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Historical Beginnings of Theories of Electricity and Magnetism

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The first records of electricity and magnetism

The most primitive electrical and magnetic phenomena -- the attraction of dry light material such as chaff to rubbed amber, and the attraction of iron to loadstone -- were no doubt observed before recorded history began. However, as far as I can find, these phenomena were not recorded by the Egyptians or any other pre-Greek civilization. The first definite statement is by Thales of Miletus (about 585B.C.) who said loadstone attracts iron because it has a soul. The prevailing view at the time was that movement of any kind indicated life, or a soul, or a god. In fact, it was advanced thinking on Thales' part to think that the loadstone's moving of the iron was caused by itself rather than by the intervention of some god. Actually Miletus was a very multicultural environment -- a flourishing commercial city in Asia Minor (now part of Turkey), trading with Babylon and also Egypt, where Thales travelled. This mixture of cultures meant that there was not a strongly repressive religious orthodoxy, as was often the case in primitive (and not so primitive) societies, so freedom of inquiry was tolerated. Sad to report, this did not lead to a more enlightened political system -- it was a slave based society, with bloody rebellion and repression.

An early Greek word for the sun - ηλεχτορ - pronounced "elector" - was also used to describe amber, because of its sunshiny color. Amber is the fossilized resin of a now extinct coniferous tree, almost all of it comes from the Baltic region in Northern Europe. Of course, this is the stuff that preserves insects from millions of years ago. It was greatly prized in the early world as jewelry, and used as such in Greece from the earliest recorded times. Amber came to be called "electron" by the Greek classic writers, but this term also referred to native gold and silver-gold alloys (same color).

First scientific-type explanations

The first discussion that begins to look like a scientific explanation I can find is in Lucretius, On the Nature of Things (*De Rerum Natura*). Lucretius was born in 98 B.C. and died in 55 B.C. or so, but he was summarizing the views of Epicurus (342 - 270 B.C.), himself a follower of Democritus. They all believed everything to be made up of atoms, Democritus thought the atoms followed natural laws, but Epicurus thought they could be deviated a bit by free will. They all thought the soul too was made of atoms, which fell apart at death so there was no afterlife, and if there were gods, they didn't concern themselves with us. Anyway, back to magnets. Lucretius states (in describing a loadstone attracting a ring of iron): " ..it must needs be that there stream off this stone very many seeds or an effluence, which, with its blows, parts asunder all the air which has its place between the stone and the iron. When this space is emptied .. atoms of the iron start forward and fall into the void, all joined together .. the ring itself follows .. with its whole body." In other word*, tiny particles emanating from the loadstone sweep away the air and the consequent suction draws in the iron*.

At least this explanation doesn't depend on gods, souls, etc. However, it has some obvious defects, which Lucretius immediately addresses. Why doesn't this mean the loadstone would attract gold -- which it doesn't? Because, he explains, the gold is too heavy, so it doesn't move. O.K., what about wood? Well, wood is so light that the effluence goes right through it, so does not bounce back and sweep away the air between the two. A nicer point is made by Galen (130-200 A.D., a famous anatomist and doctor), who says Epicurus claimed the atoms flowing from the stone were related in shape to those flowing from the iron, so easily interlocked, and after bouncing between the stone and the iron become entangled and draw the two together. However, Galen goes on, he doesn't see why anyone should believe this, because it doesn't explain why a ring thus attached to a magnet will attract a further ring to itself, and says he's seen five pieces of iron held magnetically in a chain, only the first one being in contact with the loadstone.

These are genuine attempts to explain in a natural fashion a really discrepant event. To quote Pliny (A.D. 23-79) "What phenomenon is more astonishing? Where has nature shown greater audacity? For iron, the tamer of all substances, is drawn to the magnet, following some intangible attraction, and, as it comes nearer, leaps to meet the magnet." Pliny, by the way, claims the name "magnet" came from a shepherd called Magnes, who found his iron-nailed shoes and staff sticking to the ground. It seems more likely that the name came from the Magnesia region, one place where naturally magnetic ore is to be found.

Pliny also has something to say about amber. Apparently, it was used for the end of the spindle by Syrian women spinners, and they called it the "clutcher". One possibility is that it became electrified as it spun and rubbed against their clothing, so attracting chaff, etc.

(*Note*: Since the most famous Greek philosophers are Aristotle and Plato, we probably should mention that Plato mumbled something in *Timaeus*, 80, stating that the motions of amber, the Heraclean stone (loadstone) and falling water all depended on the nonexistence of the vacuum combined with the fact that these substances are forced round and round by composition and divination ... whatever all this meant. Gilbert (see later) didn't think it meant much.)

