SCOPE, SEQUENCE, and COORDINATION

A National Curriculum Project for High School Science Education

This project was funded in part by the National Science Foundation. Opinions expressed are those of the authors and not necessarily those of the Foundation.

SCOPE, SEQUENCE, and COORDINATION

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Student Materials

Learning Sequence Item:

943

Electric Charge and Static Electricity

March 1996
Adapted by: Bill G. Aldridge, Arthur Eisenkraft, Tom Ivy, Lois Range, and Ragan Spain

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Contents

This micro-unit was adapted by: **Bill G. Aldridge** (SS&C Project Director)**, Arthur Eisenkraft** (Fox Lane H.S., Bedford, N.Y.), **Thomas Ivy** (Lee H.S., Houston, Texas), **Lois Range** (Jefferson Davis H.S., Houston), and **Ragan Spain** (Tarboro H.S., Tarboro, N.C.)

Science as Inquiry

What Is Much Stronger Than Gravity?

You have seen the power of lightning, and you have experienced the shock of touching something or someone after walking on a rug or carpet on a very dry cold day. You may suspect that these are related. And you have already heard the term *static electricity*. But what is it? And how does it happen?

For this activity you need only simple things: a balloon, a piece of fur or wool, and tiny bits of paper.

Tear up a piece of paper into many **very tiny** pieces. Drop them out of your hand, so that they fall onto a wooden or other nonmetallic tabletop. What force pulled them downward to the tabletop?

Blow up the balloon and rub one side of it with the fur or wool. Bring that side of the balloon down toward the paper pieces, but do not allow the balloon to touch any of the pieces of paper. What do you observe?

1. If the balloon can lift a piece of paper up off the tabletop, what can you conclude about the balloon's force on the bits of paper compared with the force of gravity acting on the same bits of paper?

2. The balloon is very small compared with Earth. The force of gravity that holds a piece of paper onto the tabletop is produced by all parts of Earth, with all of those forces from the entire Earth pulling on the piece of paper. Since the balloon is very small, whatever allows it to pull so hard on the bits of paper must not be gravitational; since the balloon has so little mass, the balloon cannot be exerting a strong enough gravitational force on the bits of paper to overcome that of the entire earth. The force must be some other kind and be a much stronger force than gravity. Make up a simple model for what is happening, but do so without any other information or prior knowledge that you *think* you have about electricity.

Student Sheet

Science as Inquiry

Getting a Charge Out of Balloons

How do two charged balloons interact?

You have seen that a balloon rubbed with fur or wool will pick up bits of paper, indicating that there is some force exerted by the balloon on the paper bits that is much stronger than gravity. We also know from experience that when the air is very dry and we walk on a fur or wool carpet and touch a metal object in our home, we can get quite a shock. We call this *static electricity*. But what is static electricity? And how do we know?

Blow up each of two balloons, tie the air inlet on each balloon with a knot, and then tie a string to the knot of one of the balloons. Connect the other end of that string to the ceiling, or if the ceiling is too high, to a horizontal rod attached to the lab bench or table. If a balloon can pick up tiny bits of paper, we use this fact as an operational definition of the ballon being *charged*. Charge one side of the hanging balloon by rubbing that side with fur or wool. Then holding the other balloon by your hand, charge the side of that balloon opposite where you are holding it. Bring the charged side of the balloon you are holding closer and closer to the charged side of the suspended balloon. What do you observe? Now bring the fur or wool that was used to rub the balloons closer and closer to the charged side of one of the balloons. Do the same for the other balloon. What do you observe?

Rub one balloon with one piece of fur or wool, and rub the second balloon with another piece of fur or wool. Then hold the two pieces of fur or wool, and move them closer and closer together. What do you observe? Rub your hands over the region of each balloon where you had rubbed it with the fur or wool. Then again bring the two balloons close together. What do you observe? Rub your hands over the fur which was used to rub the balloons; then bring the fur pieces close together. What do you observe?

Now repeat these same observations, but use plastic wrap instead of fur or wool to rub the balloons. What do you observe? What happens when a piece of plastic wrap used to charge one balloon is brought near a piece of plastic wrap used to charge another balloon? What do those two balloons do when brought near each other?

You have "treated" the balloon by rubbing it with fur or wool. Now try something different. You have probably seen how clothes in a dryer often stick together from what we are told is static electricity. There is even a product you buy to put into the dryer to prevent this from happening. Transparent tape can be made to behave much like clothes in a clothes dryer. Take two lengths of ordinary transparent tape, each about 4 inches long, and tape them onto a wooden or nonmetallic tabletop. When you pull the tape rapidly off the table, you are "treating" it. Pull off each tape rapidly; then holding the ends, one in each hand so that the tape hangs downward, bring the free ends of the tape near one another. What do you observe? How does this observation compare with what you saw when two balloons treated the same way were brought near each other? What happens when one of these pieces of treated tape is brought near a balloon rubbed with fur? Near a balloon rubbed with plastic wrap?

Apply about 4 inches of transparent tape to piece of cloth on the tabletop. But this time, tape another 4-inch strip on top of the other piece of tape. Then quickly pull the two pieces of tape apart. Hold each by an end and again bring the free ends close to each other. What do you observe when the tape is "treated" this way?

1. Without using any terms (that you may think that you have learned previously, like electrons or plus and minus charges), create a model or theory to account for what you have observed in these situations. Feel free to make up names for whatever is being moved from one place to another, if that is what you want to describe, but base your model or theory only on what you have observed so far. See if you can create a model that will make a prediction that you can test.

2. How does your model or theory account for each of your observations, especially the observation when you have rubbed the balloons or the fur with your hands after they were "treated"?

3. Summarize your observations for objects treated the same way and objects treated differently into an empirical law for "charged" objects. At this point, you may take advantage of the definition created by Ben Franklin, and still used today, that rubber rubbed with fur defines a negative charge on the rubber and a positive charge on the fur. Describe your empirical law in terms of objects charged alike or objects charged differently.

4. How do you know that there are only two kinds of electric charge? How would you know if there were more than two kinds? What kinds of observation or evidence would you need? Use your imagination to answer these questions.

Science as Inquiry

Strange Things with Charged Balloons

How do charged balloons interact with uncharged objects?

You have made many observations on balloons, fur, plastic wrap, and transparent tape that have been treated in certain ways to make them "charged" electrostatically. You have observed that there are two kinds of electric charge, and that like charges repel and unlike charges attract.

Inflate a balloon and tie it off so that the air doesn't escape. Rub one side of the balloon with fur or wool. Then check to see if it is charged by observing whether it will pick up tiny bits of paper. When it is charged, bring the charged side of the balloon close to objects like the ceiling, wall, or parts of your body (hair, back, etc.). What do you observe? Put the charged side of the balloon up against the wall so that it is touching the wall. What happens when you let go of the balloon?

