History of Physics Laboratory

Barnard College

VOLTA AND GALVANI: NEW ELECTRICITY FROM OLD

Experiment No. 22

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Contents

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Barnard Columbia History
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SOME DRAMATIS PERSONAE

Franz Ulrich Aepinus (1724-1802)	Professor of Astronomy at Berlin;* later Superintendent of Normal School, St. Petersburg.
Giovanni Aldini (1762-1834)	Professor of Physics, Bologna.# (Nephew of Galvani).
Sir Joseph Banks (1743-1820)	President of the Royal Society,# London.
Joseph Baronio	Physician at the "Ospedale Maggiore", Milan.
Abraham Bennet (1750-1799)	Curate of Wilksworth, Derbyshire,* England. Fellow of the Royal Society.
Ab. Giovanni Battista Beccaria (1716-1781)	Professor of Natural Philosophy,*# Turin.
Luigi Valentino Brugnatelli (1761-1818)	Editor: "Giornale Fisico-Medico",# at Pavia.
Leopoldo Caldini (1725-1813)	Professor of Anatomy, Padua.
John Canton (1718-1772)	English Experimental Philosopher. Fellow of the Royal Society.
Don Bassiano Carminati (1750-1830)	Professor of Medicine, Pavia.
Tiberius Cavallo (1749-1809)	Italian Experimental Philosopher # in London, Fellow of Royal Society.
The Hon. Henry Cavendish (1731-1810)	Eccentric English Aristocrat, Fellow* of Royal Society (London).
Charles August Coulomb (1736-1806)	French Military Engineer, Academician etc., (Paris).
Humphrey Davy (1778-1829)	Professor of Chemistry, Royal Institution (London).
Horace-Benedict De Saussure (1740-1799)	Professor of Physics and Geology,# Geneva.

Giovanni V. M. Fabroni (1752-1822)	Professor of Chemistry, Florence.*
Abb. Felice Fontana (1730-1805)	Director Laboratory of Physics & Natural History, Florence. *
Benjamin Franklin (1706-1790)	Printer, Editor, Electrician, Statesman, Postmaster, etc. etc. *
Luigi (Aloysii) Galvani (1737-1798)	Professor of Anatomy, Bologna.*#
Dominico Maria Gusmano Galeazzi (d. 1775) and Lucia Galeazzi (d.1790)	Professor of Anatomy, Bologna.# President, Academy of Science. - his daughter; wife of Galvani.
Friedrich Albert Carl Gren (1760-1798)	Professor at Hallè (Germany), # Editor, "News Journal der Physik".
Albrecht von Haller (1708-1777)	Professor of Anatomy/Surgery at Göttingen (Germany.
Friedrich Heinrich Alexander von Humbholdt (1769-1859)	German Naturalist, Explorer, Philosophe etc. etc.
John Hunter (1728-1793)	Scottish Surgeon & Physiologist.
Jan (Johan) Ingenhousz (1730-1799)	English Physician & Natural Philosopher. #
Josef Thaddeus Klinkosh (1734-1778)	Professor of Anatomy, Prague. #
Antoine-Laurent Lavoisier (1743-1794)	French Chemist & Natural Philosopher,# Paris.
Pierre-Simon (Marquis de) Lapace (1749-1827)	French Mathematician - Philosopher.#
George Christop Lichtenberg (1744-1799)	Professor of Experimental Philosophy at Göttingen University.
Jean Claude Le Monnier (1715-1799)	Physician to the King of France, Academician. (Paris).
Pieter Van Musschenbroek (1692-1761)	Professor at Leyden, Holland.*

William Nicholson (1753-1815)	English Chemist & Electrician,* Editor of "Nicholson's Journal".
Leopoldo Nobili (1784-1835)	Professor of Physics, Florence.
Abbé Jean-Antonine Nollet (1700-1790)	Preceptor in Natural Philosophy to* Court of Louis XV (Paris).
Christian Heinrich Pfaff (1729-1799)	Professor at Keil.
Joseph Priestly (1733-1804)	Non-conformist Minister & School#* Teacher, Yorkshire, England.
Johannes Wilhelm Ritter (1776-1810)	Experimental Philosopher at Jena and Munich.
John Robison (1739-1805)	Professor of Natural Philosophy, Edinburg.
Ab. Lazzaro Spallanzani (1729-1799)	Italian Naturalist, Professor at Pavia.
Johann George Sulzer (1720-1799)	Swiss Philosopher, member Berlin* Academy of Sciences.
Eusebius Valli (1755-1816)	Physician at Pisa.
Martin Van Marum (1750-1837)	Director, Tyler Museum, Harlem# (Holland).
Ab. Anton Maria Vassali (1761-1825)	Professor of Natural Philosophy,# Turin.
Allesandro Volta (1745-1827)	Professor of Natural Philosophy, University of Pavia (and Como).
John Walsh (1725-1795)	Fellow of Royal Society, London,* (Friend of Ben Franklin).
Johan Carl Wilke (1732-1796)	Professor of Experimental Physics at Military Academy; Secretary of Academy of Science, Stockholm.
Ab. Giuseppe Zamboni (1776-1846)	Professor of Natural Philosophy,* Lyceum of Verona.

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* Quoted in Volta's correspondence/publications.
\# Corresponded with (or personally known to) Volta.

VOLTA AND GALVANI: NEW ELECTRICITY FROM OLD

I. Alessandro Volta (1745-1827)

Pavia or Como in the late eighteenth century was hardly the place one would expect to be the scene of activity which would profoundly transform the science of electricity, and indirectly all science. A century or two earlier Northern Italy had been the home and the vanguard of the new natural philosophy, but since the time of Galileo science had languished, and spread and flourished elsewhere. But if science there was not exactly in full flower, the tradition of scholarship and learning was not dead; and so in 1770, far from the grand centers of science in London, where Henry Cavendish was attempting his profound analysis of electricity, and Paris where Coulomb was preparing for his entry into the academic enterprise, the young Alessandro Volta, at secluded Como in northern Lombardy (now a province of the Austrian dominions), began his modest studies of "The attractive force of the electric fire , and related phenomena". He would continue here, and at the nearby ancient university of Pavia (the old capital of the province, the former Roman Ticinum), for thirty years to explore and experiment with electricity in its numerous guises and manifestations. The climax of his work, his crowning achievement, would be his discovery of what he claimed to be a new sort or source of electricity; and in 1800, his announcement of a spectacularly simple and powerful means of generating it - the electric "Pile".

If Volta worked essentially independently and alone - no daily concourse with academicians or scientific gatherings at the Academy - he was certainly not isolated. Very early in his career he started a correspondence with fellow-scientists, near and far, whom he thought to be interested in his work, to whom he could present - and plead the cause for - his ideas, and from whom he might receive valuable criticism, comment and help. He could find respected and responsive scientists with whom to share his ideas in his own and neighboring universities: the distinguished naturalist, the Abate Giovanni Battista Beccaria, professor at Turin; professor of chemistry Fabbroni at Florence; and later, of course, Luigi Galvani, professor of anatomy at the famous school of medicine at Bologna, whose discoveries were to have such a profound effect on Volta's own work. At first, it is mostly his Italian colleagues, but steadily the circle of his correspondents is enlarged, and eventually includes many of the leading investigators of electricity in Europe. After some years of labour, when his accomplishments have begun to establish for him a reputation in his field, he embarks on a grand tour of the major scientific centers and becomes personally acquainted with many of the scientific elebrities of his day. By the time his career reaches its peak, he is well-travelled, well-known and highly esteemed in the European community of scientists.

It is mainly through his letters to his numerous correspondents (the essential content of these was often published either by Volta himself or the recipient) that we can trace the progress of his scientific work, and many of the influences that shaped it. The accounts of his work which Volta here presents, often quite detailed, are far from the carefully constructed, nicely arranged "memoir" composed after the conclusion of an investigation. The writing is personal, often passionate: hopes, doubts, suspicions, uncertainties and even bewilderment are revealed alongside proud disclosures of new discoveries and fervent advocacy of some new conviction. Correspondence seems to provide Volta with a substitute for the day-to-day converse and argument, for which he lacked opportunity: and in his letters we find a record of what would normally go unrecorded. We see how much he learned from the reports and writings of his predecessors, and how much he hoped to learn from the comments of contemporaries. And what we see above all is that it was experiment - foremost his own experiments - that were Volta's chief teacher, his most demanding critic and his most rewarding guide. Experiment is his true source of knowledge; and the art of the experimenter is to give nature an opportunity to talk, and then transmit, perhaps interpret, what she says.

Alessandro Volta was born in Como in 1745, to a distinguished, patrician, though not grand, family. After a rather slow start, he seemed to have been successful in his studies of physics and mathematics at the local state high school, and at the age of 29 he was appointed professor of physics there. After three years of teaching and research in 1777, he travelled to Switzerland, where be befriended the natural philosopher H. B. de Saussure, in Geneva, and met Voltaire, who made a great impression on the young Volta. He returned to Italy in 1779, was appointed professor of physics in the University of Pavia*, and resumed the electrical researches which were to be his primary concern for more than twenty years.

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*Como is some 30 miles north, and Pavia 20 miles south of Milan.

Apart from occasional travels abroad Volta lived and worked for the remainder of his life in Como and Pavia. He died in his native Como in 1827, where today a museum stands as a monument to him and his life's work.

A portrait of Volta in the attire of Senator, surrounded by his scientific triumphs. At his elbow are the elements of a voltaic pile and a "crown of cups". Behind him, his books, instruments, and a completed pile. The engraving was made shortly after Volta's death. *(drawn by R. Focosi, engr. by Luigi Rados, Milano, 1828, inscription condensed.)*

II. The Old (Ordinary) Electricity

Volta started out, like his contemporaries, with the "received" knowledge of his day, which for electricity meant both artificial electricity - phenomena associated with rubbing of glass or resin with silk and fur, and the more elaborate machines for doing this vigorously; and natural electricity as it occured generally in the atmosphere and was displayed most spectacularly in lightning discharges. Experimentally, the subject was very much as Benjamin Franklin had left it (around 1750); and Franklin's own ideas, and even his vocabulary were prominent and widely accepted. Volta was fully familiar with them. But Franklin's scheme - though it replaced much confusion by order - was only a beginning, far too limited a basis on which to achieve, what was so common an aim in all branches of natural philosophy; integration within the framework of the powerful Newtonian philosophy. There was some order in Franklin's electricity but it was an order to itself. Aepinus, in 1759, had made some first steps to a new scheme which gave electricity a broader and more definitive interpretive basis; but it was only a scheme, without sufficient development to give it detailed interpretive power. Volta was familiar with this work also: and his first publication, a sort of doctoral thesis (1769) in Latin , is an attempt at progress along these lines. But as Henry Cavendish's extraordinary effort (in 1771) showed, not only did progress here demand great powers of abstraction and formal analysis (for which Volta displayed neither taste nor aptitude); it meant also choosing, and restricting the "theorising" to the "cleaner" manifestations of electricity, it meant dealing with electricity as an entity whose existence was taken for granted, and eschewing the details and complexities of how it was generated (or separated). To a degree it meant choosing the phenomena studied to suit the capabilities of the theory.

Possibly, at this stage, Volta is naively innocent of the limitations of any such theories, of the immense chasm that still lay between basic, elementary Newtonian-like principles and all the practical, variegated and arcane particulars of electrical phenomena. In any event the real electricity, comes at its will - clean or dirty - without any respect for what will submit to or defy theory; and Volta, in his early experiments and observations, already becomes involved with such real electricity, the hidden details of the electrification process. He is curious to know just what happens when the silk rubs glass, and why this or that material is particularly effective. He must soon learn how much there is to learn, how unlikely it is that theory will take him - in a single leap - all the way to practical reality. A year or two after his first paper, he writes a supplement to it - again in Latin, but there are already indications of the path he is to take. Analysis and argument yield to experimental probing: there is much to be learned - experimentally - before all can be explained. But experimental observation alone, empiricism without argument, the plain probing of facts, is no more to Volta's taste than abstract theorising. If he has, unwittingly or not, become engrossed in phenomena beyond the reach of the accepted formal theory of his time, and which he himself certainly cannot complete, then he must resort to theorising of another sort: not the grand style of the overall mathematical philosophy, but theorising step-by-step, guided, indeed inspired by, experiment, borrowing where necessary from the vocabulary of established theory, but not hesitating when occasion demands or suggests, to introduce his own concepts, to invent his own vocabulary. This is the path he takes. There are no more Latin dissertations: the vernacular Italian - or occasionally French - is more suited to this, his "experimental philosophy."