St. Augustine's surprise

Moving into the Christian era, St. Augustine said he was "thunderstruck" when he first saw the magnet lift a chain of rings, each attached to the next by magnetic attraction. He was even more astonished, he says, when a brother bishop moved a bit of iron around on a silver plate by moving a magnet beneath it. He was puzzled to find the loadstone, unlike amber, would not move straw, making a clear differentiation, therefore, between electricity and magnetism. He also wrote that he had read that diamonds made magnets work less well, but had not seen checked this himself.

St. Augustine actually used these magnetic phenomena to defend miracles -- skeptics were always saying claims of miracles were false, because they couldn't be explained, well, magnetic attraction couldn't be explained either.

Unfortunately, St. Augustine was both good news and bad news for progress in E&M. He also said:

"Nor need we be afraid lest the Christian should be rather ignorant of the force and number of the elements, the motion, order and eclipses of the heavenly bodies, the form of the heavens, the kinds and natures of animals, shrubs and stones ... It is enough for the Christian to believe that the cause of all created things, whether heavenly or earthly, whether visible or invisible, is none other than the goodness of the Creator, who is the one true God."

The Dark Ages

Over the next thousand years or so, very little progress was made, with the important exception of the discovery of the compass and its use in navigation. Gilbert states that it was brought back from China by Marco Polo (which would have been in 1292), but it was definitely known and used in Europe before that time. Benjamin gives a quote (p 129) from the English monk Neckham (1157-1217) describing its use (there's a clearer Spanish quote, but from 1263, order of Alfonso X of Castile, on p 111). Benjamin's own rather romantic theory is that the compass came to Europe with the Finns, who were part of the Mongol peoples who originated in Central Asia, so maybe the same group took the secret to China. The first documented description of the compass in China is in 1297 (p 189) but there are claims that it had been known for centuries there, and that there were "south pointing carts" presumably with built-in compasses, thousands of years earlier. Unfortunately, in 200 B.C. or so the emperor destroyed all books and killed the scholars, so that earlier tales wouldn't detract from his own greatness.

An example of the non-experimental inclination during this period is given by the garlic problem: it was widely believed that garlic weakened magnets. This was first mentioned in Pliny (A.D. 23-79). One theory is that Pliny said no such thing, it was just that someone copying his work wrote "allio" (garlic) for "alio" (other) in a discussion of something affecting magnets, but sailors looking after the compass avoided garlic and onions even into the 1600's as a result.

William Gilbert

The man who began the science of magnetism in earnest was William Gilbert (1540 - 1603) whose book "*De Magnete*" was published in 1600. Gilbert studied at St. John's College, Cambridge, and became England's leading doctor, President of the Royal College of Physicians, and Queen Elizabeth's personal physician. At the same time, he worked on magnetism, and after seeing his book Galileo pronounced Gilbert "great to a degree that is enviable", not the sort of thing Galileo said too often. Gilbert was one of the earliest Copernicans, probably because the Italian Giardino Bruno gave lectures at Oxford in the 1580's. Incidentally, the year *De Magnete* was published, Bruno was burned at the stake in his native Italy because of his beliefs about the universe. Elizabethan England, fortunately, was a less dogmatic place.

Gilbert was the first to understand really clearly that the earth itself is a giant magnet. He constructed a "little earth", *terrella* in Latin, a magnetized sphere of loadstone, and showed by placing a small compass at many points on its surface that both the direction the compass pointed when "horizontal" and the angle it dipped through when "vertical" corresponded with what was observed in corresponding points on earth. From this, he also concluded that measuring the dip could give sailors the latitude. This got him in some trouble, because in fact the earth's field has enough irregularities to make this fairly inaccurate.

Gilbert's interest in the Copernican theory was not unrelated to his interest in magnetism. He thought that the fact that the earth rotated about a line almost exactly through the two magnetic poles could hardly be a coincidence. He also noted that the moon, in going around the earth, always has the same face towards the earth. He wondered if the force between the two might be magnetic, and we always saw the pole attracted to the earth.

(*Parenthetical historical note*: It is interesting to note that another famous person who wrongly thought magnetic forces might play a big role in the solar system was Kepler. He noted that the earth's orbit around the sun was an ellipse rather than a circle, and, he knew the earth was a magnet, with magnetic poles pretty close to the geographic poles (along the line of spin). He also knew this axis the earth spun around was tilted compared to the earth's orbit around the sun, so that sometimes the north pole was closer to the sun and sometimes the south. Putting all this together, and assuming the sun itself was a magnet, he conjectured that for half the year the sun's magnetic force would pull the earth closer to the sun, the other half it would be pushed away, and this would account for the earth's orbit being elliptical instead of circular. This ingenious theory is, unfortunately, completely wrong, but it took Isaac Newton and the invention of calculus to establish that an elliptical orbit was natural for a simple inverse-square gravitational force.)

Gilbert did many investigations of electrical phenomena, using an electroscope which was a light metal compass-like (but not magnetized) needle, balanced on a pinhead at the midpoint. This was much more sensitive than previous work, and he compiled a huge list of materials that could be electrified by rubbing. He also noted that electrical attraction differed from magnetic in that there were no poles in an electrified object. He also noted that, unlike magnetic force, the electrical could be shielded by a sheet of paper.