You can do the same with transparent tape that has been charged. Tape 4 inches or so along a wooden or nonmetallic tabletop; then quickly remove the tape and bring the free end near your body or near other objects. What do you observe? When you bring the nonsticky side of the tape near a wall of the room and let that side touch the wall, what happens? Try charging the balloon with the opposite charge (rubbing it with plastic wrap) and see how it interacts with the same kinds of objects. Describe your observations.

Now bring the charged side of a balloon close to, and just to one side of, a plastic ruler that is balanced on a curved piece of glass called a "watch glass." What does the ruler do? Make sure that the balloon does not touch the ruler. Try bringing the charged side of the balloon near the opposite side of the plastic ruler. What happens then?

1. Earlier you learned that you could treat an object like a balloon by rubbing it with something like fur and that it became charged. You saw that two objects charged the same way repel and two charged oppositely attract. But what is happening with charged objects being brought near other objects that have not been charged? Why do they do what they do? Expand your theory or model to account for this behavior. Your theory must somehow explain how attraction results no matter which of the two differently charged balloons are brought near the object being attracted.

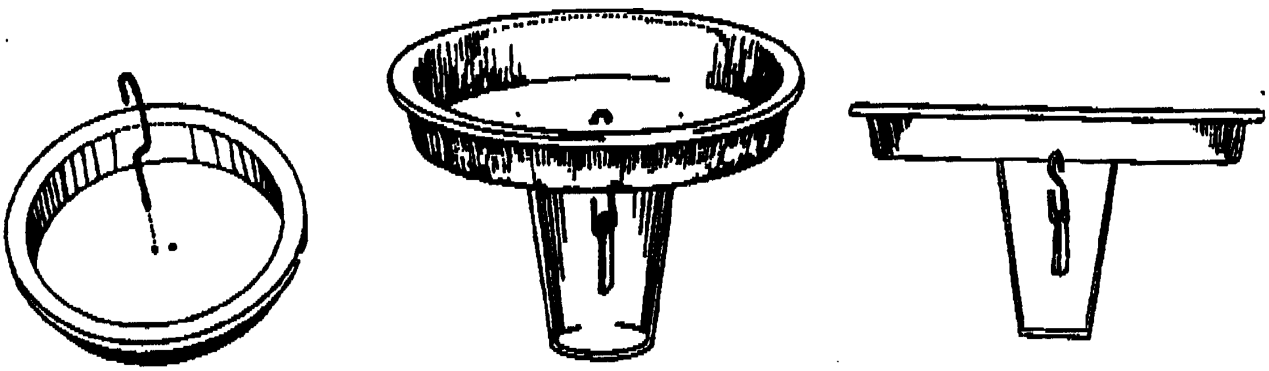
2. Test your theory by bringing the charged side of a balloon near one end of a long narrow piece of aluminum foil. Observe what happens and explain it in terms of your model what you think might be happening in the aluminum foil to account for what you observe.

Student Sheet

Science as Inquiry

The Electroscope: Keep Your Distance

You have been given a metal pie pan, some pieces of aluminum foil, a clear drinking glass, and a paper clip. Assemble these materials to make the device shown below.



Bring a charged rubber rod (or charged side of a balloon) close to, but not touching, the pan. What happens to the strips of aluminum foil hanging from the paper clip inside the glass? Touch the pan with the charged rubber rod. What happens to the foil leaves? When you remove the rubber rod, what happens to the leaves?

Charge a balloon with fur, touch the metal pan, and observe the foil leaves. Then remove the balloon, charge it again, but this time with plastic wrap, and bring it near but not touching the pan. What do you observe? Try bringing the fur or wool near the pan under different circumstances, and after each test, touch the pan with your hand. What kinds of observations do you make? Describe them carefully.

1. Use your model or theory to explain what this device is doing. Such devices are given a name. It is called an electroscope, because it detects the presence of electric charges. Using the electroscope, determine how a piece of transparent tape is charged, plus or minus, under each of the two kinds of treatment (taping to a tabletop and ripping it off or taping one piece on top of another and ripping them apart).

Science as Inquiry

Testing for Conductivity

How can we test for the conductivity of various substances using a simple light bulb and a battery?

Take the wires provided and connect the battery (or Genecon hand-crank generator) to a light bulb. Turn it on to check that it works. Now disconnect one of the wires from the battery and use that end to touch one end of the substance being tested. Use another wire to go from the other end of the object being tested back to the battery. If the thing being tested is just another piece of the same wire, you can see if your arrangement (called a circuit) is correct. If it is correct, the light will turn on when you touch the two ends of the wire being tested.

Now try other substances. Use coins, plastic material, glass, paper, strips of aluminum foil and other metals, and plastics, and for each one indicate whether the light goes on or stays off. If the light goes on, the substance must allow charges to pass through to light the bulb. If not, the substance does not permit charges to pass through. We give a name to a substance that allows such charges to pass through it. Those substances are called electrical *conductors*. Those that do not allow charges to pass through are also given a name. They are called electrical *insulators*.

Now connect one of the wire ends to a piece of aluminum foil that is submerged in a glass of water. Take the other wire and connect it to another aluminum strip in the same glass of water but arranged so that the two strips do not touch each other in the water. What do you observe? Now add the salt to the water and stir gently with a stirring rod. What do you observe now?

1. What can you conclude about various substances in terms of their being conductors or insulators?

2. What kinds of material are almost always good conductors? What kinds are almost always good insulators?

3. Create a model or theory of charges to account for what you have observed. Make up a theory to explain a conductor or insulator. Also modify your theory to explain how water and salt crystals are both insulators, but when together as saltwater the combination becomes a conductor. Do not use what someone has told you, and only make your theory in terms of charges. Use no terms from past experience for which you have no direct evidence.

History and Nature of Science

Benjamin Franklin

“While his electrical work was his greatest scientific achievement, Franklin also contributed to knowledge of heat conduction, storms, the Gulf Stream etc., and invented bifocal glasses, the rocking chair, daylight saving time, and more. He might have done more still, but after he had been working for only a few years on electricity, his country called him to other tasks. He put aside his researches reluctantly and even into his old age kept hoping to return to them.

Franklin’s discoveries were reported in his letters to his English friend Peter Collinson and were published in London in a book, from which the selections (here) are drawn. The results in Letter IV may seem commonplace to a modern physicist where they are not simply confused, but in fact most of this communication was new, startling and highly significant. A few words of explanation may help. The letter deals with a Leyden jar or “phial” filled with water connected to a terminal or 'hook' and coated with conducting foil connected to a wire or 'tail.' Also used are 'electrics,' which we now call dielectrics, such as glass or wax; a 'non-electric' is a conductor. The letter contains the first statement of the Law of Conservation of Charge, the first useful theory of the action of a condenser, and much else. We also give an excerpt reporting the kite experiment.”