Volta's detailed probing of the electrification process in due course bears fruit, and characteristically, his first notable success - in 1775 - is the discovery - perhaps invention would be a better word - of a novel method of generating electricity. It is, to Volta, a sort of perpetuum-mobile of electricity, for in contrast to the conventional generation of electricity by continuous rubbing and removal (if a continuous supply of electricity is required), here there is only a single rubbing of a resinous slab. Once this is electrified, a metal plate, fitted with an insulating (glass) handle, is brought close to the electrified slab, momentarily touched by the finger, and this then removed from the slab, the metal plate shows lively signs of electrification (sparks, shocks, etc.). The plate can be discharged, and then the process of its electrification repeated, once, twice, hundreds of times without any need to rub the slab again or to refurbish its electricity in any way. (The electricity on the plate does not come from the slab, but, in todays terminology, is induced by it. The "inexhaustible" store is in Mother Earth, and it reaches the plate via the momentary contact of the finger.) This instrument, known as the "electrophorus", is still found in the text books of today and used for instructive electrical demonstrations. The explanation of its working, in principle, is dismissed in a few lines using current, elementary, formal concepts. Today's student of electricity, meeting the electrophorus for the first time, might find it clever (for 1775!), perhaps intriguing, but hardly sensational.

But Volta's elation with his discovery is unbounded; although he communicates his excitement and his findings to Joseph Priestly in England:

> "I do not know how to stop talking about the artifice of reawakening the weak electricity...although such a finding is none other than a consequence of theory, it seems miraculous beyond means to whoever is not acquainted with such things."

But theory, explanation and miracle have their own meaning to Volta. Theory - Volta's or any other - did not suggest the invention - whatever role it may have played afterwards. Nor did explanation of the "principle" explain away the whole miracle. There was more to the electrophorus than "principle"; it was to Volta, and still is, a remarkably practical device with surprising "secondary" features. For example, with the plate in position, covering the slab, it can retain its potency for weeks, even months. Then there is the spectacular liveliness of the electricity when the plate is removed contrasted with its docility when in place. With the developed concepts and vocabulary of electricity today (or 100 years ago) it is an easy matter to distinguish the principle - which is then easily explained - and the secondary features which, if not yielding to simple explanation, can be dismissed. But in Volta's time electrical principles and theory - and certainly Volta's own - were far from the stage where such a neat division between explicable principle and complicated (inexplicable?) particulars could be clearly and reliably made. Knowing what is knowable represents a far more complete stage of understanding than the electrical probings of Volta represent. And in any case would Volta have been satisfied by an explanation "in principle"? It was not as a toy nor an elementary demonstration that he regarded his invention; but rather as a new, practical, remarkably useful instrument of research. It performed in practice as well as in principle. So whether by necessity or by desire, Volta, fortunately, could not stop short at the boundary between the clearly intelligible and the puzzling and uncertain, between what could be explained on established principles and what might need inquiry. Inevitably he would trespass beyond this vague, unrecognised boundary; irresistably he would be drawn into territory that was not well chartered by any known principle.

And there was Volta the showman (which electricians weren't?), who wanted, with due modesty, to present his discovery as new, and a little mysterious:

> "And so perhaps I venture to justify the addition of a new term; not without hesitation, since the matter is not treated scrupulously, with full rigour, do I feel that I can give this new effect [fatto] in electricity a sort of nickname - limitless induced electricity [elettricita vindice indeficienti] . And if it does not displease you, I venture to christen my little apparatus, and call it the "Electroforo Perpetuo"."

It is not just a nickname - limitless electricity. Perpetual motion of electricity - the idea, or ideal, perhaps the dream, seems to have entered Volta's mind. It will recur later, and stay with him to the end of his life.

The electrophorus is Volta's first major success; in a few years it is followed by another and the pattern is remarkably similar. He continues his probings, now of how electricity is lost as well as it is acquired. He experiments with an endless variety of materials of all shapes and sizes, suspended by silk cords and resting on the table-top, in dry atmospheres and moist; there is plenty to be examined - and no shortage of puzzles. What theory, for example, can tell him why a flat conductor retains some electricity longer when resting on a partly dried rather than on a well-dried table made of marble of Carrera? "A paradox!...seemingly unbelievable...quite marvelous...enough to pique the curiousity!" he exclaims. And to pique means to arouse, and to arouse the curiosity means to engage all his energies. For many months - perhaps for most of a couple of years - he becomes engrossed with this paradox and all its circumstantial phenomena. What makes some materials conduct electricity and others not? Is there a sharp division between the two classes? No, he decides - it is only a matter of degree: there is a whole continuous range from good conductors ("deferenti" or "conduttori"), poor or "semi-conductors", then poor insulators (his marble is such), and finally non-conductors ("coibenti" or "isolati"). His experimental labors have again yielded him a crop of new words. And once again the climax of this work is a new concept and a new instrument: his condensing electroscope, or "apparrechio ingranditore" - a sort of microscope of electricity.

Again explanation in principle once arrivedat is quite clear, and Volta presents it in his own words. But there are also many variations and complication in practice - as Volta has shown, literally, with his own hands. These must be fully accounted for. Volta's struggle with his "paradox" has taught and impressed upon him, the lesson that what makes electricity perceptable, what makes shocks or sparks or moves electroscopes, is not simply the quantity of electricity but also its tension (or voltage, as we would say!); just as what might pain one's toe is not simply the weight of material that falls upon it, but also the height from which it falls. Now Volta had also learned from his innumerable materials and surfaces that electrification is by no means an uncommon process, especially when large surface areas of different materials rub or make contact with each other. Often, however, the electricity goes unnoticed, not because there is too little of it, but because the tension is too small. What is required to make this "weak" electricity "sensible" is some means of magnifying its tension, "condensing" electricity as he calls it, somewhat ambiguously. To achieve this end, the weakly electrified body is brought into (electrical) contact with another, a test conductor, one not completely isolated, but instead lying close to another large grounded conductor yet insulated from it by a layer of "cohibent" material. The pair form a condenser (we still use Volta's term!) whose capacity, if sufficient, will ensure that the tension of the test conductor remains small, and a sizeable quantity of electricity will flow on it. But then if the test conductor is lifted from its partner (without discharging it, of course), the capacity will decrease sharply, and the tension will rise proportionately - sufficiently to render the electricity now sensible. If the pair of conductors forming the condenser is combined with a simple electroscope, the combination becomes Volta's "condensing electroscope". But there are many variations on this theme, and many problems in the correct choice of the "cohibent" material and its proper use. A favorite form of the "apparechio" is Volta's own gloved hand. The hand provides the large "grounded" conductor, and the material of old oil paintings, it turns out, serves well as the thin layer of insulating "cohibent"!

Volta is proudly delighted with his new instrument, and impressed with its potentialities. His paper (1782) entitled "On the

Method of Rendering Very Sensible the Weakest Natural or Artificial Electricity" opens with almost prophetic statement:

> "It will be readily allowed, that an apparatus capable of rendering perceptible, or, as it were, of magnifying the smallest, and otherwise unobservable, degree of natural as well as artificial electricity, is of the greatest advantage to the science of electricity..."

Fifteen years later, Volta's own work will fully vindicate this judgement. But there are some more immediate - if more modest - rewards and successes. The new technique has already been put to good use in verifying what had for some time been affirmed by some (and doubted by others) that strong signs of atmospheric electricity accompany the appearance of the Aurora Borealis (Northern Lights). Then in 1782, when Volta's first travels abroad take him to Paris, he demonstrates his technique to the eminent French scientist-savants Lavoisier and LaPlace and with them demonstrates that a separation of electricity accompanies the familiar process of evaporation (of water).

Volta has established his reputation as a master of electricity. He has attained his place as a man of the world, of science.

LUIGI GALVANI

III. Galvani's Announcement

By 1790 Volta has been working with electricity, natural and artificial, and demonstrating his power to unravel its subtle manifestations for some 20 years. For the past few years he has also been engaged with his second major interest - chemistry, in particular with the chemistry of gases - a subject very much in vogue at the time. His skill, experience and virtuosity are unquestioned - but are there achievements to match? It is as if he awaits some real challenge to his powers. In 1792 the challenge comes: and Volta moves swiftly to meet it. There is no doubt about the immediate stimulus that started Volta on the intense, unremitting decade of experimentation whose climax was the invention of the pile. It was the receipt from his colleague Galvani of a remarkable account of experiments and observations on the electrical stimulation of dissected animals - in particular frogs.

Luigi Aloysii Galvani (1737-1798) was born in Bologna, studied medicine in the university there, became professor of anatomy in 1762, and married Lucia Galeazzi, the daughter of his own anatomy teacher, Dominico Galeazzi, the distinguished president of the Academy of Science of Bologna. With deep family roots in, and intimate cultural attachment to his native city, Galvani spent his whole life there, practicing medicine, studying and teaching anatomy, and quietly pursuing, and sometimes publishing his anatomical researches in the local "commentarri" of the local Academy.

There was nothing surprising in the subject of Galvani's researches. Speculation and inquiry into the nature of the relationship between muscular response and nervous stimulation was long standing; and the rapid growth of electrical knowledge in the mid-18th century soon drew attention to the "subtle" electric fluid as a naturally attractive candidate for the equally subtle (and elusive) fluid which was presumed to be required to propagate messages along the nerve channels. Italian experimental philosophers were amongst the first to explore this field. Tommasso Laghi in the 1750's at Bologna, where Galvani was a medical student, Beccaria at Turin and later Felice Fontana at Florence had all experimented with the electrical stimulation of particular organs of living and dead animals, and speculated on the role of electricity in normal nerve-muscle responses. Galvani himself had acquired an electrical machine as early as 1780. And it is clear, from his unpublished papers, that he had been pursuing his investigations of the electrical stimulation of dissected frogs for many years before he published his remarkable findings in 1791. What was sensational in Galvani's publication was his demonstration, apparently, of the exact role played by electricity in the animal nerve-muscle system - and the implications of his discovery, if true, for the physiology and medicine of his day. But what immediately struck Volta was the revelation by Galvani of electricity in a wholly new guise.

Galvani's wide experience was in anatomy and physiology, and although he worked with electricity the subject was for him rather alien - even mysterious. His electrical terminology was unsophisticated, even for his day, and he made no pretentions to conceal his limited understanding of what he regarded, as the field of "natural philosophy". When in his characteristically modest manner, he attributes some of his more surprising discoveries to "chance" or "good fortune" he may be doing less than justice to honest, perceptive observation and painstaking efforts. But that his physiological experiments should open the way to major discoveries in electricity itself, was if not wholly "accidental", certainly wholly absent from Galvani's intentions. His purpose was to elucidate physiology. Not surprising he termed his discovery "Animal Electricity".

Galvani's long memoir (He calls it brief, which is understandable enough when one remembers the many years of work it represents.) was written years after many of the experiments were made, but there is no reason to doubt his statement that it is an

> "...accurate account of the discoveries in the same order of circumstances that chance and fortune in part brought to me, and diligence and attentiveness in part rewarded,"

especially since he goes on to admit that he will

> "...occasionally add inferences, conjecture and hypothesis to the account of the experiment with the primary purpose of paving the way for the undertaking of new experiments."

It is hard to believe otherwise than in this long sequence of experiments, ideas for their interpretation grew, were formed and reformed as the work progressed, and guided and inspired their continuation. In preparing a consecutive account retrospectively it would have been more than human for Galvani, even though his conclusions are presented as tentative, not to introduce the occasional suggestion, emphasis or reordering that might make the argument more convincing.