He argued against the old theory that the attractions were caused by effluvia somehow wafting the air and creating a partial vacuum, because swishing the air around takes time, and the attractions were *instant* if you suddenly moved one object close to another.

He also noted that both electric and magnetic attractions became more powerful as the objects got closer together.

It is remarkable (or is it?) that he failed to find electrical repulsion, and interpreted magnetic repulsion as a sort of preliminary maneuver to get the "right" poles together.

Gilbert's Approach to Science

Perhaps the most important contribution among the many Gilbert made was that he showed clearly how science might be fruitfully pursued, and how empty and futile was much of the work published up to that point, by authors who simply read what other people had written, over centuries, about phenomena, and hadn't bothered to check it. This was part and parcel of the whole attitude of medieval society, a belief in absolute authority, first the church, then including also the old Greek writers, who were very good, but science wasn't their strong point.

On page 77, he writes:

Many modern authors have written about amber and jet attracting chaff and other facts unknown to the generality: with the results of their labors booksellers' shops are crammed full. Our generation has produced many volumes about recondite, abstruse and occult causes and wonders, and in all of them amber and jet are represented as attracting chaff; but never a proof from experiment, never a demonstration do you find in them. The writers deal only in words that involve in thicker darkness subject-matter; they treat the subject esoterically, miracle-mongeringly, abstrusely, reconditely, mystically. Hence such philosophy bears no fruit; for it rests simply on a few Greek or unusual terms---just as our barbers toss off a few Latin words in the hearing of the ignorent rabble in token of their learning, and thus win reputation---bears no fruit, because few of the philosophers are themselves investigators, or have any first-hand acquaintance with things ...

Gilbert goes on to state that investigation uncovers many other substances that will attract chaff, and goes on to show how such electric properties can be more sensitively detected using an electroscope -- an important advance in experimental technique.

So what Galileo did at almost the same time for the science of projectiles Gilbert did for electricity: he got people away from poring over obscure old books, to checking out phenomena for themselves. In writing up his own work he explained clearly what he did so that it was all open to confirmation by others.

It would be nice to report that no-one writes books any more in which long or learned-sounding words are used to obscure a lack of real content, but at least there aren't too many recent books of that type on electrostatics.

Otto von Guericke

Otto von Guericke (1602-1686) was the Burgomaster of Magdeburg, Germany for thirty-five years. He was a lawyer, mathematician, engineer and politician, who spent a lot of time doing experiments. He invented the air-pump (in about 1650), because he was interested in astronomy and knew the planets move through an airless space -- a vacuum -- and he wanted to try to reproduce that environment on earth. He succeeded in building a pump and pumping the air out of various containers. He demonstrated the pressure of the atmosphere by using his pump to create a partial vacuum between to copper hemispheres fitted together (but not bolted together), and showing that teams of horses couldn't pull them from each other, but when he opened the tap to let air in, they just fell apart. Actually on his first attempt at this demonstration, one copper hemisphere collapsed as the air was pumped out, and he realized it had been made unevenly, with a flat part that couldn't take the outside atmospheric pressure.

What interests us here is that he also thought that gravitational attraction was electrical in nature, and in place of Gilbert's magnetic little earth (*terrella*), von Guericke made (in 1663) an electric one, a sphere of sulphur (about the size of a child's head, he says) with a wooden rod through the middle, the ends of the rod resting on supports so that the sphere is easily rotated. If it is then rotated and rubbed, it is found to attract chaff, feathers, etc. He also found that once a feather had touched the globe, it was repelled, and he lifted the globe by the rod through its middle and chased a charged feather around the room, keeping it aloft by repulsion, and, suitably guiding it, was able to get it to land on a pointed object, such as a nose.

Much later (in 1734) Du Fay repeated this experiment and proposed an explanation for what he termed "the caprices that seem to accompany most of the experiments on electricity." He noticed that "leaf-gold is first attracted by the tube; and acquires an electricity be approaching it; and of consequence is immediately repell'd by it. But if, while it is thus sustained in the air, it chances to alight on some other body, it straightway loses its electricity; and consequently is re-attracted by the tube, which, after giving it a new electricity, repels it a second time; which continues as long as the tube keeps its electricity." The same effect was seen and analyzed a little later by Franklin.

It is important to note that with his rotating sphere von Guericke had invented the first electrical *machine*. (He also observed *electrical conduction*, by noticing that a thread over a yard long attached to the globe would show electrical attraction at its far end.) This type of machine rapidly became the standard way of producing electricity, and remained so for over a century, the sulphur ball replaced by large glass cylinders or spheres supported on wooden frames, and with a piece of leather or other material to do the rubbing. The charge on the cylinder was often transferred to a large metal object, such as a gun barrel.