Excerpted with permission from *Selected Papers of Great American Physicists* (S.R.Weart, Ed.). New York: American Institute of Physics, 1976.

History and Nature of Science

Experiments and Observations on Electricity, Made at Philadelphia in America

By

Benjamin Franklin, L.L.D. and F.R.S.
To which are added,
Letters and Papers

On

Philosophical Subjects.

LETTER IV.
From
Benj, Franklin, Esq.; in Philadelphia
To
Peter Collinson, Esq.; F.R.S. London

Farther Experiments and Observations in
Electricity
1748

There is one experiment more which surprizes us, and is not hitherto satisfactorily accounted for; it is this: Place an iron shot on a glass stand, and let a ball of damp cork, suspended by a silk thread, hang in contact with the shot. Take a bottle in each hand, one that is electrified through the hook, the other through the coating: Apply the giving wire to the shot, which will electrify it positively, and the cork shall be repelled: then apply the requiring wire, which will take out the spark given by the other; when the cork will return to the shot; Apply the same again, and take out another spark, so will the shot be electrified negatively, and the cork in that case shall be repelled equally as before. Then apply the giving wire to the shot, and give the spark it wanted, so will the cork return: Give it another, which will be in addition to its natural quantity, so will the cork be repelled again: And so may the experiment be repeated as long as there is any charge in the bottles. Which shews that bodies having less than the common quantity of Electricity, repel each other, as well as those that have more.

From pp. 10–34 of *Selected Papers of Great American Physicists* (S.R. Weart, Ed.). New York: American Institute of Physics, 1976.

Chagrined a little that we have been hitherto able to produce nothing in this way of use to mankind; and the hot weather coming on, when electrical experiments are not so agreeable, it is proposed to put an end to them for this season . . . (.)

Questions:

1. Make a diagram of the setup for this set of experiments.

2. Why was the cork sometimes attracted to the metal shot and sometimes repelled?

3. Why was the hot weather less agreeable to performing experiments involved with electrostatics?

4. Franklin was not able to find anything useful for mankind involving electrostatics. What are some useful applications that have since been discovered?

History and Nature of Science

New Experiments and Observations on Electricity

Letter XI

From

Benj. Franklin, Esq.; of Philadelphia
Oct. 19, 1752

As frequent mention is made in public papers from Europe of the success of the Philadelphia experiment for drawing the electric fire from the clouds by means of pointed rods of iron erected on high buildings, etc., it may be agreeable to the curious to be informed that the fame experiment has succeeded in Philadelphia, though made in a different and more easy manner, which is as follows:

Make a small cross of two light strips of cedar, the arms so long as to reach to the four corners of a large thin silk handkerchief when extended; tie the corners of the handkerchief to the extremities of the cross, so you have the body of a kite; which being properly accommodated with a tail, loop, and string, will rise in the air, like those made of paper; but this being of silk is fitter to bear the wet and wind of a thunder-gust without tearing. To the top of the upright stick of the cross is to be fixed a very sharp pointed wire, rising a foot or more above the wood. To the end of the twine, next the hand, is to be tied a silk ribbon, and where the silk and twine join, a key may be fastened. This kite is to be raised when a thunder gust appears to be coming on, and the person who holds the string must stand within a door or window, or under some cover, so that the silk ribbon may not get wet; and care must be taken that the twine does not touch the frame of the door or window. As soon as any of the thunder clouds come over the kite, the pointed wire will draw the electric fire from them, and the kite, with all the twine, will be electrified, and the loose filaments of the twine will stand out every way, and be attracted by an approaching finger. And when the rain has wet the kite and twine, so that it can conduct the electric fire freely, you will find it stream out plentifully from the key on the approach of your knuckle. At this key the philial may be charged; and from electric fire thus obtained,

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From pp. 10–34 of *Selected Papers of Great American Physicists* (S.R. Weart, Ed.). New York: American Institute of Physics, 1976.

spirits may be kindled, and all the other electric experiments be performed, which are usually done by the help of a rubbed glass globe or tube, and thereby the fameness of the electric matter with that of lightening completely demonstrated.

B. F.

Questions:

1. Draw a picture of what Franklin's kite looked like.
2. Why was it necessary that the silk at the end of the twine not get wet?
3. Why was it necessary that the twine not touch the frame of the door or window?
4. Why do both the kite and twine have to be wet with rain before the "electric fire" will flow freely?
5. Explain why this is a particularly dangerous experiment to perform.

History and Nature of Science

Attraction and Repulsion

The soul of amber

Familiarity with static electricity phenomena goes back to early Greek times. Thales of Miletus was aware that a stick of yellow amber when rubbed briskly with wool gives off tiny sparks. Amber is a yellow, hard, fossil resin of ancient pines, found on seashores, and used mostly for jewelry. It was easy to confuse the attractive powers of charged amber with the similar behavior of the long familiar substance, magnetite (Chapter 16). Fascinated with the remote power, some suggested that these special substances may possess a form of life. They draw material to themselves as an animal does when it sucks in breath. Perhaps amber and magnetite have souls. Magnetite could even impart its "spirit" by giving its special property to "dead" iron. Another ancient explanation touted was that electric and magnetic objects move other objects by moving the air in between.

By holding a candle flame near a piece of charged-up amber, the Elizabethan scientist, William Gilbert, showed that the air in between is not involved at all, because he could disrupt air currents at will by heat and observe no effect whatsoever on the attraction exerted by the amber. Better known for his research on magnetism, which we will discuss in Chapter 16, Gilbert also dispelled many superstitions about magnets. It was Gilbert who coined the word "electricity" from the Greek word "electron" for the precious stone, amber. He found at least 20 other substances, besides amber and glass, which acquire electricity when rubbed, and called them electrics. However, a metal like brass did not exhibit any electrical properties after rubbing. It was the first hint of a classification of substances between conductors and insulators. We take the distinction so easily for granted today, but it was quite a major feat, given how small the charges were, and the rapidity with which they would dissipate.

A Machine to Bounce Feathers

In these early stages, the study and scope of electrical phenomena was limited to small charges, easily obtained by rubbing glass or amber. Even ordinary humidity rendered the sometimes remarkable results of early electrostatic experiments irreproducible and confusing. Already famous for his spectacular experiments on vacuum (Chapter

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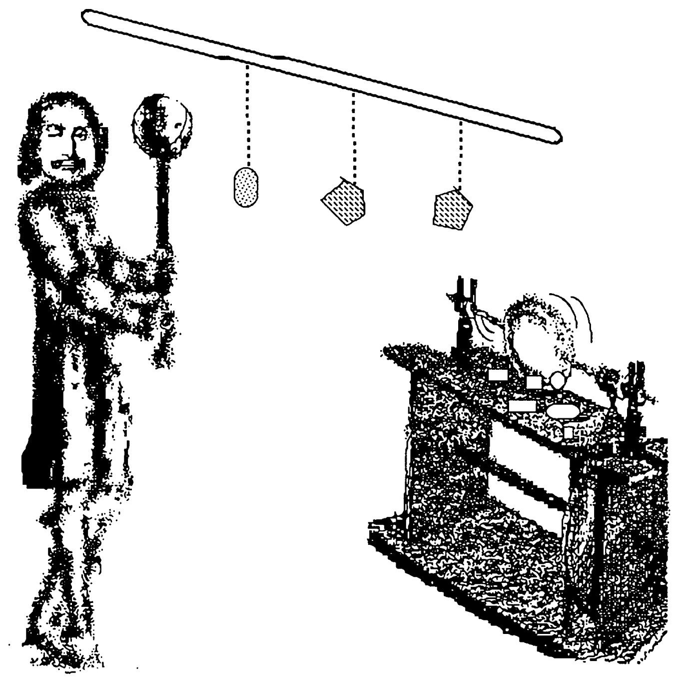


Von Guericke devises a static electricity machine to build up strong charges.