The base from which Galvani set out was familiar enough: the study of muscular motion produced by artificial electricity. His first surprise was the "chance" observation that electrical stimulation could occur even where there was apparently no conducting path between the source of electrical disturbance - the accidental discharge of a nearby electrical machine, and the animal under examination - a special prepared frog whose crural nerves were in contact with the probing scapel. But the stimulus was in some way electrical ; if the scapel had a bone (non-conducting) rather than a metal (conducting) handle there were no muscular convulsions. From "chance" observation Galvani soon turns to deliberate experiment, whose purpose is clear: to examine under just what conditions this remote, or at least indirect, electrically correlated stimulus arises. Electrical conducting wires of various lengths are attached to the spinal column of the creature (or what remains of it), the electrical machine is removed from the proximity to a distance, the wires are covered with wax, the "prepared frog" - as it is euphemistically called - is sealed in a special glass container, which in turn is enclosed in other sealed containers, which are even partially evacuated: all precautions to ensure no electrical contact, even "through the layer of air". But though no electricity enters the frog, nothing prevents the muscular convulsions when the machine sparks. In Galvani's electrical repertoire real electricity must mean electricity that enters, via a conductor. Here then there must be a new sort of electricity; "electricity that becomes activated through a spark" - some intrinsic source of electricity, perhaps, which is triggered off in some way or other - who knows? - by the external electrical disturbance. For Galvani, the physiologist, action-at-a-distance is alien; but some strange, undiscovered internal animal response would be no novelty in principle. Animals are still full of unfathomed mysteries.

The frog is not unique: other animals whole and decapitated, warm and cold blooded are put to the same test. The anatomical preparation necessary for success varies; but basically the response is the same. Another logical continuation of the experiments: if remote "artificial"electricity works, what can natural electricity - the electricity of the atmosphere, in the clouds, in thunderstorms (which is even more remote) - do? The prepared frog - either placed in open air or sealed in the special glass container - is taken to the top of the house, a long wire is fastened to the spine, another reaches down to the water in a deep well. Expectations are confirmed:

> "As we hoped, the result completely paralleled that in the experiment with artificial electricity; whenever lightning flashed all the muscles immediately fell into numerous violent convulsions."

But even greater surprises were in store for Galvani; a reward for his patience, and eventually for his impatience. The muscular contractions occured

> "...not only when lightning flashed, but even at times when the sky was quiet and serene."

He surmises, at first,

> "...that these contractions had their origin in changes which occur during the day in the electricity of the atmosphere...", and so he "...began diligently to investigate the effect of these atmospheric changes on the muscular movements."

The outcome of this diligence is best described in Galvani's own words:

> "Therefore at different hours and for a span of many days I observed the animals which were appropriately arranged for this purpose, but scarcely any motion was evident in their muscles. I finally became tired of waiting in vain and began to press and squeeze the brass hooks which penetrated the spinal cord against the iron railing. I hoped to see whether muscular contractions were excited by this technique and whether they revealed any change or alteration related to the electrical state of the atmosphere. As a matter of

fact, I did observe frequent contractions but they had no relation to the changes in the electrical state of the atmosphere.

"Now since I had observed these contractions only in the open air and had not yet carried out the experiment elsewhere, I was on the point of postulating that such contractions result from atmospheric electricity slowly insinuating itself in the animal, accumulating there, and then being rapidly discharged when the hook comes in contact with the iron railing. For in experimenting, it is easy to be deceived and to think we have seen and detected things which we wish to see and detect.

"But when I brought the animal into a closed room, placed it on an iron plate, and began to press the hook which was fastened in the spinal cord aginst the plate, behold!, the same contractions and movements occurred as before. I immediately repeated the experiment in different places with different metals and at different hours of the day. The results were the same except that the contractions varied with the metals used; that is, they were more violent with some and weaker with others. Then it occurred to me to experiment with other substances that were either non-conductors or very poor conductors of electricity, like glass, gum, resin, stones, and dry wood. Nothing of the kind happened and no muscular contractions or movements were evident. There results surprised us greatly and led us to suspect that the electricity was inherent in the animal itself."

This is the climax of Galvani's work. All possible sources of external electricity, artificial or natural have now been eliminated; yet the excitation of the muscular contractions persists! Some internal, animal agency - surely electrical in nature? - must be responsible. Logically it is an extraordinary sequence. One starts with electrically administered convulsive shocks; one proceeds to observe convulsions with electricity remote - playing some indirect (?) role; the external electrical stimulus is further removed, finally it is eliminated altogether, and all that is left is the metallic connection between nerve and muscle. Yet now the animal response is interpreted not as a consequence of action of electricity, but as evidence for the presence of electricity: Animal Electricity! To be sure the metallic connections, as good electrical conductors, might hint at electricity, but what else might not metals imply?

Bare logic does not explain how an idea is born and nourished in the sequence of experiments. Galvani started out, clearly enough, even if accidentally, with electricity. Each successive experiment confirmed, or at least was fully consistent with the essential, if obscure, electrical nature of the phenomena. The notion becomes entrenched; hypothesis takes on a progressively more specific form; it is a new brain child and as it grows it becomes progressively more appealing to its parent; finally the child becomes the parent of the man. If the conjectured electricity is sufficient to explain the new phenomena, why look elsewhere for an explanation. If internal animal electricity can be triggered by an external spark - why not by some other stimulus, such as the metallic connection. And now consciously or not, Galvani can find support for his theory from still further experiments; and with his wide knowledge of anatomy he can cast it in a more explicit form.

No long wires in the "deep well", no railings at the top of the house, no lightning. All can be demonstrated on the dissecting table with simple short lengths of wire. Nerve convulsions are now produced easily simply by two wires - of different metals - making contact with each other at one end; and at the other, one with the crural nerve and the other with the muscle. Two different metals are essential; some pairs are more effective than others. Silver or copper with iron, he finds best. Plausible enough because:

"...to our way of thinking, silver is the best of all metals for conducting animal electricity."

To complete this theory of animal electricity, Galvani would like to trace it to its actual seat. Despite his assiduous efforts he has to confess that

"...this problem, which would not be sufficiently defined by experiment, must be left to conjecture."

The conjecture is an appealing one. For electricity to flow there must first be some electrical imbalance; and then, if the accumulated electricities, of opposite sign, are presented with a conducting path, a current can flow, and electrical equilibrium is restored. To Galvani, his innumerable experiments provide evidence for "...the coursing of electricity from muscles to nerves", or vice-versa. And does not the layered structure of the muscle vividly suggest an analogy with the Leyden jar, the already famous instrument for storing electricity? And equally what could be more suited to the passage of electricity than the moist, nervous filament, so appropriately encased by its oily sheath to prevent the dissipation of electricity? All the external metal-arc has to do is to complete the path from the two sides of the muscle, via the nerve. The electrical circuit is complete; one can overlook the gaps in the logic!

As Galvani moves from experiment to theorising the haziness of his electrical notions becomes all too evident. In what more subtle ways than by direct injection - ways which Galvani could not perceive - might not electrical disturbance be excited! As Volta would later comment: Galvani was far more mystified than he need have been by the original "chance" observation. But if Galvani had known more, and been puzzled less, what motive would he have had for years of perservering probing? There would have been no mystery to unravel! And no discovery to make! No matter what path led him there, he did discover the remarkable phenomenon of the muscular convulsions produced by the bi-metallic arc. And if he felt his theory of animal electricity to be an "extremely convincing hypothesis", he declared his readiness to abandon it

"... should the learned scholars contradict, or discoveries of natural philosophers and new experiments ...bring forward another that is more suitable."

Here was a clear invitation, even a challenge; and "natural philosopher" Volta, the master of Electricity, lost no time in accepting it.

IV. Volta's Response to Galvani's Discoveries

The world of frogs and nerves and muscles, the anatomy of animals dead and alive, whole or dissected, was to Alessandro Volta a wholly unfamiliar one. During the decade when Luigi Galvani was devotedly teaching and quietly persuing his physiological researches at Bologna, Volta at Pavia was employing his mastery of electrical techniques to extend his scientific activity into many branches of physics and chemistry, and corresponding with a growing circle of leading scientists. Periodically he made grand tours of the leading European centers. His reputation grew apace; in 1791 he was elected Fellow of the Royal Society of London. But his skill, his knowledge and his accomplishments notwithstanding, his discoveries were hardly sensational. It was as if his latent powers awaited a really major challenge. In 1792, it came - from an unexpected quarter and in a most surprising form - Galvani's animal electricity. But whatever its origin, electricity in any shape or form was Volta's business. A new source or sort of electricity, as Galvani believed he had discovered, whether from rubbing, machines, thunderclouds, the atmosphere or from the inside of every creature, could not fail to command his attention. And not simply to learn and argue about it; but to examine it - and with it the animals, nerves, muscles - with his own hands and eyes. For Volta there is only one sure path to knowledge - experiment: now he must enter Galvani's domain with all its dissections, dismemberings and decapitations.

He does so without reservation or delay. Within weeks of receiving Galvani's memoir he is experimenting with frogs, chickens, rabbits, lizards, salamanders - indeed with every species he can lay hand or scapel on. First he must check Galvani's observations - which he soon confirms. And the facts were convincing enough to lead Volta - guided no doubt by Galvani's persuasive arguments - to the same conclusion as his older and respected colleague. Here indeed is a remarkable new source of electricity, stored within the animal. The metallic connection discharges the electricity in the muscle via the nervous filament. It can be observed even in killed animals, even in parts thereof - as long as some "vital force" remains therein. Volta is all admiration for this splendid new discovery, and high praise for its discoverer: his colleague and fellow-countryman. To be sure, there have been many spurious claims and theories about "animal electricity", which in the past Volta himself has strenuously repudiated; there has been no shortages of unsupported surmises that electricity is somehow related to the nervous or vital fluids; but this new discovery of Galvani's is a demonstration of animal electricity of a different order: "Who now can doubt its existence?" Its discovery opens up "a new epoch in physics and medicine."

But simply to follow Galvani is not enough. Volta, the superb electrician, cannot remain in awed perplexity at the mysteries of electricity: he must explore its source and trace its path - with his own instruments. Already in April 1792, in a letter to Dr. Baronio , he is not only relating his confirmation of Galvani's discoveries, but reformulating Galvani's theory more precisely on the basis of his own observations and measurements. He has measured this new animal electricity; compared its quantity with the familiar artificial electricity that produces shocks and convulsions when administered to whole, living creatures. Galvani's electricity is, astonishingly, very much weaker; but more than that, there is no qualitative difference, Volta asserts, between the two. He can trace a whole sequence of phenomena, from the large quantity required to excite convulsions when applied from head to foot of a living frog; the smaller quantity (about 1/20th) sufficient for a decapitated frog with electricity applied between the limbs and a needle inserted in the spine; and the minute amount - only detectable with the most sensitive electrometer - when applied to the "prepared frog" à la Galvani. And when external electricity is applied with carefully contrived metallic contact to nerve, so little sufficies that it can be detected only by Volta's own micro-electometer! The reason for this greatly enhanced sensitivity is also clear to Volta: it is because the passage of the electric fluid , to and from the muscle, is concentrated along the sensitive nerve. It is precisely because of this concentration that Galvani's "prepared frog" is sensitive enough to display, in the vigorous muscular contractions, the passage of the very weak animal electricity. By comparing the discharge of a very weakly charged Leyden jar in both directions from the nerve to muscle, Volta is even able to convince himself that he has discovered in which direction the animal electricity flows in the Galvanic metal arc! But this, it turns out, is one of the few instances in which Volta is to retract one of his own experimental findings.

There is no physical mystery for Volta, as there was for Galvani in his original observations, in muscular convulsions produced by a remote electrical disturbance, without any direct conducting path. Volta's understanding of electricity tells him that electrical disturbances can readily be "induced" without contact, and though these may be smaller than those directly administered, has he not shown that only a minute quantity of electricity suffices to excite the "prepared" frog? Electrically, everything is consistent; it is a question of how the electricity - artificial or animal, external or internal - makes its passage through the flesh, blood, tissues, muscles and nerve. To explore this Volta must push deeper into the realm of physiology and anatomy. Within a few months Volta seems at home in this new domain; he is as dispassionately dissecting his frogs and chickens and sheep, as formerly he discharged his Leyden jars. His further experiments confirm the "irrefutable investigations" of "our Galvani". Any doubts he may have had seem to be dissipated: "Now I am converted", he decleares (May 1792), "I've seen for myself; I have myself made these wonderful experiments, and perhaps gone from a disbeliever to a fanatic." But not for long!