A Jarring Event

By 1746, these machines had improved sufficiently to be dangerous. Pieter van Musschenbroek, a physics professor at Leyden, Holland, tried storing the electricity in a jar filled with water, with metal foil around the outside. This arrangement is still called a *Leyden jar*. When he touched both inside and outside of the jar at the same time, to see if electricity was indeed being stored, he writes that he thought: " .. it was all up with me .." and he would not repeat the experiment if offered the whole kingdom of France.

Naturally, such a dramatic experiment was widely copied, and improved upon when it was discovered that people could be shocked in pairs, and even in chains. A French academician, Le Monnier, shocked 140 courtiers in the presence of the king, and writes; "It is singular to see the multitude of different gestures, and to hear the instantaneous exclamations of those surprised by the shock." They also tried adding side-chains of people, but found those on the side didn't feel the shock -- an early example of electrical *circuit* theory!

Benjamin Franklin

Benjamin Franklin (1706-1790), born in Boston, was the first American to make major contributions to science. In 1747, he suggested that Du Fay's hypothesis that there were two types of electricity was unnecessarily complicated. He observed that all these shocking phenomena could be consistently accounted for assuming only one electrical fluid, as explained in the following extract from one of his letters:

THE ONE FLUID THEORY OF ELECTRICITY

1. A person standing on wax, and rubbing a tube, and another person on wax drawing the fire; they will both of them, provided they do not stand so as to touch one another, appear to be electrified to a person standing on the floor; that is, he will perceive a spark on approaching each of them with his knuckle.

2. But if the persons on wax touch one another during the exciting of the tube, neither of them will appear to be electrified.

3. If they touch one another after the exciting of the tube and drawing the fire as aforesaid, there will be a stronger spark between them than there was between either of them and the person on the floor.

4. After such a strong spark neither of them discover any electricity.

These appearances we attempt to account for thus:

We suppose, as aforesaid, that electrical fire is a common element, of which every one of these three persons has his equal share before any operation is begun with the tube. A, who stands upon wax, and rubs the tube, collects the electrical fire from himself into the glass; and his communication with the common stock being cut off by the wax, his body is not again immediately supplied. B, who stands upon wax likewise, passing his knuckle along the tube, receives the fire which was collected from the glass by A; and his communication with the common stock being cut off, he retains the additional quantity received. To C standing on the floor, both appear to be electrified; for he, having only the middle quantity of electrical fire, receives a spark upon approaching B, who has an over quantity, but gives one to A, who has an under quantity. If A and B approach to touch each other, the spark is stronger; because the difference between them is greater. After such touch, there is no spark between either of them and C, because the electrical fire in all is reduced to the original equality. If they touch while electrising, the equality is never destroyed, the fire only circulating. Hence have arisen some new terms among us. We say, B (and bodies alike circumstanced) is electrised positively; A, negatively; or rather B is electrised plus, A, minus. And we daily in our experiments electrise plus or minus, as we think proper. To electrise plus or minus, no more needs be known than this; that the parts of the tube or sphere that are rubbed, do in the instant of the friction attract the electrical fire, and therefore take it from the thing rubbing. The same parts immediately, as the friction upon them ceases, are disposed to give the fire, they have received, to any body that has less.

In fact, the one-fluid theory gives a coherent account of all these experiments in which a spark passes between people or objects. But it does not give a full explanation of electrostatic attraction and repulsion. It is perhaps plausible that a body with an excess of electrical fluid will attract one with a deficiency, as is indeed observed. Furthermore, two bodies, each with an excess of electrical fluid, will repel each other. It is more difficult to understand why two bodies each having a *deficiency* of the fluid will repel each other. Why should *lack* of fluid causes a force? This is explained naturally in our present picture, a two "fluid" model, in which ordinary material contains *both* positive and negative charges, normally in exact balance. The negative charges -- electrons -- are light and mobile, and rubbing together two appropriate materials (such as glass and silk) causes some electrons to transfer from one material to the other, leaving electrical charge out of balance in both materials. Consequently, if either of the two materials comes in contact with a third material, the electrical imbalance will tend to cause a flow of electrons into or out of the third material. However, there are some substances, called *insulators*, which electrons cannot pass through readily. Wax is one example. Franklin's experiments succeeded because he had everyone standing on blocks of wax, so excess electrons could not escape, and a material deficient in electrons was prevented from capturing any. Thus the charge imbalance generated by the rubbing was preserved for a considerable time. (Eventually, charge escapes through the thin layer of moisture that forms on all surfaces if there is any humidity in the atmosphere. This is why electrostatic effects, like sparks, are so much more noticeable in winter, in a heated room, where the air is very dry.)

In a way, Franklin was right -- there is only one *moving* fluid, the electrons, in all these experiments. But what he didn’t realize was that half of the electrical charge in a body, the positive charge in his own notation, doesn’t move around at all, it is fixed in the body. (Actually, when electricity flows through a liquid, as it does in a car battery, both positive and negative charges flow, in opposite directions. But batteries came into the world after Franklin's time.)