8), the flamboyant mayor of Madgeburg, Otto von Guericke invented a machine to produce strong charges of static electricity, opening the road to fascinating new electrical experiments. (It was the year 1663, only two years before Newton conceived of universal gravitation.) Intrigued by Kepler's suggestion that the sun holds celestial bodies in orbit through the force of magnetism, von Guericke, the avid experimentalist tried to recreate this force by making a sphere of earth. By coincidence, the finished sphere had a substantial amount of sulphur in it. On rotating and rubbing the sphere, he drew a healthy stream of sparks.

Von Guericke launched a century of electrical discoveries. Supporting the sulphur ball with a metal rod like a wheel on an axle, he rotated the ball of sulphur above a wooden table. When he rubbed the spinning ball against his bare hands, he felt his hair rise and got a strong shock when he touched the metal supporting rod. Light objects, like bits of paper lying on the wooden table jumped up from the table towards the sphere.

He used the spinning ball to build up strong charges on various objects. In one experiment, he touched a charged sulfur ball to some bits of paper and cloth hung from the ceiling with silk strings. After contact, he was surprised to find the suspended objects swing away from the charging sulphur ball.

It seemed as though objects were being charged with different types of electricity. In some cases, the charged sulphur sphere attracted them, and in others it repelled them. A feather placed between a charged sulphur ball and the floor would jump up and down between the two. [As we now know, at first the feather (being in proximity to the charged ball) was charged by induction with the opposite charge; hence it was attracted to the sulphur ball. If it acquired the same charge by touching the sphere it would be repelled by it. On touching the floor it would drain its charge and the cycle repeated.]

A Universal Property

Electric charge can move from place to place. When Stephen Gray electrified a long piece of tube at one end, he found that the cork which plugged the other end was also electrified. But it had not been touched by the charging object. So, like a fluid, electricity can flow. How far can charge move? He stuck the longest glass rod he could find through one of the corks, and noted that the charge transferred to the far end. Then he tied pieces of silk strings to the rod. Even as the distances grew immense, the charge continued to find its way to the end of the strings. When the silk threads started to break due to the weights of the long segments, he replaced them with stronger metal wires. But the metal wires could not hold a charge. There was clearly something different about the behavior of metals; it was hard to electrify metals; they belonged to a different class.

Eventually, even metals could be electrified. The right circumstances were demonstrated by Charles Dufay, whose official capacity was gardener to the King of France. When separated from the earth by glass, a metal can also acquire electricity by rubbing. Could electrification be a universal property of all matter?

It also appeared as though there are different kinds of electrical fluid. Two pieces of cork would repel each other when electrified by a glass rod, charged by rubbing with silk. Similarly two pieces of cork repelled each other when electrified by an amber rod rubbed with fur. However, the glass-electrified cork would attract the resin-electrified cork. Dufay concluded that all matter can be electrified and there must be at least two kinds of electricity: resinous (from amber) and vitreous (from glass), and perhaps other kinds too. Although he had no formal scientific education, the chief gardener possessed unusual talents, eventually securing an appointment as a chemist in the Academy des Sciences.

History and Nature of Science

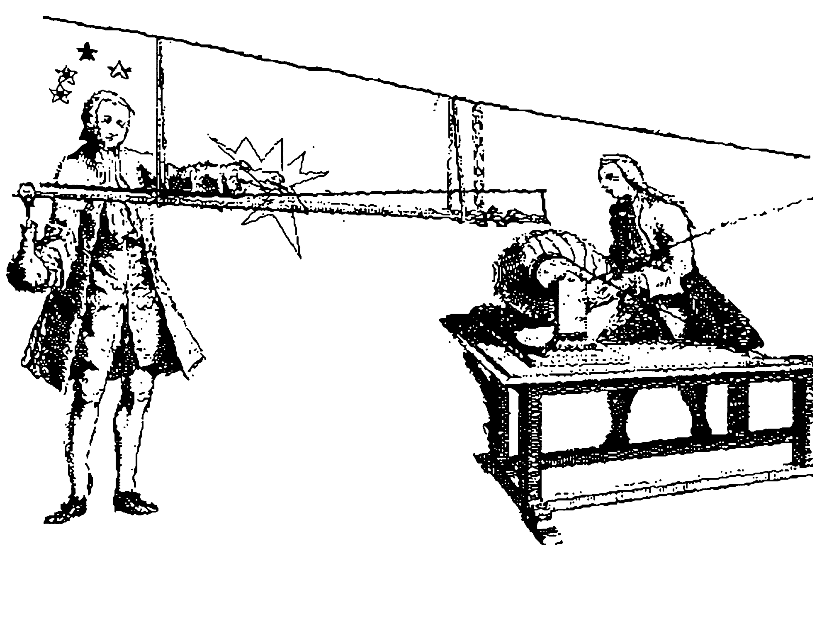
Storing Electricity in the Capacitor

Shocked by a Jar

Static electricity was a fleeting condition. In a short time, especially in humid weather, the charge would leak away from von Guericke's sulphur ball. By providing a method to store electricity, the leyden jar played an pivotal role in the rapid evolution of electrical science.

While experimenting with the electrical properties of water, in 1746, Peter van Musschenbroek, a Professor of mathematics and natural Science at the University of Leyden received a very nasty shock. Musschenbroek was using von Guericke's static electricity generator to charge up a beaker of water, which he held in one hand. A gun barrel, hung from silk threads was rubbing against the rotating sphere. At the end of the barrel was a wire, which he immersed into the jar of water. While the machine ran, he touched the barrel with the other hand, and received a severe shock which intimidated him so much that nothing in the world would tempt him to try such an experiment again.

Judging from the powerful shock delivered, it appeared that the water-filled jar could hold more electricity than any object of the same size. Somehow, electricity accumulated in it. Perhaps the electric fluid condensed in the water.



After storing up a large quantity of charge in a jar, Musschenbroek gets a nasty shock.