The occasion is an address to the University of Pavia, marking some academic promotion. It gives Volta an opportunity to review the whole subject of animal electricity - old claims as well as the new discoveries. Galvani's inborn animal electricity is still accepted as a reality; but there has been no let-up in Volta's incessant experimentation. More animals have been subject to test: bipeds and quadrupeds, hot and cold-blooded, dogs, cats, mice, pigeons, reptiles and fish. Increasingly the questions become anatomical and physiological as well as physical. How long after "death" does the "vital-force", evidenced by the muscular responses, survive? Is the manner of death significant? What differences are there between hot and cold-blooded animals? What is the relationship between the electrically induced muscular contractions and those produced by action of the will? And how does the new electricity compare with the well-attested powerful electricity of the electric fish and the electric eels? To answer these questions Volta turns his attention to the "quality, quantity and form" of the new electricity. It is weak electricity, far weaker than the violent form of the electric fishes; just as atmospheric electrcity is a much milder form than lightning. And this mild form of animal electricity seems to play a role in the animal economy generally. When the muscle responds to an act of the will, (or to some accidental cause or illness) the electrical equilibrium is disturbed, and the subsequent flow is directed to some special member of muscle. Artificial electricity, externally applied, can likewise disturb the electrical equilibrium. And now, as Galvani's discoveries show, there seems to be another possible way. Might not the provision of an additional external path — for the flow of electricity urged by the inner electrical "striving", be the cause of electrical disturbance; or the means whereby an intrinsic electrical stress is more rapidly restored to equilibrium? Volta, no less than Galvani, knows that a simple metallic conductor, or even a conductor comprising two metals (no special attention is paid at this time to this feature!), cannot excite electricity, it can only transmit it. The source must be internal; but it is, as Volta now sees it, a remarkable example of a much wider phenomenon, and indeed a clear demonstration, at last, of the essential physiological role of electricity.

If Volta in this first survey departed only just perceptibly from Galvani's ideas, essentially in the direction of generalising them, there are already hints that these are not final conclusions. Even as he sets down his views in writing, an incessant stream of new observations and experiments are beginning to unsettle the whole picture. Indeed in a second memoir, dated only days after the Pavia address, Volta opens up the basic questions to reexamination, and adduces important new results. He begins remorselessly to part company with Galvani.

Pursuing his aim of measuring the new electricity and tracing its path more accurately, Volta constructs a little special apparatus in which a frog, or some part of it, may be electrically isolated and electricity applied unambiguously between two points of the animal. Now he begins to see in Galvani's prepared frog a most sensitive <u>detector</u> of electricity, far more sensitive than any other, even Volta's own most refined instruments. An "animal electrometer" he calls it, as in fact Galvani had on an earlier occasion. Soon he perceives that this extreme sensitivety depends on the localisation, perhaps concentration, of electricity in the nerve: the reaction of the muscle seems to be an indirect one, controlled it seems by the nerves connected to it. Why then, may not the nerve-muscle relation be the normal physiological one - as in any voluntary nerve-muscle system? Here is a different generalization; more specific, perhaps, than Galvani's (and his own) universal electricity, but an equally appealing one, and certainly one which fits all the facts!

Once accepted, Volta writes, he is "compelled" to follow a new line of investigation. Electricity can be applied to the nerve itself - in fact to two points separated by only a very small distance - and indeed lively convulsions of the muscle are produced. It is quite unnecessary to make connection to the muscle at all. To be sure application of electricity to muscle directly also stimulates contractions; but surely this can be attributed to the invariable presence of some nerve filaments within the muscle tissue. And this is consistent with the observation that the electric charge necessary in this case is much larger than when application is made directly and exclusively to the exposed nerve. This new role for animal electricity is much more restricted than the original interpretation - as the "nerve juice", the "life spirit" which, moving along the nerve to the muscles,excites this directly. Now the electricity simply excites the nerve: how the nerve controls the muscle is still a mystery. Galvani's discovery leaves this mystery just where it was - in the domain of physiology and medicine. "How nice it all was" - to have had such a grand and general theory - "but it was not firmly grounded in experiment." This new interpretation does not, Volta insists, rob Galvani of his "wonderful discovery of animal electricity..."whose ...value will remain forever perfectly unassailable." But with this debt acknowledged Volta is free to pursue his own interpretation, and to press on with new experiments.

If the muscular convulsions are excited by transmission of electricity through the nerve itself - and even between a minute part of it, remote from the muscle, with the muscle now removed as a possible reservoir of electricity, without, indeed, any plausible internal source of electricity at all, where can one look for this electricity but outside the frog? (Like Galvani before him, Volta having begun with electrical stimuli continues to associate all muscular responses with electricity, even after all explicit sources have gone!) Maybe in the bi-metallic arc? Why are two dissimilar metals necessary? This is not easy to understand, Volta confesses, but it is a fact, confirmed by experiment. Soon there are many more experimental facts.

If electricity acts on the nerve, if the reaction of the muscle is secondary and incidental (physiological rather than electrical), what happens if a nerve not associated with a muscle is stimulated? To answer this question Volta turns to experiment on his own person. Two metallic strips - one tin,one silver - are applied to neighboring points on the tip of the tongue. When the opposite ends of the metal are brought in contact, there is a distinct acid sensation on the tongue ; but no movement is stimulated. The nerves here, Volta argues are related not to movement, but the sensation of taste. (Volta is, so he asserts later, unaware at this time, that similar observations had been made by the Swiss natural philosopher Johann Sulzer some 40 years earlier.) To confirm this interpretation, Volta experiments with a tongue severed from a freshly slaughtered lamb. When the bi-metallic arc is applied to the area at the root of the tongue, where the nerves controlling tongue movement are located, he observes - as expected - muscular contractions of the tongue! It is the excitation of the nerve that is crucial; and "the effect of excited nerve always follows its natural function."

This is Volta's new principle - his first real break with Galvani - and he promtly puts it to exhaustive tests. More species are examined - snakes, worms eels; and different metals in numerous pairing combinations - zinc, lead, iron, copper, gold, platinum and mercury. Both animals and metals are classified: the former in respect of their nerve-muscle systems, the latter in regard to their mutual powers of exciting the nerves. Literally thousands of experiments ("mille experiences") are made. All are in accord with the new viewpoint. Where there is no natural "nerve" control of the muscle (as, for example, with the intestines, the stomach or the heart), correspondingly there is no response to the bimetallic stimulus. Equally, when the stimulus is applied directly to the nerve, whether it be a whole animal, a severed limb, or even a small piece of these, the response is invariably elicited. Moreover, some metallic pairs seem more effective than others, and this in all cases. Whether passive or not, the metals seem to be acting as something more than simple, passive conductors. But what is still not clear; or Volta is still not ready to commit himself. Having abandoned Galvani's "grand hypothesis", he has, he declares now "laid aside indefinite, speculative ideas." He will

> "...restrict himself to direct experimental results and applications thereof. This is the way I have followed up to now; and which I will not depart from in future publications."

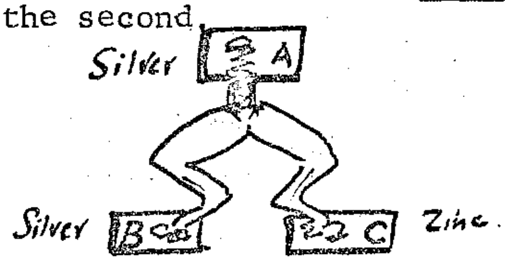
This resolute avowal of his intentions - to eschew speculation and pursue experiment - may have been honest enough, but the influence of hypothesis could not be, nor was, so simply put aside. What experiments would be chosen? With what questions in mind? Volta was soon criticising Galvani's experimentation - and not simply his conclusions - for having "run in too narrow a circle" ; for having, in essence, been restricted to those which seemed to confirm, or conform to, his theory:

"Had he varied his research more, as I have done, so he would also have noticed that this double contact of nerve and muscle...was by no means always necessary."

Indeed Volta's more varied and electrically more sophisticated experimentation had already loosened the grip which Galvani's conclusions had had on his own viewpoint. He was free to examine the situation in wider perspective. Quickly his minds eye fixed in a new direction. It is a view wholly opposite to Galvani's.

If the electricity of the muscle can no longer be asserted; if only the nerve, and even only a minute piece of the nerve is involved in the stimulation of convulsions, where does the electricity come from? How implausible to assign its origin at any or every point on the nerve! Perhaps there is no animal electricity at all; the source of the electricity is outside - in Galvani's bi-metallic arc!

Already in early summer (1792) he mentions in a letter to the Abate Tommaselli, that he believes he has "discovered", a "new and unsuspected virtue of metals" (and possibly of all conductors), that they do not act simply as passive conductors ("conduttori parfetti") but also as motors of electricity ("motori de'll elettricità"). By August he is expounding his new views at great length. All his "mille experiences", and many new extensions and variations are now presented as clearly illustrating and confirming his new principle: "not a law of animal electricity, but a law of common electricity." A month or two later (September/October 1792) he reviews the whole subject again, in letters to his friend Tiberius Cavallo in London: First a full refutation of Galvani's nerve-muscle electricity; then a detailed exposition of his new theory; and now with new compelling evidence, which, if it doesn't completely dispose of Galvani's animal electricity, it makes it completely unnecessary. Amongst the new experiments is one which Volta will return to time and again, an "experimentium crucis" whose verdict is clearly pro-Volta, and contra-Galvani. It is a beautifully simple demonstration; it invokes only the most general principles of symmetry; the conclusions seem inescapable. A prepared frog is laid with the crural-nerve on a piece of metal, A (say silver), one limb on a similar metal B, and the other one on a different metal (zinc), C. Now when a conducting metallic arc is connected across A and C there are pronounced convulsions; but when the same arc is connected across A and B, none. Thus the convulsions are produced by an external asmmetry (silver-zinc), as in the first case; but not by an internal asymmetry (nerve-muscle) as in the second.



In all cases, as other experiments with frogs, tongue, etc. show, it is the dissimilarity of the external metals, even if these do not both make direct contact with tissue, that stimulate a response.

Volta was earlier led to thinking along these lines, when he asks in his letter to Tommaselli, how it comes about that two metals are necessary, if the essential function of the metallic arc is, according to Galvani, to restore an electrical dis-equilibrium generated inside the animal? Would not, in this case, a symmetrical conductor be just as effective? Now he has the answer: the muscular response is not an indication of the restoration of electrical equilibrium, but rather of its disturbance. And the agent causing the disturbance is external: the bi-metallic arc.

Meanwhile experiments continue with undiminished vigour. More animals are subject to test: cows, tortoises, snakes, crayfish, beetles, butterflies, earthworms, slugs and oysters. In addition to the stimulation of the tongue, there is experimenting with the eye. To drive home a point Volta sets up in one and the same circuit a bi-metallic arc, and contacts with a prepared frog, his tongue and his eyes - all in series - and observes simultaneous responses from all when the two metals are brought into contact! Yet now attention is turning from the variety and response of the animal species, to the variety and power of the different metals. Volta is returning to physics - to the origin and nature of the new electricity. The physiological responses - which are after all responses to electricity, not generators of it - he can leave "to the physiologists and the doctors." He is fully convinced by his new theory; thousands of experiments confirm it. Now he must inform his learned colleagues of his new findings and convert them to his new views. In letters to leading electrician Van Marum, in Holland, to his colleagues in Italy, he ardently expounds the same thesis he has put to Tommaselli and Cavallo. For the followers of Galvani, his attack on their theory is now relentless. Volta has, he insists, no wish to detract from his colleague the glory of his great discovery, but as for its interpretation

> "...the whole edifice is in ruins. The materials remain - the fine discoveries, which if not now, certainly soon, will provide the foundation for a new edifice!"