Joseph Priestley

Joseph Priestley was born near Leeds, Yorkshire, England in 1733 to strict Calvinist parents. Early in life he rejected the authority of the established churches, and he became a dissenting minister at 22 (many of the facts recounted here are from the *Encyclopaedia Britannica*). He taught at a dissenting academy, classics, literature and experimental science, probably the first educator ever to teach experimental science to schoolchildren. He wrote about government, advocating complete religious liberty. As a dissenter, he was sufficiently fearful of state control to be skeptical of any sort of social welfare legislation, even proposals for a national system of education. His religion evolved to a very broad Unitarianism: he denied the existence of a soul separable from the body, and eventually rejected the divinity of Christ, although he felt Christ was sent as an example of how to live. He espoused the cause of the American colonists, and, later, of the French revolutionaries. All these opinions and convictions made him widely unpopular in England.

Priestley made many scientific discoveries. He lived near a brewery, and became interested in the gas that lay over the liquids in fermentation (carbon dioxide). He manufactured the gas by dissolving chalk in acid, and dissolved it in water to produce "an exceedingly pleasant sparkling water" -- the first manufactured soft drink! He also discovered oxygen in 1774 (although it was named by Lavoisier).

His contributions to electricity came about as a result of his meeting with Benjamin Franklin, in England, in the 1760's and 1770's. (Franklin spent a lot of his time in England, representing various American interests, and even considered making his home there until trouble arose.) Franklin told Priestley about an odd result he had found (in 1775, according to the PSSC book), in that if he charged up a metal can, standing on an insulator, and dangled a small cork near it, if the cork was on the outside of the can, it was attracted to it, became charged and bounced off, in the usual way. However, if the cork was lowered *inside* the can, without touching it, it showed no tendency to move towards the side of the can. Apparently there was no electrical attraction. Priestley gave a brilliant argument as to why this should be so. He recalled that Newton had shown that there is no gravitational force inside a uniform spherical *shell* of matter (hollow on the inside, like a spherical bubble) because if you take any point inside and consider the gravitational attraction at that point towards a small patch of the bubble, this is exactly cancelled by the attraction towards a corresponding patch at the other end of a line from the first patch through the point. This only works because the law of gravity is inverse square: the further away patch is bigger in proportion to the square of the distance, so these factors cancel out. Anyway, Priestley knew this argument of Newton's, and he figured that if there was no electrical force inside Franklin's metal can, there was probably no electrical force inside a perfectly spherical charged can either, and for a spherical can you know that the charges will spread themselves evenly, because one place is as good as another. Therefore, a uniform spherical shell of electrical charge will exert no force on a small charge inside it, just like Newton's gravity shell, and it is hard to avoid the conclusion that this means the force between charges has the same dependence on distance as the gravity force, that is, it goes as the inverse square.

The inverse square nature of the electrical force was confirmed by Charles Coulomb in 1785 by a direct measure using a torsion balance of the force between two charged conductors.

Priestley ended his days in America. On the second anniversary of the Fall of the Bastille (July 14, 1791) there was mob rule in Birmingham, England where Priestley was then living. They burned down his house, his church and his laboratory. He escaped in disguise. He eventually settled in Northumberland, Pa.

Priestley and Jefferson

(Reference for this section: *Thomas Jefferson, Statesman of Science* by Silvio Bedini, Macmillan, New York, 1990, pages 284,285. Cultural remark: note from the description on page 288 that Jefferson's own religious views appear essentially indistinguishable from Priestley's.)

(*from the above reference*) Jefferson had long been contemplating the prospect of a new state university ever since he had made his famous revision of Virginia's laws to reform its educational system. Although his plan to import the faculty of the College of Geneva to Virginia had failed, Jefferson continued to be concerned about the state of higher education in Virginia. He had originally proposed that the College of William and Mary could be revitalized if moved to Albemarle County and modernized. This met with great opposition from those who were concerned with its Episcopal tone so that nothing had come of the proposal.

He was ready to try once more, and consulted with Dr. Priestley for assistance in setting up a science curriculum. When Dr. Priestley, discoverer of oxygen, whose experiments with electricity and gases brought him great renown, left England in 1794, he had established himself in Pennsylvania. However, the persecution which had forced his departure followed him, as Federalists labeled him "atheist" and "Jacobin."

To Priestley, Jefferson described the College of William and Mary as "just well enough endowed to draw out the miserable existence to which a miserable constitution has doomed it. It is moreover eccentric in its position, exposed to bilious diseases as all the lower country is, & therefore abandoned by the public care. as that part of the country is in a considerable degree by its inhabitants."