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Fortunately, Musschenbroek's students were not as terrified. Together with their teacher, they developed the reservoir idea into the leyden jar. They covered the outside of a water filled jar with a metal foil, and closed it with a wooden lid through which a rod of metal was inserted. The metal foil and the metal post became the two terminals. The spark from the discharge across the terminals of the leyden jar jumped over larger gaps of air than anything before. Since there were no quantitative units to accurately describe the strength of the built-up charge or the resulting shock, people started to quote the length of the spark in air. The stronger the charge, the larger the distance over which a spark could form.

Electric Kisses and Other Games

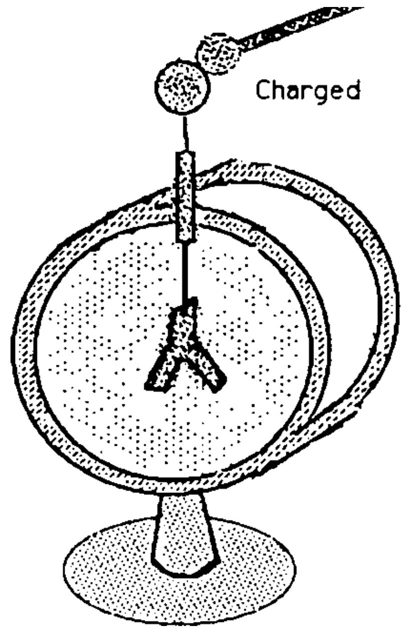
Along with von Guericke's electrostatic machine, Leyden jars soon became common electrical apparatus. In France, the new device provided wonderful court spectacles. In one demonstration, 180 soldiers of the King Louis XIV's guard were made to jump in unison, with a precision exceeding any of their military manoeuvers. 700 monks from the Convent of Paris joined hands while a leyden jar discharged through them. The synchronism of their jumps was more impressive than a corps of professional ballet dancers. But more than a dozen leyden jars hooked up in series proved lethal.

Electrical experiments became the rage of the times. Electric shows travelled around Europe with cart loads of equipment to please the growing crowds. It became fashionable to have electrical shows at social gatherings. In one of the most popular demonstrations, a beautiful girl was suspended horizontally from the ceiling with insulating silk chords and then electrified by a hidden machine. Volunteers from the audience were invited to come up to the stage to steal a kiss from the prone lady, with a shocking result of course. University students complained that they could hardly find any seats at lecture demonstrations as the general public crowded them out. New discoveries in electrical science were hurriedly reported in the popular press, bypassing the traditional method of submission to scientific journals where they could be read and criticized by peers.

Quacks abounded everywhere ready to swindle the believers in the therapeutic powers of electricity. Some even suggested that electrical shock therapy should be applied to allieviate the poor from their misery In one of the most bizarre cults, a Temple of Health in London offered the use of an electrical bed for a childless couple to reverse their fate under the therapy of an electrical charge while they engaged in sex. At the temple, special hostesses who helped out were called the "Goddesses of Health and Hymen".

Inducing Across Empty Space

But the leyden jar was proving to be more than just a source of amusement at parties. The spark it could generate played a pivotal role in chemical experiments. As we saw earlier, Priestley, Cavendish and Lavoisier established the composition of water by exploding a mixture of hydrogen and oxygen with a spark from a leyden jar. (Chapter 11) Priestley used to carry out the sparking of gases inside discarded gun barrels, and Volta, who we will meet in the next Chapter, made glass pistols filled with explosive gases which he triggered with an electric spark. The chemist Berthollet showed that repeated sparking resolves ammonia into nitrogen and hydrogen.



As a quantitative detector of charge, the gold-leaf electroscope played a major role in the advance of electrical science. Because leaves of gold could be made paper thin, a very small charge could deflect them.

Besides the rotating sulphur ball and the leyden jar, another instrument which played a vital role in the evolution of electrical science was the electroscope. The first version, devised by John Canton, consisted of two balls of elder pith, a spongy plant tissue, suspended by separate threads so that the balls touched. When the same charge was transferred to the balls, they separated. Later hanging straws were used, and finally a pair of gold leaves, thinner than cigarette paper. Cavendish added a scale to the device to make quantitative studies.

It was to be a crucial advance in electrical science when Canton identified a new method of electrification, one which involves no rubbing at all. He supported a metal rod by silk threads and brought a charged body near it, but did not touch it. At the end near the charged object, the metal rod showed a charge, as measured by bringing up an electroscope, while the far end of the rod showed the same amount of charge (but of the opposite sign, as we know now). Canton had discovered the method of charging by induction. For the first time electricity was imparted from one object to another, through empty space, without rubbing or contact.

History and Nature of Science

Benjamin Franklin's Electrical Research

A Single Fire

By Franklin's time, electricity had grown into a novel and fascinating subject, judging from accounts of von Guericke's machine and the amusing stories of powerful jolts from the leyden jar. Electrical demonstrations spread to colonial America, where Franklin witnessed his share. But what was this electrical fire? How many different kinds of electrical fluid exist? Such questions fascinated the American. The point of view by his time was that there are two kinds of electrical fluids, or "electrical fire": vitreous and resinous. The scientists of the 18th century had by now concocted many different kinds of imponderable fluids: caloric, phlogiston, ether, electric and magnetic fluids.

Franklin repeated many of the popular electrical experiments. Having read Newton's "Optics" (Chapter 21), he knew that systematic experiments could lead an analytic mind to brilliant discoveries. By emulating Newton's probing approach, Franklin's observations on charging led him to a brand new idea that at once unified the jumble of electrical notions. Electrical fire is not created. It is only collected. All kinds of electricity can be explained by transfers of electric fire.

If all substances can be electrified, the electric fluid must be present in all matter. Each object possesses a natural quantity of electrical fire. If it loses some, it behaves negatively charged. If it gains some, he called it positively charged. With this illuminating perspective, Franklin pioneered the concept that there is just one single fluid of electricity. Electrical fluid merely shifts from one body to another. A charge of vitreous electricity can neutralize a charge of resinous electricity, leaving no charge behind. The two types of charge are not different; they are opposite.

The simplified + and - description was a major breakthrough. It was the obvious explanation for why electricity flows; negative electrical fluid moves towards the positive to restore the natural balance. Underlying the nomenclature of the positive-negative nature of electricity is a fundamental, quantitative principle, the conservation of charge, now a basic law of physics, like the Law of Conservation of Mass. Franklin demonstrated the conservation of charge in a dramatic display. Two volunteers stood on separate insulated platforms. After rubbing a glass tube with a piece of fur, he charged one participant with the glass and the other with the fur. When their fingers came together, a spark flew between them and both were neutralized. The total quantity of charge in the exchange was conserved.