Attack, not surprisingly, provokes counterattack: the debate turns into a battle between partisans. Galvani's nephew, Aldini, introduces new ammunition: muscular contractions have been observed by E. Valli of Pisa and others, with only a single metal in the conducting arc; and even with conducting paths of moist materials which comprise no metals at all. Volta's reply is patient and reasonable, but unrelenting. He admits that in his thesis of a bi-metallic arc, perhaps "he went too far, and must now retract or qualify" that statement. This would not be to abandon his principle but to generalise it. Any asymmetry in the conductors may suffice to excite convulsions: even two different wet conductors, as the Abb. Felice Fontana had already shown. As for the single metal, who can be sure that both ends of the metallic arc are identical in composition, in hardness, roughness, temperature, etc? But better than any verbal argument is the evidence of experiment. Volta repeats the experiments of his critics with thorough scrutiny. To be sure convulsions are to be obtained; but in contrast to those stimulated by the bi-metallic arc, they are weak and the specimens and the conductors never clean - homogeneity of the conductors far from being scrupulously ensured is carelessly ignored. How different from the "truly wonderful discoveries of... the worth professor of Bologna" are these new experiments, which serve only to bolster "empty ideas, useless and groundless", to make "a dark, vague idea, even darker."

Ironically as the rift between Galvani and Volta deepened, the scientific separation of their theories narrowed. If external heterogeneous substances, even fluid conductors, could excite electricity and stimulate convulsions, how could one be sure that such circuits could not possibly occur within the nerve and tissue of the organism, and that their disturbance, by an external conductor might not then activate the muscle? Volta's experiments gave a clear disproof of Galvani's nerve-muscle theory, but this was a different matter from asserting the entire absence of animal electricity.

But Volta is no longer defending his own interpretation of Galvani's discovery; it is his own new discovery that he is propounding. To establish and maintain his claim, it is imperative that it be clearly and distinctly different from Galvani's. Reconciliation with Galvani may be possible, but not at the price of merging his own ideas with Galvani's. From now on there is a new drive in Volta's work: to move as far from Galvani's animal electricity as is possible. That his new electricity can explain Galvani's discoveries, must not be confused with it being <u>only</u> such an explanation. In fact to Volta, his new principle is of far greater generality: frog-responses and the like are but a special case. Galvani's theory can be dismissed not only as unjustifiable but unnecessary. Why, except through obstinacy, should anyone want two theories (Galvani's and Volta's) when one (Volta's) suffices? To advance his own ideas Volta still yields to the temptation to attack Volta's: his own victory means Galvani's defeat. In due course through endless experiments and remorseless arguments, his views prevail. His discoveries bring him honor and renown: in 1795, the highest award of the time, the Copley medal of the Royal Society is conferred on him; the citation is unequivocal in its praise:

> "The experiments of Prof. Galvani, until commented upon by Prof. Volta, had too much astonished, and perhaps, in some degree perplexed many of the learned in various parts of Europe. To Prof. Volta was reserved the merit of bringing his countryman's experiments to the test of sound reasoning and accurate investigation; he has explained them to Dr. Galvani himself and to the whole of Europe, with infinite acuteness of judgment and solidity of argument; and through the medium of the Philosophical Transactions he has taught us, that the various phenomena which presented themselves under the modifications of Dr. Galvani's experiments hitherto tried, are wholly owing to the excessive irritability of the nerves when subjected to the actions of portions of the electric fluid, too minute to be discovered, even by the delicate electrometer of our ingenious brother, Mr. Bennet* of Worksworth; and he has detected in the metals, which Dr. Galvani considered as mere agents in conducting his animal electricity, that very existing principle which the Doctor and his followers had overlooked."

The battle between the vigorous unrelenting Volta and the gentle, retiring Galvani had been an unequal one. The scientific controversy apart, personal misfortunes had overtaken Galvani: the death of his beloved Lucia, his failing health and political per-

*The inventor of the gold-leaf electrometer, which, when supplemented with Volta's condensor to make it more sensitive, plays an important role in Volta's later researches.

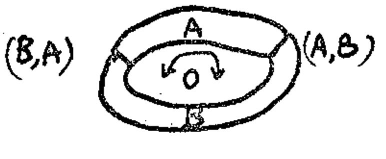
secution. Refusal to accomodate himself to the Napoleonic order had cost him his professorship at Bologna; and although this was restored in 1798, a few months later Galvani died - defeated and dispirited.

<u>Volta's New Electricity</u>

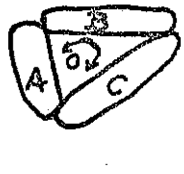
Although the victory over the Galvanists' seemed decisive, Volta's own theory of bi-metallic electricity was by no means unassailable. As long as detection of this new electrical power was inextricably involved with animals and all their vagaries and complexities, Volta could never enjoy full confidence in the independence and identity of his own discovery. To free himself entirely from this possibly subordinate association with Galvanism, the task for Volta is to demonstrate, by entirely physical means, the reality of his new electricity. This would place his discovery beyond doubt and confusion; the complete vindication of his position. But how can he dispense with the prepared frog - that most sensitive, "animal", electrometer which has proved so indispensible in the discovery of his new electricity? He must return to physics, examine his new electricity as thoroughly as possible, understand its nature, and then exploit his mastery of electrical technique to demonstrate its independent reality.

Early in 1793 Volta had arrived at a provisional formulation of his new electrical principles. The new electricity is generated at the contact between two dissimilar metals, or as later generalised at the boundary between any two different conductors. This contact causes the electric fluid to flow "...in large quantities, but quite gently...if the electrical equilibrium is disturbed a circulation ensues."

Unlike the familiar momentary electrical discharge, for example of the Leyden jar, this circulation continues indefinitely, without restoring equilibrium: witness the continued muscular contractions which are maintained as long as the bi-metallic arc is held in place. For this to be possible there must, of course, be a closed electrical circuit, so that no counter-pressure of electricity is built up. Yet this circuit cannot be comprised entirely of metallic conductors, since then there would be several bi-metallic contacts whose combined effects would cancel. This is obviously so for two metals, (a), where the force at contact AB is exactly opposed by BA.

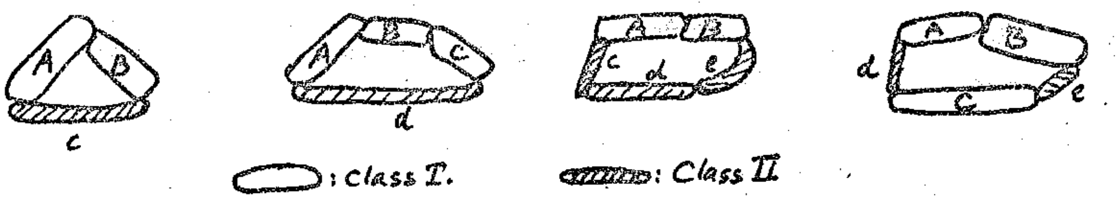


(a)



(b)

But even with three metals, (b), the motive force at AB, Volta postulates, is just cancelled by that at BC and CA. How then is continuous circulation of this bi-metallic electricity possible? Volta's answer is simple: the force at the contact between a metal - a class I conductor, as he terms it - and a wet, or class II, conductor is much smaller than that between two metals. Thus in a circuit comprising two class I conductors and one class II, continuous circulation of electricity is possible, (c); the motive

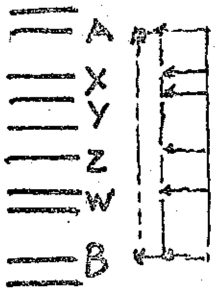


(c) (d) (e) (f)

force AB is no longer counterbalanced. Likewise for any number of class I and one (or more) class II conductors; e.g. (d), (e), (f).

Now the significance of the prepared frog is completely clear. Not only does it provide a most sensitive detector, not only does its particular form ensure that the flow of electricity is concentrated on the responsive nerve; it also provides the electrically "passive" class II conductor which completes the electrical circuit.

Now if metals are, as Volta conceives them, active "moteurs d'électricité" it should be possible to arrange them in a hierarchy, so that for any pair of metals one higher in the hierarchy has a greater motive power than one lower; and their relative ranks will determine the net power, and the direction of flow of electricity. Volta goes further: he postulates that the net power of the contact AB is equal to the sum of the contacts, for example of AX, XY, YZ, ZW, WB; i.e. as far as the overall power is concerned the metals intermediate in the circuit play no role, or, expressed another way if we picture the hierarchy of the metals as a ladder, and the power of a contact represented by the vertical spacing between its components, then the theorem clearly follows.



The test of this hypothesis, and to some degree its genesis, is the demonstration that the ranking of the metals is the same no matter what animal or physiological response - prepared frog, Volta's tongue, grasshopper or eel - is used to "measure" the bi-metallic power. The experiments are now still further multiplied;

not only a variety of animals, but with the whole range of available metals in every possible combination. By early 1794 (letter to Vassalli) Volta has already drawn up a hierarchy of some dozen metals; with zinc and tin at the top and silver and mercury at the bottom. All the evidence indicates that by and large the order in the hierarchy is the same no matter what the physiological test. It represents truly physical characterization of the metals. Why metals behave in this way is a problem of a different order; but to Volta the facts speak for themselves:

> "This faculty whereby metals no longer may be regarded as simple conductors, but as true motors of electricity is now proved in such a variety of ways, and springs to the eye in all my research, that it would be futile to entertain any doubts, even though it is hard to conceive. But when a fact, or a general law of phenomena is certain, and all particular facts conform to it, it is not necessary to know how."

Anyway who really knows how the old ordinary electricity (of rubbing) arises? Is it not "just because the facts are so familiar that one does not bother to fathom the cause?" (1792)

Not only was the origin of his new electricity a mystery, but Volta was also still undecided as to the exact location of its source. There were two possibilities: either metals acted directly, one on the other; or the motive force was a combined effect of the metals and the wet-conductors in contact with it at each end. In either case each metal could be characterized by specific power; since, at least approximately, all class II conductors were equivalently "passive" in themselves. Formally then both "theories" were equally consistent with all the facts. But there were other factors, in addition to experiment, to influence Volta's decision. Galvani's discoveries had excited the widespread interest: Volta was not alone in exploring the new phenomena; and others saw matters through different eyes and drew different conclusions. His fellow-contryman Fabbroni, professor of chemistry at Florence, had drawn attention to the many parallels between chemical interaction and Galvanism: the Galvanic phenomena - and especially the Sulzer type experiments - were always accompanied by chemical action; perhaps they were essentailly chemical in origin? The spirited young Johannes Ritter, at Jena, produced even more convincing evidence. Experimenting with frogs he showed that the order of metals, as in Volta's hierarchy, corresponded to its chemical affinity with oxygen! For Ritter, chemistry lay at the basis of both Volta's electricity and Galvanism!

Here for Volta was a new challenge. Could it be that the prize that he had wrested from the Galvanists he was now in turn to lose to the chemists! But again Volta, the master electrician, rises to the occasion. In his correspondence of 1794 and 1795 we already see him emphasising the role of metals, and though he still has no experimental proof of his new electricity which entirely dispenses with animals, let alone all wet conductors, he leaves no doubt about his own convictions. His task is to convince others. Volta well knows that in a purely metallic circuit no continuous circulation of electricity is possible; but if metals really act as "motors", then in the simple contact of two different metals, <u>some</u> electricity will be urged from one to the other - until the counter-pressure built up stops the flow. On separation, the two metals should be slightly electrified, the one with excess (positive) and the other with the corresponding deficit (negative) of electric fluid. Could this small disturbance of electrical equilibrium be detected? No one was better qualified than Volta to detect such a weak electricity - if it were true. Had he not more than a dozen years earlier invented his "microelectrometer" for just such a task? In the meantime Volta's condensing technique had been developed, by William Nicholson, into an instrument which, by cyclically repeating the "condensing" process, could magnify, at least theoretically, to an arbitrary degree any original electrification. The test is soon made: both with and without the presence of the wet conductor, the experiments are successful. Electrification is produced by "mere contact", without animals, and even without moist conductors! Moreover the new technique provides Volta with a new "experimentum crucis"; when silver and tin are used as the two metals, one sign of electricity is produced; when the roles of the metals are interchanged the sign is reversed. In his letters to Van Marum in Holland and Gren in Halle, in 1796, he announces the new proof of his metallic electricity and details of innumerable experimental variations. Yet the evidence is still not wholly satisfactory. Nicholson's multiplier is not an easy instrument to use: it all too readily magnifies <u>any</u> stray electricity that happens to be around, and this often confuses the evidence. It is not, to most, a familiar instrument, whose operation is direct, simple, well-understood and trusted. Evidence obtained with it may be suspect: there should be a more direct irresistable proof of the new electricity that no one can question. Volta finds it; and demonstrates his unrivalled mastery of the electrical art!