His plan was to establish a university in upper Virginia where a healthier location prevailed, and which would be more centrally located in the state. It was to be designed on a liberal and modern plan so that it would attract students from other states as well. To achieve this, it was necessary to develop a good curriculum which included "a judicious selection of the sciences practically grouped together in an institution meant chiefly for use." He felt no one was as familiar with subjects to be taught as Priestley, and for that reason requested his cooperation. He again consulted Priestley about the teaching of languages, which Jefferson did not consider essential in teaching the sciences except as they might be useful in studying them.

"The Gothic idea that we are to look backwards instead of forwards for the improvement of the human mind," he confided to Priestley, "and to recur to the annals of our ancestors for what is most perfect in government, in religion & in learning, is worthy of those bigots in religion & government, by whom it has been recommended, and whose purposes it would answer." Priestley promptly forwarded his "Hints Concerning Public Education."

Galvani and Volta

The material in this section is largely based on the extracts from Galvani's and Volta's work in *A Source Book in Physics*, by W. F. Magie. I have also used the account in *From Alchemy to Quarks*, by Sheldon Glashow, Brooks/Cole 1994.

Luigi Galvani (1737-1798), a doctor and anatomy professor at the University of Bologna, no doubt routinely spent a lot of time dissecting animals. He also had in his laboratory an electrical machine, which charged up a conductor some distance away, which he was using in some electrical researches. One day (around 1790) one of the people working in the lab noticed that on touching a freshly dissected frog's nerve with a metal scalpel, the frog's leg twitched violently, and this occurred if the electrical machine was sparking at the same time. Further investigation revealed that the twitching only occurred if the scalpel (which had a bone handle) was held in such a way that the person holding it was touching the metal part. If the scalpel was replaced by a glass rod, nothing happened, if by an iron rod, the twitching always occurred when the electrical machine sparked.

Having established that the frog's legs twitched in response to electrical stimulation from a machine, Galvani wondered if they could be used to detect atmospheric electricity, possibly even when thunderstorms were not present. Therefore he hung prepared frogs with a brass hook through the spinal cord to an iron railing enclosing a garden at his house. He found twitching did occur, but it didn't seem related to thunderstorms. " ..showed the usual contractions not only when there was lightning but also when the sky was clear and fair, I thought the origin of these contractions might be found in the changes which nevertheless were going on in the atmospheric electricity." But the contractions were few and far between. "Finally, tired of this useless waiting, I began to squeeze and press the hooks which were fastened in the spinal cord against the grating, to see whether such an artifice might excite the contraction of the muscle .." It did! He "quite often" observed contractions on pressing the hook, and it didn't seem to depend on the weather at all! He thereupon decided that maybe his assumption that the twitching was caused by atmospheric electricity was wrong. As Galvani writes, *"So easy is it to deceive oneself in experimenting, and to think that we have seen and found that which we wish to see and find."*

So he moved indoors, laid the animal on an iron plate, pressed the hook which was in the spinal cord against the plate, and, as he says, "behold, the same contractions, the same motions!" He found consistent results from day to day. He also found that if the brass hook was replaced by an iron hook, the contractions either did not occur or were very small. For some weird reason, it was apparently important to have *two different metals.* He found zinc and brass to be very effective.

He concluded that since the contractions (or twitching) occurred with no electrical machine present, and indoors away from possible atmospheric electricity (and in any case on a calm day), "possibly the electricity was present *in the animal itself*" (my italics).

Of course, Galvani had stumbled on to something important: the nerves *do* transmit messages from the brain to muscles using electrical impulses. But he believed the electricity was somehow life itself -- and his nephew, Giovanni Aldini, was a real showman. Aldini was awarded the Copley Medal of the Royal Society for apparently reanimating a decapitated felon using an electrical discharge.

(Teaching note: as Andy Jackson pointed out to me, Mary Shelley's Frankenstein was inspired by Galvani, and talks about his work in the preface. Andy did a joint unit on this with the English teacher.)

Alessandro Volta (1745-1827) became a professor of physics at the University of Pavia in 1779. He repeated Galvani's experiments, confirmed his results, but came to a different, and startling, conclusion. It might be relevant to mention that both men were in an area recently taken over by Napoleon, Galvani's sympathies were with the old regime, but Volta threw in his lot with the French. Possibly during this period animal electricity seemed like an old superstition -- Mesmer's animal magnetism had been discredited not long before. Anyway, Volta set out to find a non-mystical explanation.

To appreciate how clever Volta was, it is important to bear in mind that the whole development of the science of electricity up to this point had consisted of more and more efficient ways of collecting the "electric fluid" from "electric materials" such as amber, glass, etc., and storing it in metals or Leyden jars. The *metals* were called *non-electric* materials -- you couldn't build up a charge by rubbing a piece of metal, the metals were considered passive in electricity, they were handy for transferring electricity from one place to another, but didn't generate it.

