *http://blog.yovisto.com/william-gilbert-the-father-of-electrical-studies/*

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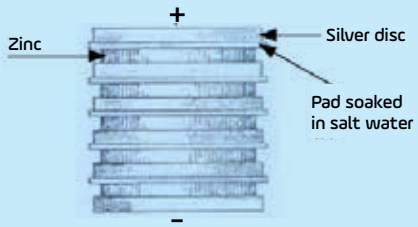
Original Cruikshank's galvanic trough.
Source: *collectionsonline.nmsi.ac.uk*

Around a century later, in 1663, German physicist Otto von Guericke invented the world's first electrostatic generator [2], a device subsequently used in many experiments pertaining to electricity.

Then, in the late 18th and early 19th centuries, Italians Luigi Galvani [3] and Alessandro Volta [4] conducted pioneering groundwork in electro-chemical energy storage. (Today, their names live on in the terms 'galvanic cell' and 'volts'.) It was Galvani's experiments with 'animal electricity' in frogs that led Volta to invent arguably the world's first battery, the 'voltaic pile', which produced continuous electric current to a circuit in a process now known as electrolysis [5].



The voltaic pile.
Source: *astarmathsandphysics.com*

In light of the Industrial Revolution, the work of Galvani and Volta excited great interest in galvanic electricity. Two Englishmen to take up the baton were Sir Humphrey Davy [6], who conducted important investigations into electrochemistry, and Dr William Cruickshank [7]. In 1802, Cruickshank designed the 'trough battery' (a variant of the voltaic pile) and, voilà, the first electric storage device capable of mass production was born.

The nature of electricity, and the challenges of how best to create, store and use it, captured the imaginations of high- and commercially-minded scientists and inventors worldwide, among them such instantly recognisable names as Ampère [8] (France), Faraday [9] (the UK), Jungner [10] (Sweden), Edison (the US) [11] and Tesla [12] (a Croatian who moved to the US).

Assiduous research, not to mention rivalry, contributed to stand-out innovations like telegraphy, power delivery, the telephone, broadcast radio, television, computers and now, in the 21st century, a plethora of products – from electric vehicles and machinery through consumer electronics and power-storage devices to aerospace applications – considered essential (or soon to be) to life as we know it.

Genesis of the Li-ion battery

Steve Levine, writing for *Quartz*, avers that in the past 60 to 70 years the two most powerful inventions in terms of their social and economic import are the transistor and the Li-ion rechargeable battery. The former, created at Bell Labs in 1947, transformed electronics, while the latter, commercialised by Sony in 1991, "took the clunky electronics enabled by the transistor and made them portable. [It] gave the transistor reach."

In the 1970s, Stanley Whittingham, a British professor of chemistry and materials science, and colleagues at Stanford University discovered and named the concept of intercalation of electrodes, whereby lithium ions are inserted within layered sheets. The lithium ions can be shuttled from one electrode to the other, resulting in a rechargeable Li-ion battery. Whittingham's rechargeable lithium battery had a titanium disulphide cathode and a lithium-aluminium anode. On the basis of this research, ExxonMobil patented a lithium-titanium disulphide battery in 1976; however it proved unworkable [13].

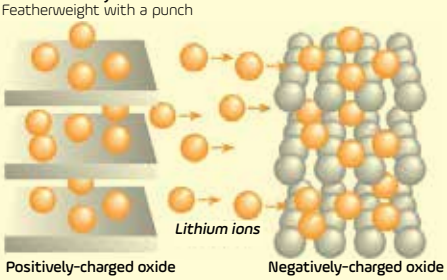
In 1979, American physicist John Bannister Goodenough [14], then heading the Inorganic Chemistry Lab at Oxford University, improved significantly on that Li-ion battery technology. His brainchild?