With systematic experiments on the leyden jar, Franklin provided the foundation for a basic understanding of the capacitor, the device which stores electrical charge. By analyzing the distribution of charges in a leyden jar, he showed that the

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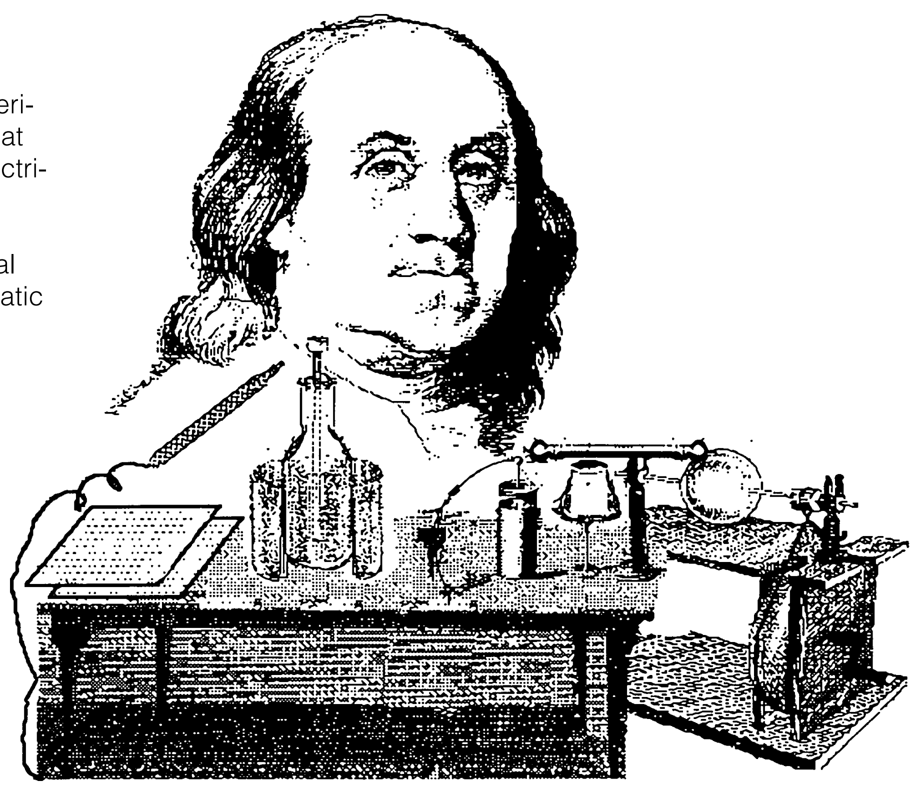
inner conductor is charged opposite in sign to the outer conductor, and that the exact same amount of charge is carried by both conductors. Further experiments revealed that the charge in a leyden jar resides not in the water but in the glass. Carefully removing the water from an electrified leyden jar, he showed that the water gives no shock. On the contrary, the electricity lingers in the glass of the bottle.

Pursuing this useful property of glass to store electricity, he invented the first parallel plate capacitor, a piece of window glass between two sheets of lead. After charging the plates, a violent spark occurred if the two plates of lead approached to touch. If the glass was removed, the metal plates were harmless, but the glass could still emit a series of tiny sparks. It was clear that the essential fire resided in the glass. He could make the storage content of the parallel plate capacitor greater with a thinner plate of glass. By creating a battery of capacitors, 11 panes of glass, all charged together, he accumulated the capacity to store electricity. To describe his capacitor experiments, Franklin added the words charging, discharging and battery to our electrical lexicon. But at the time, the terms all referred to leyden jars (capacitors), not to chemical batteries for which we use the same terms today.

A Brilliant Deduction from a Hollow Tin Can

During his experiments, Franklin made an important discovery about the distribution of charge on an electrified metal can. The charge resides completely on the outside surface. There is zero charge on the inner surface. Soon after



Apart from his famous kite experiment to prove that lighting is an electrical discharge, Franklin made a number of crucial discoveries in static electricity.

Franklin's observation, his friend, Joseph Priestley made a brilliant deduction from this property. The law of electrical force between charged objects must be a law of inverse square with the distance, like the law of universal gravitation. But first he felt it was necessary to verify Franklin's discovery for himself. Using a tin can on a wooden stool, he electrified the can and then gently lowered a pith ball hanging on a silk thread. As the ball approached the can, it was attracted to the outside of the can. However, when he positioned the ball completely inside the can, there was no force on it at all, independent of where in the can the ball was located. The ball was always completely free. Inside the can there was no electricity.

Priestley, who we met in Chapter 11 while discussing research on gases, had migrated to America to escape persecution in England for his radical political views in support of the American and French revolutions. In the New World, he befriended Franklin and wrote a complete text book on the science of electricity.

History and Nature of Science

Benjamin Franklin and the Nature of Lightning

St. Elmo's Fire

Lightning has always been one of nature's most mysterious and frightening phenomena. In his divine wrath, Zeus hurled thunderbolts at those he aimed to punish. When Columbus set out on his historic voyage seeking the fabled spice islands, he sailed the open treacherous ocean for two long months without any sign of land. His crew was about to mutiny. On the same day an ugly storm was brewing. As the sky blackened, there appeared a miraculous sight. A glow of purple streamers filled the air from the tips of the masts, shooting up to heaven. While the crew was still awe-stricken, Columbus seized the moment. St. Elmo, the patron saint of sailors, sent his holy fire as a blessing for their voyage. God commanded that the search for land should not be abandoned.

A popular superstition of the time was that lightning is a diabolical agency acting in storms. The devout rang church bells to drive away the evil destructive forces and prevent harm. Many church bells bore proud inscriptions testifying to the power of the bell in successfully dissipating the effects of thunder and lightning. In the light of these "miracles", the faithful easily forgot how many churches were struck by lightning bolts, and how many bell ringers were killed during storms. Recognizing that over the past 30 years more than 100 bell ringers were struck dead by lightning, the Parlement of Paris passed an edict, in 1786, to ban the practice of ringing bells in a thunderstorm.

Aside from myths and superstition, there were rational explanations offered as well. One among these, rooted in alchemical and phlogistonic thinking, was that fiery vapors accumulate in thunderstorms and burst into flame in the form of lightning. Many experimenters in electricity frequently noticed similarities in the appearance and behavior between lightning and electricity. Even Newton conjectured a relationship.

But Franklin was the first to provide experimental proof for what was merely guesswork up to this point. After listing a large number of intriguing comparisons, he offered a direct experiment to establish the connection. In his early research on the nature of electricity, one of his remarkable discoveries was a special way to drain the charge from objects. A grounded metal rod when brought up to a charged object, could discharge the object without even touching the object (induction). In particular, if the metal rod was pointed, it could drain off the charge far easily, and when placed further away than a blunt rod. (This observation later provided the foundation of Franklin's lightning rod.)

"Electrical fluid is attracted by points. We do not know whether this is a property of lightning. But since they agree in all particulars wherein we can already compare them, is it not probable that they agree likewise in this? Let the experiment be made."