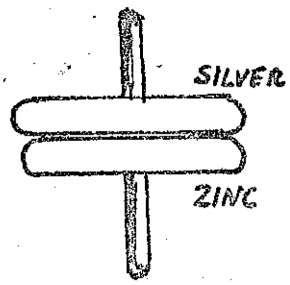
If mere contact between two metals, at one or two points, leads to detectable charging, will not, Volta asks, the effect be magnified if contact is made over a large area? Is not this just the principle he exploited in his electrophorus and the condensing electroscope? And might not this already enhanced electricity be further magnified by the multiplying technique used in the electrophorus-Leyden jar experiment. In this way he might even cause the electrometer leaves to fully diverge; he might even produce sparks - the true hallmarks of electricity. And all this with clean, dry metals. By early 1797 he has mastered the technique. With two dissimilar metals, such as zinc and tin, metallic or contact-electricity can be demonstrated directly by

> "...experiments that are all the more clear and decisive in that they are simple. For these experiments one needs nothing more than plates of different metals, as described, a Bennet electroscope with the finest gold leaves...a small Leyden jar and a small condensor..."

The simplest experiment - and it would be hard to imagine a fundamental experiment that is any simpler - is to take two flat smooth plates, carefully polished and dry, one of silver, the other of zinc

> "...placed in the most precise possible contact, and from this position separated briskly and perpendicularly."

On separation both plates are electrified (as shown by the sensitive electroscope), the silver positively and the zinc negatively.



Here at last is direct and incontravertible evidence of the reality of metallic electricity: electrification of dissimilar metals by simple contact. Not only the sign but also the degree of electrification can be measured; and by purely electrical techniques. For if, after separation, the charge on one or the other metal plate is deposited in a Leyden jar, the process can be repeated, until sufficient charge is accumulated to be easily detectable on an electroscope; or , in favorable cases (very dissimilar metals), for the Leyden to give a small spark on discharge. By simply counting the number of contacts and separations required to produce a specified effect, the strength of the bi-metallic force can be measured for any pair of metals. No frogs, no animals, no tongue, not even the wet conductors; clean, dry, contact electricity, measureable with the familiar tools of ordinary electricity.

Now Volta can check that the bi-metallic power as roughly measured by the Galvanic effect, is indeed the same as determined with his new technique. The hierarchy of the metals is confirmed. It is not only independent of the particular sensation or response: it is independent of all animals whatsoever. With his new technique he can explore further into the nature of this new electric power. To confirm his ideas he must make the new electricity come and go at his command. By varying the mode of making and breaking the contact or by changing the smoothness of the surfaces, the degree of electrification can be drastically and predictably altered. All doubt is removed.

Nor had Volta any doubts that his new contact,"bi-metallic", electricity was one and the same whether observed with animate or inanimate apparatus, whether wet or dry. Of course there were secondary differences: in some cases there was a closed circuit and continuous circulation; in others only a momentary disturbance of the electrical equilibrium, a small accumulation, and then no more electricity flowed. In some cases the flow was concentrated - in others spread widely. The new techniques offer scope for infinite experimental variations and all observations confirm the essential principles, that:

> "The two metal plates behave simultaneously as motors of electricity by virtue of their mutual contact, and as condensors of electricity because they present to each other a large surface, which results in their opposite electricities being counterbalanced."

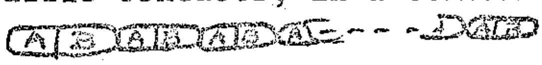
Exactly as in Volta's condensing electroscope of nearly 20 years ago! And yet only six years earlier (1791) Galvani had listed in his famous memoir, as one of the essential differences of the new (animal) from the old (ordinary) electricities:

> "...the lack...of even the smallest deflection in any electrometer so far invented..." !

<u>The Pile</u>

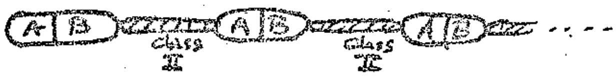
From a purely scientific point of view the climax of Volta's work is surely his recognition and unambiguous demonstration of electrification by simple contact. Yet this fundamental discovery was not the achievement which brought him greatest fame in his own lifetime, which had the most dramatic effect on his contemporaries, or which had the greatest impact on the subsequent development of science. This was the discovery, or invention, of the Voltaic pile. For Volta the pile was the next, and last, step in a long struggle; but for the world of science it was the beginning of a new epoch. We have seen how eager Volta always was to enhance the intensity of his new electricity to the point where it produced the irrefutable hallmarks of ordinary electricity. He had eventually just managed to accomplish this, but striking though the demonstration was, it could hardly match the spectacle of a powerful electrical machine delivering a continuous succession of lively sparks. Volta's new technique was arcane, and tedious - only after 50,100,or more successive contacts, alternatively charging and discharging, could he muster sufficient electricity to produce a tiny spark. It was a remarkable new electricity all right, but how feeble and vulgarly undramatic. But Volta himself <u>knew</u> that there was an ample <u>flow</u> of electricity; and that with wet conductors the flow was continuous. If only he could magnify the intensity, as he had in the contact experiment, without sacrificing the continuous flow. This was the problem that he confronted in the final years, from 1797-1799, and we can guess what must have been his reasoning.

It was no use simply adding, one after the other, simple, dry bi-metallic contacts, in a continuous chain:



There would be as many contacts A→B in one direction as B→A in the opposite sense: the net result - nil. It would be no better if each metal pair (A|B) were connected to the next by some other metal, C;

since his own principle taught him that the contact power (A|B) would be just counterbalanced by (B|C) + (C|A). But if instead of a metallic link, C, a relatively impotent wet conductor was used:



would not the cummulative powers of the A→B contacts prevail, and even add together to a much larger electrical force? Moreover the whole chain could be closed by a wet, class II conductor, and a continuous circulation would also be possible.

The solution was incredibly simple: all one had to do was literally pile one element on another in correct sequence - almost ad infinitum. This basically is Volta's pile: the simple instructions are given in Volta's own words:

> "Thirty, 40, 60 or more pieces of copper, or better, Silver, applied each to a piece of Tin (or Zinc... which is better) and as many strata of water or any other liquid, such as salt-water, ley, etc. or pieces of paste-board, skin, etc., well soaked in these liquids. Scuh strata interposed between every pair or combination, of the two different metals in an alternate series, and always in the same order of these three kinds of conductors...are all that is necessary to produce my new instrument.
>
> Having all the pieces ready in a good state... the metallic discs very clean and dry, and the non-metallic ones well moistened...I have nothing to do but to arrange them, a matter exceedingly simple and easy."

Even for Volta, after all his earlier successes, this final triumph is unbelievably simple.

It is 1800, some 30 years after he started out on his long journey. He has arrived at his final destination - his elation is unconcealed. He must convey the news to the world. His claim to his new contact electricity can no longer be disputed; the very title of his announcement asserts its finality: "On the Electricity Excited by the Mere Contact of Conducting Substances of Different Kinds".

In its new form, his electric generator is fully a match for the old electricity: it can deliver all the familiar sparks and shocks and electroscopic movements. Moreover it can do so continuously - a steady stream of electricity in contrast to the old intermittent supply. His old dream - the "perpetuum mobile" of electricity is realized. What does it matter if he cannot explain <u>how</u> his new electricity works? The pile speaks for itself - it works:

> "This endless circulation of the electric fluid, this perpetual motion may appear paradoxical, and even inexplicable, but it is no less true and real: and you may feel it, as I may say, with your hands."

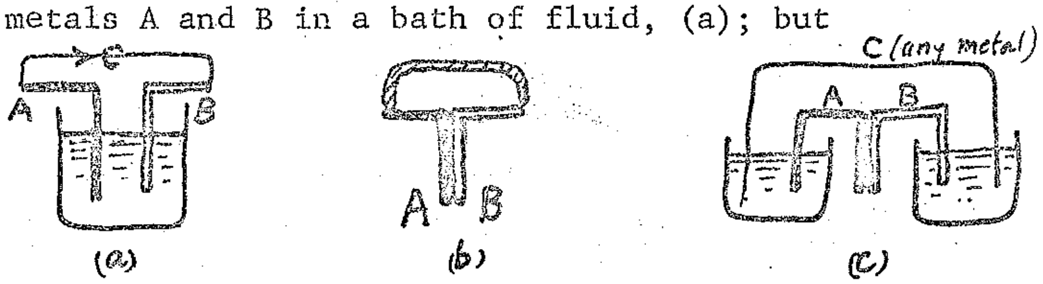
Not only is Volta's success indisputable; it is indisputably his own. In his elucidation of Galvanism the honors were shared with its first discoverer; in his discovery of dry contact electricity the effects were subtle, and perhaps controvertial; but in his new invention - the combination of, and climax to all his earlier work - the demonstration of his own contribution is unequivocal and striking. The pile is an immediate and dramatic success. Easy to construct and unmistakable in its potency, Voltaic piles of all sizes and shapes are assembled in all the leading scientific centers; within days or weeks they are put to use, and speedily open up whole new vistas of electrical phenomenon. In 1800 the era of the new Voltaic electricity began, and the study and application of electricity is transformed.

It was difficult to argue with success on this scale. But the success of the pile notwithstanding, the notion of any "perpetuum mobile" - of electricity or anything else - was not one easily swallowed by many of Volta's contemporaries. It was a discredited notion from an archaic past. But for Volta himself there was no doubt of the essential identity of his dry contact electricity and the electrical drawing force in the pile - and all that this identity implied. This had been the constant driving force and guide in his own work, justified now by resounding success, so that now he has

> "...no need, and this is not the place to bring forward proofs of such an endless circulation of electric fluid...This proposition, which I advanced in my first researches and discoveries on the subject of Galvanism and always maintained by supporting it with new facts and experiments, will, I hope, meet with no opposers."

Amidst the cries of acclaim, the voice of opposition found itself hard to be heard; but they were not silent. They could - and did - express skepticism; but there was no unity in the opposition, no clear alternative to Volta's "proposition". It would take many decades - indeed more than a century in development of science - before the relationship between Volta's contact electricity and the workings of the pile could be satisfactorily understood. In the meantime those who confuted Volta's theory of the pile could only be perplexed by, or remain silent about, Volta's very real discovery of true dry contact electricity.

Ironically neither the discovery of contact electricity - which inspired Volta, nor the invention of the multi-element pile - which claimed the attention of the world, represented the essence of what transformed the science of electricity. This was the discovery of the Voltaic cell as the means of generating a large sustained flow of electricity - without, necessarily, large electric tensions. For this dry bi-metallic contact was useless, and the multi-element pile unnecessary. One or two elements, of sufficient area - something like the original frog stimulators on a much larger scale - would have, and later did, suffice. But for the new electricity to claim recognition its identity with (and even superiority to) the old had first to be demonstrated. Volta had to create an instrument which exhibited both the tensions of the old, as well as the currents of the new, electricity, before the reality and potentialities of the latter could be clearly perceived. And, perhaps, there was another reason - for Volta himself. For Volta, wedded to the contact principle, the simplest "circuit" for delivering current was not, as we picture it today, two metals A and B in a bath of fluid, (a); but



two (A,B) metals in dry contact and a circuit closed by a wet conductor - hardly the most convenient supplier of current. The simplest cell on Voltaic principles would be rather like two elements, driven by a single dry contact (A,B). Indeed for many years the followers of Volta constructed their cells or piles along these lines: the simplest cell was the multi-cellular pile in embryo!