... the cobalt-oxide cathode, the single most important component of every lithium-ion battery. From Mogadishu to Pago Pago, from Antarctica to Greenland, and all lands in between, Goodenough's cathode is contained in almost every portable electronic device ever sold. Others have tried to improve on the cobalt-oxide cathode, but all have failed. [15]

Goodenough's discovery opened up new and exciting possibilities for rechargeable battery systems. In 1980, French Moroccan scientist Dr Rachid Yazami developed a graphite anode, which paved the way for Akira Yoshino, a Japanese chemist also researching rechargeable batteries. Yoshino combined Goodenough's cathode with lithium cobalt oxide as the anode, creating a prototype in 1983. This led to development of the lithium-graphite anode used in modern Li-ion batteries.

Sony produced the world's first commercially viable Li-ion battery in 1991.

Lithium battery
Featherweight with a punch



Sony's 1991 Li-ion battery used lithium-cobalt-oxide for the positive electrode and graphite (carbon) for the negative one. As the battery is charged, lithium ions move out of the cobalt-oxide lattice and slip between the sheets of carbon atoms in the graphite electrode – a state of higher potential energy. Discharging the battery causes the ions to move back again, releasing energy in the process. This is known as a 'rocking chair' design.
Source: Hooked on lithium, The Economist 2002.

Decades on, improving that technology – to increase the range of electric vehicles, create ever-smarter consumer electronics and efficiently store energy from renewable sources at both domestic and commercial levels – remains the Holy Grail of battery manufacturers the world over.

In light of Earth's woes, including global warming, could batteries – and Li-ion batteries in particular – be the greatest innovation since the Industrial Revolution? Time alone will tell!

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Notes

[1] Benjamin Franklin (1706-1790) was a leading author, printer, political theorist, politician, freemason, postmaster, scientist, inventor, civic activist, statesman and diplomat. One of his major scientific discoveries was that lightening is an electrical discharge and he subsequently invented the lightening rod.

[2] Otto von Guericke (1602-1686) proved that a vacuum could exist; before that, no one believed it possible. His discovery was essential for further research into electricity. Circa 1660, von Guericke devised a contraption that produced static electricity by friction. It consisted of a glass globe within which a large ball of sulphur was mounted on a pole. When the sulphur ball was rotated by a hand crank, it rubbed against a pad and the resulting friction generated sparks of static electricity. Although von Guericke had no idea what these sparks signified, his device was subsequently used in early experiments with electricity.

[3] Luigi Galvani (1737-98), an Italian physician, physicist, biologist and philosopher, is recognised as the pioneer of bio-electromagnetics. In 1781, Galvani found that he could induce twitching in the muscles of a dead frog when they were touched with different metals or the current from a static electric generator located nearby. He thought, incorrectly, that the fluid in the frog's body was the source of the electricity.

[4] Count Alessandro Volta (1745-1827), an Italian physicist and chemist, made discoveries in electrostatics, meteorology and pneumatics. He is most famous, however, for inventing the first battery. In 1800, Volta proved that the electrical reaction in frogs noted by Galvani was in fact caused by the animal's body fluids being touched by two different types of metal. Subsequently Volta invented his 'voltaic pile', a stack of alternating metal discs of silver and zinc separated by cloth or cardboard soaked in salt water. This wet pile of 'dissimilar' metals created a small electrical current that could be drawn off through wires and used for experiments; several piles assembled side by side and connected with metal strips could create a power source of higher energy. Volta gave his name to the term 'volt', a unit of electrical energy.

[5] The process whereby an electric current is passed through a liquid (electrolyte) that conducts electricity, promoting a chemical reaction between metals (electrodes). To conduct electricity a liquid must contain ions; that is, atoms or molecules with a net electric charge caused by the loss or gain of one or more electrons.