Volta repeated Galvani's experiments, and in particular noticed that, as earlier noted by Galvani, the twitching, indicating presence of electricity, occurred when two different metals, each touching the other, had their other ends touching the frog. In contrast to Galvani, however, Volta didn't believe the animal itself was the source of the electricity. But that presented the tough question of *where* the electricity could possibly be coming from. There were no "electric" materials present! In fact, he had few options. The effect was there with just two bits of wire -- one iron, one brass -- and the frog. If it wasn't coming from the frog, it had to be coming from the two pieces of wire. But he couldn't get a spark -- the real indicator of electricity -- from the two pieces of wire.

This is where he made the great leap forward. Having decided that the animal nature of the frog was irrelevant, he took two metal strips (following Galvani, he chose zinc and brass) with cardboard soaked in saltwater between them (more convenient than frog), and to intensify the effect, piled as many as *sixty* of these sandwiches on top of each other. When he placed a conductor from one end of this "battery" (as he called it) to another, it *did* produce a spark -- much feebler, he admitted, than that from a Leyden jar, but definitely a spark, and, unlike a Leyden jar, you didn't have to recharge this battery -- you could keep retouching the conductor and it continued to spark.

He also constructed what he termed a "crown of cups" a row of (nonmetallic) cups filled with brine, a wire joining a strip of brass in each cup to a strip of zinc in the next, to form a chain. This gave essentially the same results as the pile of plates.

Thus Volta invented the battery, which, in contrast to the electrical machines previously developed, provided electric charge in really large quantities, and initiated most of the technological developments that have changed the world so much since that time. However, Volta himself apparently did not go on to investigate the consequences of a continuous source of electrical charge. In fact, his writing gives the impression that he never used the battery to provide a steady current -- in comparing it to a Leyden jar he calls it "a battery of an immense capacity; but which further infinitely surpasses the power of those batteries (Leyden jars) in that it does not need, as they do, to be charged in advance by means of an outside source; and in that it can give the disturbance every time that it is properly touched, no matter how often."

In 1801, Volta was invited to Paris to give three lectures, with demonstrations, on his work, and Napoleon attended them all (Glashow, page 312). Napoleon said that the experiments should be carried out on a larger scale, and later, when Casvy at the Royal Institution in London had a voltaic pile with 2,000 units, Napoleon ordered that piles be constructed at the Ecole Polytechnique, including one bigger than anybody else's.

Electrolysis in England

The above quotation from Volta comparing his pile, or battery, to a Leyden jar, is from a letter he wrote from Como on March 20, 1800, to Sir Joseph Banks, then president of the Royal Society. Sir Joseph showed the letter to William Nicholson, a wealthy London businessman who published his own science journal. Nicholson and a friend of his, Sir Antony Carlisle, a surgeon, wasted no time: on April 30, they constructed a Voltaic pile using 17 silver half crowns, zinc plates and pasteboard soaked in salt water.

They felt the mild shock, but saw no leaf separation when the pile was connected to a gold leaf electroscope. However, they were able to establish the presence of electrostatic charge by some ingenious mechanism called a doubler. (This may have been a variable capacitor of some kind: for example, if two very close large parallel plates are connected across the electroscope, on pulling the plates apart the voltage will increase and the leaves diverge.) They went on to see if they could still feel the shock if they connected the two ends of the battery with various substances, and verified that the electricity was indeed able to shock them through metals and a short path through salt water, but not through glass, etc.

Here they made an important discovery. Nicholson writes: " ... the contacts being made sure by placing a drop of water on the upper plate, Mr. Carlisle observed a disengagement of gas around the touching wire. This gas, though very minute, evidently seemed to me to have the smell afforded by hydrogen..." They realized that the electricity must be decomposing the water, which they knew to be a combination of hydrogen and oxygen. They also realized that the oxygen would be more difficult to see, because it combined with the metal to form oxide. A week or so later, they set up an experiment with 68 sets of plates in the pile, connected to two platinum (and so noncorroding) wires under water, with inverted tubes filled with water set over the wires. They ran the experiment for 13 hours, and found the gas on one side displaced 72 grains of water, that on the other 142 grains -- so these are measures of volume. It was already known that by volume two parts of hydrogen combine with one of oxygen to make water, so their decomposition was quantitatively confirmed. The work was published in July, naturally with no trouble, in Nicholson’s own journal.

They also noticed that the decomposition of the water wasn’t the only chemical reaction taking place. In the battery itself, the zinc was being rapidly oxidized. In fact, they note with "some surprise" that on looking back at Volta’s account of his work, he fails to mention this. Perhaps this was because Volta never allowed a steady contact to be maintained, so a steady current would flow, but simply drew a series of sparks (?).

The Royal Institution

After the experiment of Nicholson and Carlisle described above, most of the important British work in understanding electricity took place at the Royal Institution in London. The Institution was founded in 1799 by Count Rumford, who was born Benjamin Thompson in Woburn, Massachussetts in 1753, and indentured to a Salem merchant at age 13. Over the next few years (info from Glashow’s book), he learned some science on his own, became a schoolmaster, became a major in the New Hampshire militia and at the same time a spy for the British. He left rather hastily in 1775 for a job in London.