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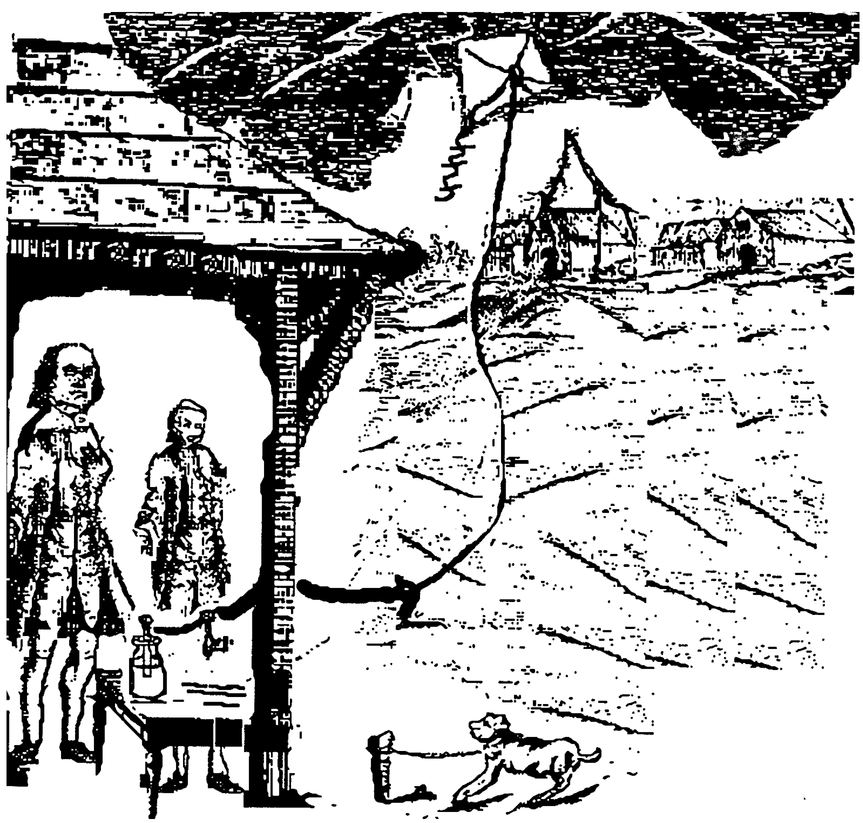
If there is indeed electricity in the clouds, Franklin wished to attract it with a pointed conductor. He devised the sentry box experiment, describing in detail how to tap into the electrical fire of the clouds with a pointed iron rod emerging from a sentry box on top of a tall building, such as a church steeple. An experimenter could stand in the sentry box.

"If the electrical stand be clean and dry, a man standing on it might be electrified and afford sparks, the rod drawing the fire to him from the clouds. If any danger, then let him stand on the floor and bring near to the rod a loop of wire that has one end fastened to the ground, holding the wire by a wax handle so the sparks will fly from the rod to the wire and not effect him."

Before conducting the experiment, Franklin sent his paper to The Royal Society in England, the most prestigious scientific body of the time. But they did not consider the foreigner's idea worthy of publication. Not to be deterred, he announced his proposition in The Gentleman's Magazine. Then he arranged for a 100 foot iron rod to be erected over Christ Church in Philadelphia. But it took a long time to acquire such a tall rod.

Catching Lightning in a Bottle

Meanwhile, at Marly (near Paris), D'Abilliard, an avid reader of Franklin's work, ventured to test the hypothesis. Being unaware of Franklin's



Franklin and his son, snatching lightning from the cloud with his kite and storing it inside a leyden jar.

(mistaken) suspicion that a supreme height would be necessary, he set up a modest, but more readily available, 40 foot iron rod, 1 inch in diameter. The way he insulated it from the ground was rather creative and typically French. He used a wooden plank resting on three wine bottles. What better purpose for empty wine bottles than for a landmark scientific experiment? It did not take long for Nature to provide the desired thunderstorm. The rod gave off electrical sparks and made crackling noises. The prior of Marly, who was first on the scene, drew off the electricity into a small leyden jar.

For the first time man harnessed electricity from the clouds. Here was the definitive proof that lightning involves electricity. It was only 6 years ago that the leyden jar was invented. The crucial device, initially only a source of amusement, now captured nature's awe-inspiring force. As the word spread, many in Germany and England rushed to repeat the experiment. Franklin became famous in Europe.

Before news of the successful sentry box experiment in Paris reached him in America, Franklin was growing impatient to test his idea. After waiting for a long time for the tall rod he originally wished to erect over Christ Church, he finally abandoned the idea, and devised the famous kite experiment. Still believing that a substantial height would be necessary, he strove to reach as high as possible with a kite made from a large silk handkerchief. Near the ground, at the bottom of the twine, he attached a silk ribbon to safely insulate the flier from the electricity in the cloud. At the junction of the twine and the silk ribbon he attached a metal key. In his writings, he warned that the person who flies the kite should stand under cover, so that the protective silk ribbon may not become wet, and so lose its insulation.

Franklin and his son, whom he recruited to help, did not have to wait long for a violent thunderstorm. When the storm reached sufficient force, they launched the kite. Soon the fibers of the hemp cord above the silk ribbon began to crackle as they repelled one another upon charging and spread apart. Franklin received an encouraging spark when he cautiously touched the metal key with his knuckles. He used the key to charge a leyden jar as in the sentry box experiment. Only after personally capturing lightning in a bottle, was Franklin totally satisfied that the atmosphere works with static electricity on a grand scale. The earth and the sky form a giant, charged-up leyden jar, until lightning and thunder accompany their violent discharge.

Franklin unified atmospheric and man-made electricity. By explaining lightning as a discharge of electricity, he tamed one of nature's most baffling and terrifying phenomena with a rational explanation.

Electrocutions

As we know now, both the kite and the sentry box experiments are very dangerous, especially if the precautions that Franklin spelled out are neglected. If the silk ribbon had been soaked, Franklin or his son may have been electrocuted. Young Benjamin Thompson (Count Rumford, whom we met when we discussed the nature of heat) almost killed himself with the kite experiment. Richman in St. Petersburg who improperly performed the sentry box experiment was electrocuted. He insulated his "thunder machine" from the ground, not realizing that it could easily build up a lethal quantity of charge. Even his assistant, who stood nearby, was knocked unconscious. On the ill-fated occasion, Richman was also standing on the floor, not on an insulated stand, as recommended by Franklin. The state of his organs after his gruesome death was described in great detail in scientific publications.

News of the electrical accident spread quickly around the world. The faint hearted viewed it as a warning that Nature's mysteries must be treated with humility and respect. The report probably spared the lives of many amateur scientists who may otherwise have made a fashion out of lightning experiments.