[6] Sir Humphrey Davy (1778-1829) was a leading British chemist and philosopher and inventor of the miner's safety lamp. In 1801 he installed what was then the world's largest, most powerful electric battery in the Royal Institution of London. Davy attached it to charcoal electrodes to produce the first electric light, which, according to witnesses, was "the most brilliant ascending arch of light ever seen." He had begun testing the chemical effects of electricity in 1800 and soon found that, when electrical current passed through certain substances, it caused them to decompose in a process later termed 'electrolysis'. The voltage generated as a result of this process was directly related to the electrolyte reacting with the metal. Davy's assistant, Michael Faraday, went on to establish a reputation even more prestigious than that of his mentor *(see note 9 below)*.

[7] Dr William Cruikshank (died 1810 or 1811) was a Scottish military surgeon, Fellow of the Royal Society and professor of chemistry at the Royal Military Academy in Woolwich. He devised the trough battery, comprising joined zinc and copper plates placed in a wooden box filled with electrolyte (brine or diluted acid) and sealed with cement. Grooves in the box held the metal sheets in place. This 'flooded' design, which did not dry out with use, produced more energy than Volta's stacked disc arrangement.

[8] In 1820, André-Marie Ampère (1775-1836) made a revolutionary discovery: that a wire carrying electrical current can attract or repel another, adjacent wire also carrying electrical current. While the attraction is magnetic, no magnets are required to produce the effect. Ampère went on the formulate Ampere's Law of electromagnetism, producing the best definition of electrical current of his time. He further proposed the existence of a particle now recognised as the electron, discovered the chemical element fluorine, and grouped elements by their properties more than half a century before Dmitri Mendeleev produced his periodic table. The International System of Units (SI) unit of electric current, the ampere (amp for short), is named in his honour.

[9] Michael Faraday (1791-1867), an English scientist, is considered one of the greatest scientific explorers of all time. His contributions to the fields of electromagnetism and electrochemistry, principally in relation to electromagnetic induction, diamagnetism and electrolysis, were remarkable, and his electromagnetic rotary devices formed the basis of electric motor technology. The SI unit of capacitance, the farad, is named in his honour.

[10] In 1899, Swedish engineer Waldemar Jungner (1869-1924) invented the nickel-cadmium electric storage battery, using nickel for the positive electrode and cadmium for the negative.

[11] American Thomas Edison (1847-1931) was a pioneer in applying the principles of mass production and teamwork to inventions to make them commercially viable. He is perhaps best known for devices such as the phonograph, the motion picture camera, a practical, long-lasting electric light bulb and, more controversially, the electric chair, created to illustrate the perils of alternating current (AC) as opposed to direct electrical current (DC), of which he was a firm advocate. In 1901, Edison produced an alternative to Jungner's battery, replacing the cadmium with iron. Cost considerations, however, limited the practical applications of either type of battery.

[12] Nikola Tesla (1856-1943), born in Croatia, moved to the US in 1884. There, he worked briefly with Edison before the two parted ways. Tesla made a significant contribution to the development of AC (as opposed to DC) electrical systems to supply long-distance power, and AC became pre-eminent in the 20th century (it remains the worldwide standard), and also discovered the rotating magnetic field, the basis of most AC machinery.

[13] Steve Levine, author of *The Powerhouse: Inside the Invention of a Battery to Save the World.*

[14] Whittingham's rechargeable lithium battery was based on a titanium disulphide cathode and a lithium-aluminum anode. Titanium disulphide was a poor choice, in that it had to be synthesised under completely sealed conditions, a very costly process. Also, when exposed to air it stank, because the moisture in the air reacted with the titanium disulphide to make hydrogen sulphide. Moreover, because lithium is highly reactive, burning in normal atmospheric conditions due to the presence of water and oxygen, metallic lithium electrodes present significant safety issues.

[15] Among the many prizes he's received, Dr Goodenough was awarded the $450,000 Japan Prize in 2001 in recognition of his work. Still going strong at the age of 93, and currently professor of mechanical engineering and materials science at the University of Texas, Goodenough wants to develop a 'super-battery', a quantum leap in storage capacity that will make electric vehicles, for instance, more competitive and the harnessing of power from renewable sources more economical.