Rumford’s major achievement as a physicist was to establish that heat was *not* a fluid that flowed from hot bodies to cold bodies, and that could perhaps be shaken out of matter by friction or chemical effects. He proved that heat could be produced in indefinitely large amounts by friction, specifically by grinding or boring a gun barrel. This convinced him it couldn’t be some fluid being squeezed out of the matter, as many thought, for how could the matter hold an indefinitely large amount? He decided instead that heat was a matter of *motion* of the microscopic constituents of matter, a view we now know to be correct.

Rumford was a royalist, he didn't believe democracy was a good idea, but he did believe that the royal rulers were bound for trouble if the people were not treated reasonably well. He worked for some years in the kingdom of Bavaria, where he took the homeless from the streets, giving them food and shelter and setting them to work manufacturing military equipment. He reformed the Bavarian army, schooling the soldiers and increasing their salaries.

Rumford was a real inventor: in his attempts to keep the army reasonably happy he discovered that trapped air was the crucial element in effective warm clothing, and invented thermal underwear. He also invented the drip coffeepot, the Rumford stove and the pencil eraser (info from Glashow's book).

Quoting now from J. D. Bernal's *Science in History*, "Returning to England he saw at once that the Industrial Revolution could not be a success unless there were some means of training a new type of mechanic who could base himself on science instead of blind tradition. For that he persuaded the wealthy to put up the money for an institution under royal patronage for:

....diffusing the Knowledge and facilitating the general Introduction of useful mechanical Inventions and Improvements, and for teaching by Courses of Philosophical Lectures and Experiments the applications of science to the common Purposes of Life."

This Royal Institution was founded in 1799, and its first director was a young Cornishman, Humphry Davy. Davy was a great showman, but did not consider common mechanics worthy of his brilliance, so the Institution rapidly evolved to presenting lectures for the wealthy, who paid to attend. In Rumford's original plan, there had been a back door through which the poor could access a balcony to hear the lectures from a distance for free. Davy had it bricked up. The Institution did, however, perform a very valuable function in that it was a subsidized science lab (one of the very few in the world) where Davy was able to make many important discoveries in electrochemistry, using very large voltaic piles to electrolyze soda and potash, for example, which had been considered to be elements up to that time. He discovered sodium and potassium, as well as other elements. Davy also invented the electric arc lamp, which was to be the brightest light for a century or so, and a miner's safety lamp for working in gassy mines.

Cultural note from Bernal (p 540). In Davy's introductory discourse as director of the Royal Institution in 1802 (at age 23):

The unequal division of property and of labor, the difference of rank and position amongst mankind, are the sources of power in civilized life, its moving causes, and even its very soul.

Although Rumford was certainly a Tory, this might have been a bit much even for him (but I'm not sure -- he did quarrel with his co-organizers, and left for the continent about this time. He subsequently married Lavoisier's widow). Davy's philosophy certainly did not accord well with Michael Faraday's views on life, and the two had a very tense relationship over many years.

Michael Faraday

Books: a good account of Faraday's life and work begins on p 129 in *The Great Scientists*, Jack Meadows, Oxford 1994 (paperback).

See also Glashow, and *Great Experiments in Physics*, Morris Shamos, Ed., Dover 1987.

Michael Faraday was born in 1791 near London. His father was a blacksmith from the North of England, who moved looking for work at a time of depression. The father had health problems that made work increasingly difficult, so the family was very poor. Young Faraday became an errand boy for a bookbinder and bookseller. Then at age 14, he apprenticed to learn the trade. He read a great deal, and in particular was fascinated by science books. He joined a science club that met weekly. In 1812, one of the bookshop's customers bought him some tickets for Davy's lectures at the Royal Institution.

To be continued …

Book list

1. *De Magnete*, by William Gilbert, London, 1600. Dover reprint (in English!) available.

2. *Opticks*, Sir Isaac Newton, London, 1730, Dover edition available.

3. *A History of Electricity*, by Park Benjamin, Wiley, NY, 1898.

4. *A Source Book in Greek Science*, Cohen and Drabkin, Harvard, 1966.

5. *A Source Book in Physics*, Magie, Princeton, 1935.

6. *A History of Electricity*, Canby, Hawthorn Books, NY, 1963.

7. *History of Western Philosophy*, Bertrand Russell, Allen and Unwin, 1957.

8. *A History of Science*, Dampier, Cambridge 1929 (but 1989 paperback available).

(Note in this last, remark p 33 that Aristotle didn't understand density - no-one did before Archimedes - like acceleration, if Aristotle didn't get it, students most likely haven't got it either.)

9. On Galvinism: *The Ambiguous Frog* sci eng QP341. P4713 (1992)