Volta, though he lived until 1827, never weakened in his faith in his contact electricity. But after 1800 he soon withdrew from the controversy he created, and which long survived him. Nor did he participate actively in the innumerable investigations that his own discoveries made possible. Acclaimed, honored, and bemedalled by his countrymen, his colleagues and by no less an admirer than Napoleon Bonaparte, he soon retired to a life of elder statesman and dignified domesticity. To have witnessed the discovery of the full significance of his contact electricity he would have to have lived a century longer. But had he lived only a few years more he would have seen some dramatic turns in his argument with Galvani: the discovery of true animal electricity, which, if not exactly of the sort Galvani pictured, was generated within and accompanied all nervous activity. It was a discovery made possible by the great developments in electrical science and technique which Volta's own achievements had initiated! And Volta himself, for all his strenuous efforts to establish the independence of his own discoveries from those of Galvani's, never wholly severed the umbilical cord that attached them to their nascent beginnings. Even in his great hour of triumph, in his announcement of 1800, for all his insistence on pure-contact electricity, it is to the electric fish and its animal electricity that he looks for an analogy to his pile. It might even be dressed up with skin and head and tail to "have a pretty good resemblance to the electric eel". Either the electric eel is a natural version of the pile, or the pile may be regarded as an "artificial electric organ"! Volta seems willing to share the honors with his deceased colleague, Galvani.

History has vindicated both; and revealed the mistakes of both. Neither Volta nor Galvani possessed a chart of the territory they set out to explore. Nor indeed could either, when each reached what he believed to be his destination , turn around and survey the whole new terrain. The explorer beats out his own path, and forms the picture of the new territory from what he learns en-route. It is those who come afterwards who map out and occupy the new domain; and in the process discard, and even obliterate, the path of the pioneer.

Notes on Volta's Use of Multipliers and the Condensing Electroscope

I. Spurious Charges

A recurrent difficulty confronts Volta, and anyone who seeks to repeat his experiments to establish the reality of his "contact" or "bimetallic" electricity. It is the appearance of spurious electrical effects which can seriously mask, or masquerade as, the "real" phenomena he is seeking. Basically this is due to the very small (fractions of one volt) potential-differences between the separated charges in true "contact" electrification; and the need, consequently, to magnify their effects greatly to render these "visible".* For Volta, in his time, and to convince his peers, a 'proof' of the reality of his new electricity demanded a demonstration of the typical signs of 'ordinary' (i.e. frictional) electricity: shocks and sparks, or at least some movement in an (electrostatic) electroscope. Electric sparks typically require potential-differences of thousands of volts, - even though the quantity of charge may be quite small (micro-coulombs or less). A typical pith-ball or gold-leaf electroscope of the period required a potential-difference of hundreds of volts for a sensible deflection; although here again the charge could be extremely small ($\sim 10^{-9}$ coulombs).

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* A rough general measure of the potency of an electrical phenomena is provided by its energy: i.e., the product, QV, of charge and potential-difference. When some basic electrical process separates a significant amount of charge, the potential-difference can be enhanced by subsequent separation, in which mechanical energy is of course supplied.

The multiplication techniques Volta uses on different occasions are of three sorts:

i) Increase in the spacing, and hence in the potential-difference of some separated charges. This is the principle of the condensing-electroscope (cf. p.8).

ii) "Multiplication" of the small separated charges by repeated induction and mechanical separation. This is the principle of the Nicholson, and other multipliers (cf. p.29). It is also, of course, the basis of the electrophorous which Volta had earlier developed.

iii) Repetition of the primary charge-separation process itself, followed by transfer of (one of) the separated charges to a condenser of sufficient capacity that only moderate potential-differences are produced. When the process has been repeated sufficiently often the energy stored in the condenser may be sufficient to be detected (e.g. by shock); or, after separating the condenser (i.e., after reducing the capacity), the voltage may be sufficient for electroscopic detection (cf. p.30), or the production of sparks.

In each case, the greater the effective "magnification", the greater the danger that some spurious charge is also magnified to the point where its effects are manifest.

<u>Examples</u>

i) <u>Shocks</u>. A large condenser (C) is 'charged' ($\pm q$) weakly (p.d. = q/C is a few volts). Discharging through the body will give no appreciable shock (the current is too small). If instead the plates are first separated, the potential (with respect to 'ground') of each plate will be $\frac{C}{c}q$, (here c is the capacity of each plate to 'ground'); i.e., a 'magnification' of $\frac{C}{c}$, which in practice may be several hundreds, is attained. If now either plate is discharged through the body the shock may be perceptible. The charge passing through the body is no greater than in the previous case (in fact it is approximately one-half), but the instantaneous current is much higher.

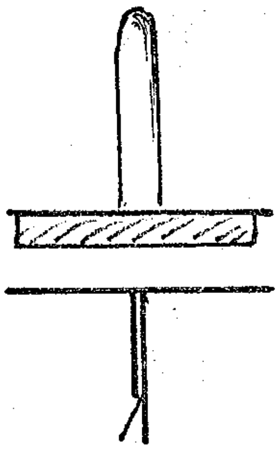
When this procedure is used to detect or measure charges accumulated at low potential-differences, it is imperative that the condenser be thoroughly discharged initially. The usual procedure of shorting the two sides, either metallically or through the body, may not be adequate, especially when the dielectric of the condenser is a good insulator. A small surface charge on this dielectric will, as is easily seen, result in a charging of the plate when the two are metallically connected and then isolated. (This is the principle of the electrophorus!) Even if there is no net charge, any residual polarization of the dielectric will likewise lead to spurious charging. Generally speaking, the better the insulator, the harder it is to remove completely these residual charges and/or polarization. It is not, then, surprising to find that Volta refers repeatedly to the great care that must be exercised to remove all traces of electricity initially. One method he uses to achieve this is to make the dielectric (for example, of his condensing electroscope) a poor insulator or "semi-conductor", for example, marble. But there are problems with this simple solution: if the insulation is too poor, it may not be possible to maintain the charge separation for sufficient time to complete the observations. Ideally one would like a condenser which would store electricity for about 5 to 10 minutes, - sufficiently short to permit proper initial discharging, and sufficiently long to enable one to make typical measurements.

ii) Sparks. Similar considerations apply here. To observe a spark of, say, a few millimeters in air, one needs potential difference of the order of 10 kv. ; the quantity of charge is of secondary importance. It may be quite small, say one-tenth micro-coulomb, but since a spark-discharge is extremely rapid (10^{-9} sec.), the instantaneous current may be quite large - tens of amperes. Even very small residual charges may then, if the potential magnification is large enough, give rise to detectable sparks. (Common induction machines start with minute residual charges and by multiplying by induction produce sparks of 50 or 100 kv.)

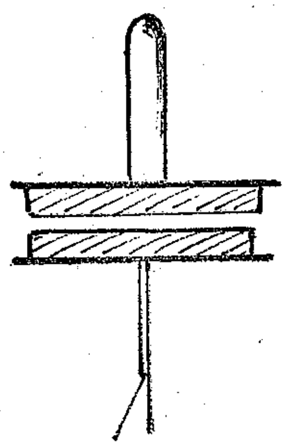
iii) Electroscopic Measurements. Stray charges can be most troublesome here, where the detection sensitivity is, typically, made as high as possible. (Potential-differences down to 100 v., charges as small as 10^{-10} coulombs*.)

When the electroscope is used with a separable condenser, as for example in Volta's condensing electroscope, it is imperative that it be initially charge free. This can and should be checked by shorting the two plates with the condenser closed, and checking for absence of detectable charge when the condenser is opened. An asymmetry between the plates, as in (a), (see next page), coupled with some stray charge on the dielectric surface (or residual polarization) will, inevitably, create spurious charging. A symmetrical arrangement, as in (b),

* The charge on an isolated sphere, 1 cm. radius, with a potential-difference of 100 v. with respect to surroundings.



(a)



(b)

is less likely to produce stray charges, or to redistribute charge when the plates are 'shorted'.

Notice that the metal plates of the condenser should be of the <u>same</u> material - otherwise there will always be some small charge ("contact potential-difference") in the condenser when the plates are shorted.

Quite generally, any rubbing, pressing, striking, sliding, etc. etc., is liable to produce small surface or polarization charges. "Grounding" with one's hands (especially if dry) is as likely to generate charge as remove it! Volta refers to his own troubles with these residual charges on numerous occasions. In one context he mentions placing the multiplier out in the sun for days as a means of removing the traces of charge. (Perhaps it was ionization, due to sunlight, that provided the mechanism for removing the surface charges?)

II. Sensitivity of the Condensing Electroscope

In any electroscope, of given construction, a certain deflection of the leaf (needle, etc.) is produced by a specific charge on the insulated part (i.e., the leaves together with the supporting stem, and the plate or knob). In so far as the geometry (and hence the capacity) of this section, with respect to the 'grounded' case and the environment is fixed, a specified charge results in a definite potential-difference between this insulated part and the case, or 'ground'.

If now, with the charge on the electroscope fixed, a grounded conductor is brought near the plate, and its capacity to ground thereby increased, the potential-difference, and likewise the deflection of the leaf, decreases. More physically, on the approach of the grounded conductor, charge of the opposite sign is induced in it, and at the same time there is a redistribution of charge in the insulated part of the electroscope - in fact, charge is drawn away from the leaf and stem and the repulsive forces thereby reduced.

If one neglects the small change in capacity due to the movement of the leaf*, and one assumes that the pattern of the electrical forces inside the electroscope proper is independent of what goes on outside, then a specified charge on the leaf + stem implies a specific potential-difference between insulated and grounded parts of the electroscope: the two quantities are simply proportional to each other. The electroscope itself may,

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* There must, in principle, be some change in the capacity - otherwise the leaf would not move! Here we are considering the effect of external bodies, and we could imagine the electroscope always used with a constant deflection!

therefore, be regarded as either a charge-measuring or a potential-difference measuring device. Representing by S_Q (deflection per unit charge) the charge sensitivity, and by S_V (deflection per unit potential-difference) the potential-difference sensitivity, then for the electroscope itself:

$$S_Q = S_V / C \quad .$$

Here C is the <u>total</u> capacity between insulated and grounded parts, assumed independent of leaf-position.

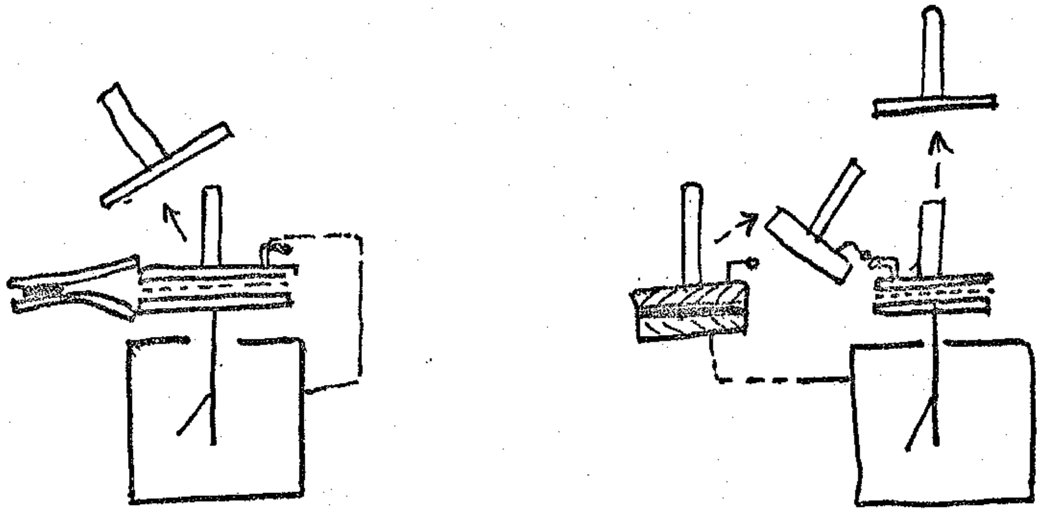
Consider now the electroscope modified by the presence of some grounded body. If the total capacity is changed <u>externally</u>, then with the assumptions mentioned, S_V is not changed, but S_Q is ; so that the new relationship is

$$S_Q' = S_V / C'$$

where C' is the new total capacity. Increasing C, e.g. by introducing the grounded plate of the condensing electroscope, with a fixed charge on the electroscope, will result in a decrease of the deflection, θ $(= S_Q \cdot Q)$; and conversely.