Franklin himself had several personal encounters with danger during his experiments with electricity. The first occurred near Christmas 1750 when he tried to electrocute a turkey for his Christmas dinner. Instead, he took the charge on his own body. The turkey was unharmed! Upon recovering, he remarked that he had nearly killed a "goose" while trying to kill a turkey.

Piercing the Heavens with Sharp Points

In later years, Franklin devised an amusing experiment to signal the passing of charged clouds, and rang a pair of bells located in his study. The first bell was connected with a rod ending in a sharp point on the roof, and the second bell was grounded by a rod going into the earth. In between the two bells, he hung a little metal ball. Whenever an electrified cloud passed overhead, it transferred its charge to the first bell. Charged up by induction with the opposite sign, the ball in between moved to strike the charged bell. On contact, the ball acquired the same charge as the bell and was repelled towards the grounded bell, where the charge drained off to the ground. The cycle could repeat. Franklin just reproduced von Guericke's bouncing feather experiment with atmospheric electricity as his source, and a more dazzling demonstration.

Having confirmed that lightning is a thunderous discharge of electricity in the clouds, much like the discharge of the leyden jar, Franklin lept to the idea of using a lightning rod to divert the potential damage from a lightning strike. Two ways were possible. The pointed rod could disarm a passing cloud, just as it drained charge from an electrified object in the laboratory. As a second possibility, it could conduct the electrical fire from the lightning stroke safely to the ground.

Franklin's valuable innovation was clearly the fruit of pure scientific research, driven by his sheer curiosity about the nature of electricity. In time, the lightning rod stood over many roofs as a symbol of the progress of human knowledge. Here, as a magnificient example was one concrete realization of Francis Bacon's perspective that knowledge and understanding of nature will ultimately lead to control over nature's forces. Could the enhancements of man's power from this intimidating force of nature be far behind?

The use of lightning rods spread quickly. In England and in the American Colonies, the sudden appearance of so many sharp points piercing the heavens caused great anxiety among the superstitious. A dreadful fate lies in store for anyone who tampers with the forces of Nature. Was not Icarus with his wings of feathers and wax justly punished when he aspired to rise up higher than man should go? The sun's heat melted his wings as he fell to his death. When Prometheus stole fire from the heavens and gave it to man, together with the knowledge of how to control fire, Zeus in his wrath inflicted a terrifying punishment. He bound Prometheus to Mount Caucasus and sent a vulture every day to devour his liver, which grew again at night, so the torture could continue for all eternity.

Churchmen openly attacked the use of lightning rods. In New England, a minister even attempted a scientific attack against the sharp points of iron. He warned that drawing electrical fire from lightning to the earth would charge up the earth and lead to terrible earthquakes. One way or another, there could be no escape from the mighty Hand of God. The best that man could do was to seek protection in prayer.

Simliar fears prevailed in Europe and England. People were charged with blasphemy for erecting lightning rods. A popular satirist of the time, Antoine de Rivarol wrote:

"You may distinguish the learned and the superstitious man when it thunders. One seeks protection in sacred relics, the other in a lightning rod."

It took a long time to convince the religious enthusiasts that the Glory of God was not diminished by erecting a thin metal rod on the roof. The success of rational scientific progress vitalized the struggle against religious dogma surrounding nature's secrets. Eventually the religious objections dissipated and even ministers placed lightning rods on their houses. Nearly two centuries earlier, Shakespeare had already captured the changing times in "All's Well That Ends Well":

"They say miracles are past;
And we have our philosophical persons,
to make modern and familiar,
things supernatural and causeless.
Hence it is that we make trifles of terrors,
Esconsing ourselves into seeming knowledge,
When we should submit ourselves to an unknown fear."

Fashionable Parisian hat makers provided a lightning-proof hat for ladies and lightning-proof umbrellas for men with a pointed rod above and a trailing discharge wire that ran down to the ground.

Lightning strikes were an ever present danger to gunpowder arsenals now widespread over Europe. When lightning destroyed a giant arsenal in northern Italy and 200 nearby houses with it, the Italians approached the Royal Society for a way to prevent another such calamity.

At one point there was also a notorious political feud over the exact shape that a lightning rod should have. During the struggle for American independence, King George III reacted against Franklin's rebel tendencies by insisting that lightning conductors at the Kew Palace in England should have rounded knobs instead of Franklin's sharp points. Sir John Pringle, the president of the Royal Society refused to carry out the unscientific royal decree, preferring to resign. A contemporary captured the rival scientific and political exchange with this poem:

"While you Great George, for safety hunt,
And Sharp conductors change for blunt,
The nation's out of joint.
Franklin a wiser course pursues
And all your thunder fearless views."

It is remarkable how little the early study of static electricity was related to any practical need until the invention of the lightning rod. Static electricity was largely a scientific curosity. Certainly there were the intriguing effects of shocks and sparks, which often lent to amusing experiments. Yet it was the mystery of electrical phenomena that drew many like von Guericke and Franklin to study the unfamiliar, without sensing any connection to its possible uses.

Revolutionary, Scientist, and Inventor

Franklin began his scientific work at the age of 40, having previously been too busy earning a living. By the time of the American Revolution, he became one of the world's most distinguished scientists. His book on electricity was published in ten editions in four languages. The Royal Society, which at first rebuffed his sentry box experiment proposal, awarded him a membership and their highest honor, the Copley medal. As a scientist, Franklin is best remembered today for his research into the nature of lightning with the kite experiment, but it was his work on the nature of electricity that was far more influential on the progress of science.

Fame from his political activities came well after his scientific prominence. Serving as the delegate from Pennsylvania to the Continental

Congress, he helped to draft the Declaration of Independence. When he went to Europe to seek military and financial assistance from the French, he became popular in France as the man who led his people to freedom from the shackles of British monarchy and the feudal past. Almost 50,000 French soldiers and sailors left France to assist George Washington in America. After helping to negotiate the treaty with England that recognized the 13 colonies as a sovereign nation, Franklin joined the Constitutional convention to help frame the U.S. Constitution, the bedrock of law in the United States.

Europeans of the period always recognized Franklin first and foremost as a scientist. His gifts as a writer made him one of the most readable and understandable scientific writers of the time. Louis XV was so fascinated by Franklin's writing that he ordered Franklin's experiments to be performed in his presence.

Besides the famous lightning rod, Franklin was responsible for several other practical inventions, most prominently bifocal lenses and the fireplace stove. The Franklin Stove gives more warmth than an open fireplace, in which the hot air is lost as it rushes up the chimney. His idea of daylight savings time made it possible to use sunlight more intelligently and thereby to economise on the use of candles. He established several first of a kind institutions for North America such as a fire company, a library, a hospital and an academy, which eventually grew into the University of Pennsylvania.

When he died, the French, who were at the time in the throes of their own revolution, eulogised him as symbol of freedom and enlightenment. Franklin's epitaph aptly describes the man who:

"snatched lightning from the heavens and sceptres from Kings"