Notice that no matter under what circumstances charge is communicated to the insulated part, it is the <u>final</u> state of the electroscope and the charge on it which determines its <u>final</u> deflection; and its intrinsic sensitivity is then always characterized by S_V . There are essentially two ways in which the multiplying electroscope may be used. Volta exploits both.

(a) To explore the potential-differences of 'wet' "contact electricity", i.e., the "e.m.f." of a 'wet cell' (cf. p. 29). Here, (assuming the condenser plates are of the <u>same</u> metal), the 'cell' establishes a potential difference of V ,



(a) (b)

so that the total capacity C' may be charged by an amount $C' V$ by momentary contact with the cell. Then, isolating the electroscope, i.e. removing the grounded condenser plate, the charge remains the same but the new capacity is C . The deflection is now: $S_Q \cdot C' V = S_V \cdot \frac{C'}{C} \cdot V$. I.e., we have effectively increased the voltage sensitivity by the ratio $\frac{C'}{C}$, which may be very large (Volta asserts that he used values of this ratio up to several hundred).

(b) To explore the charges induced on two dry metals (cf. pp. 30-31) brought into contact and then separated. The condenser now plays an essentially different role. Here, with each contact of the two metals, by whatever the mechanism, a certain separation of charge Q is effected. We must assume that each plate is uncharged before contact, and therefore all the charge produced by the previous contact has been removed. The condenser - whether as part of the condensing electroscope or as a separate condenser, - now enables the metal plate, after each contact, to be more-or-less completely discharged. Since, if the condenser capacity C' is large, its potential-difference will change by only (approximately) Q / C' each time, and by only $n\ Q / C'$ for the whole sequence of n contacts. Provided this potential-difference is small compared with the potential-difference acquired by the plate on separation after each contact, essentially all the charge from the repeated contacts will be 'dumped' into the condensing electroscope. Its deflection before the condenser plate is removed will be small ($n\ Q / C'$ is, deliberately, a small potential-difference), but on removal of the condenser plate, the potential increase in the ratio $\frac{C'}{C}$, i.e., to a value $\frac{n\ Q}{C}$. The deflection is now $S_V \frac{n\ Q}{C}$. This is independent of C', the capacity of the multiplying condenser! This is as it should be, because the purpose of the condenser here was simply to ensure that all the contact-charges ended up on the electroscope. And the final deflection of the electroscope, with the grounded condenser plate removed, depends only on the magnitude of the charge transferred to it, and its intrinsic sensitivity.

Practically then, in case (a), a very large multiplication ratio ($\frac{C'}{C}$) is necessary to observe the small potential-differences produced by a single cell. In case (b), however, this ratio need only be sufficiently large to keep the potential small during the charging process. And since spurious charges are likely to be more troublesome the larger the multiplying factor, it is better to work with moderate ratios.

In addition to the ratio $\frac{C'}{C}$, the actual values of C and C' are not insignificant, and should be chosen judiciously. In observing potential-differences (case (a)), the charge acquired is proportional to the capacity of the (condensing) electroscope, so that quite large plates may be used. In (b), however, it is the size (and materials) of the contacting metal plates that determines the charge transferred to the electroscope, so that the (intrinsic) capacity of this latter should be kept small for maximum sensitivity.

In any event, these properties of the multiplying condenser should be carefully examined in the context of the particular electroscope and insulating materials employed. Instruments must be thoroughly uderstood before they can be trusted and exploited successfully to discover new, and especially unexpected phenomena, as Volta's experience emphatically teaches.

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V. 2. 1775 Scelta d' Opuscoli: Account of the Electrophorus.

V. 3. 1782 Of the Method of rendering very sensible the weakest Natural or Artifical Electricity. Phil. Transactions of the Royal Society LXII. p. 237-280. (The Condensing Electroscope)

V. 4. 1792 Two letters to M. Van Marum (Interpretation of Galvanism) (Le Opere Vol. I. pp. 119-142 .

V. 5. 1792/3 Two letters to T. Cavallo F.R.S. Phil. Trans. of the Royal Society I. pp. 10, 27 (Le Opere Vol. pp. 170-197). Reproduced (in German) in: Ostwald's Klassiker, No. 114. Briefe über Thierishe Eletricität (This booklet contains German translations of several of Volta's papers and correspondence about Galvanism, of the period 1792-1795)

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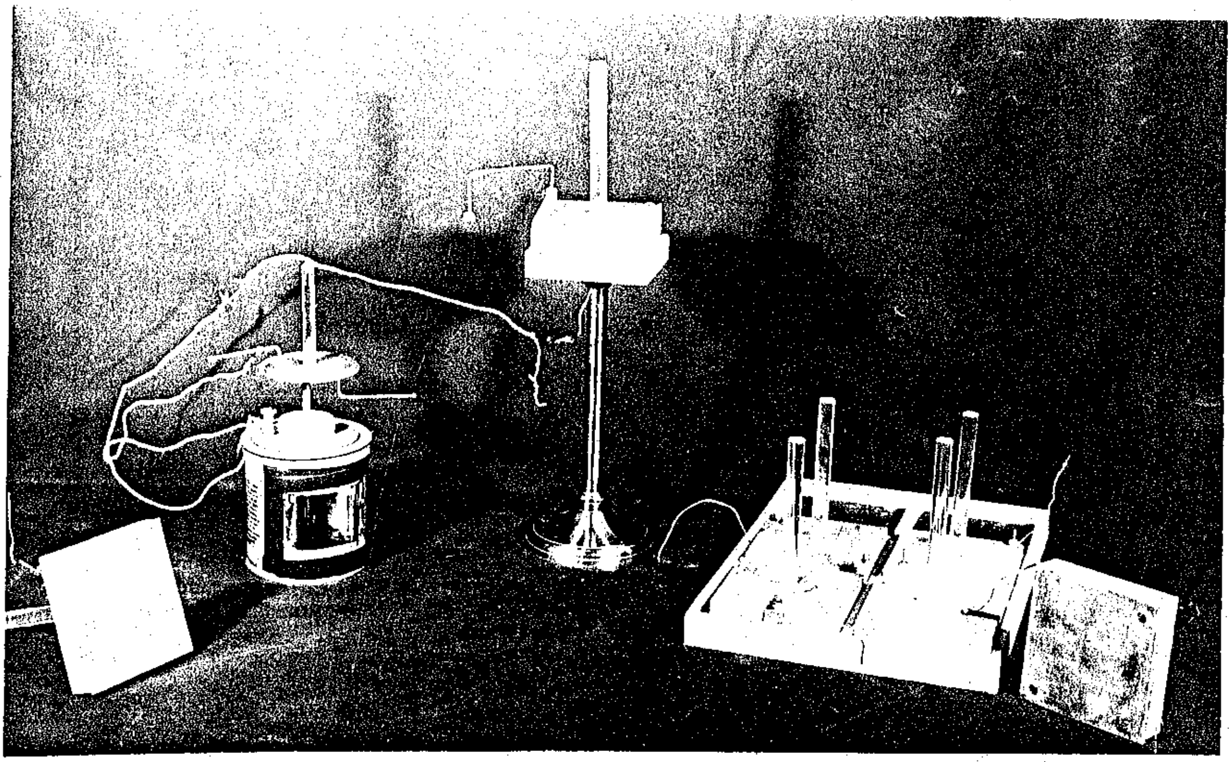
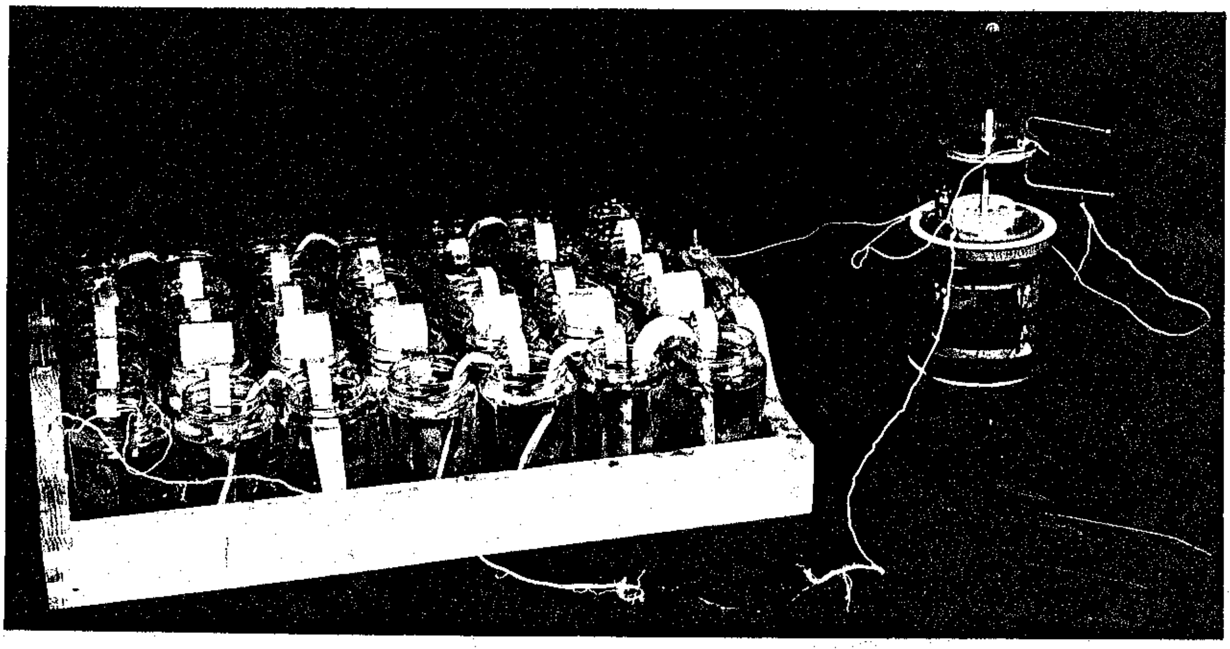


Condensing Electroscope and Dry Contacting Metals (c.f. p. 61)



Crown of Cups and Condensing Electroscope (c.f. pp. 61,62)

V. Laboratory Notes

Volta's triumphant attack on Galvanism is intimately and ineluctably related to his earlier experience with electricity. An appreciation of his later successes is hardly possible without some familiarity with the electrical phenomena he had studied and the techniques he had already developed and mastered. These, then, provide a fitting prelude to an investigation of "Voltaic Electricity".

In any realistic representation of Volta's (not to mention Galvani's!) inquiries, it would hardly be meaningful to proceed directly to the physical investigations of Galvanism, etc., omitting the physiological experiments entirely. However experiments with dissected frogs, etc. have not been included, for reasons which may easily be imagined. Physiological phenomena are represented by some of the simpler experiments with tongue, taste, etc., i.e. Volta's fuller exploration of the phenomena first observed by Sulzer.

The suggested order of experiments, whose sequence is sketched in outline below, is then:

A. Electrophorus, Condensing Electroscope, Examination of Weak Electrification

B. Physiological Experiments

C. Metallic-Contact Electricity

D. Construction and Properties of the Voltaic Pile

E. An Illustration of "Animal Electricity"

A. Electrophorus Action

A simple demonstrable electrophorus of some 4" to 6" diameter, with which the electrification of the different parts can be explored, is most suitable (see p. 63 for details).

1. Examine electrification of the plate (a) when the base is "grounded" permanently, (b) when isolated, and the electrophorus is used in the normal ("correct") way; i.e. plate and base are connected together (by hand) before separation. This test is now repeated but without the momentary connection of plate and base.

Tests could be made of the ability of the electrophorus to yield charges repeatedly, without further rubbing.

2. The electrophorus is charged, by rubbing, and the electrification of the separate parts is examined, both before and after operation. Examine (experimentally) the relationship between the charge on the plate and that on the insulator.

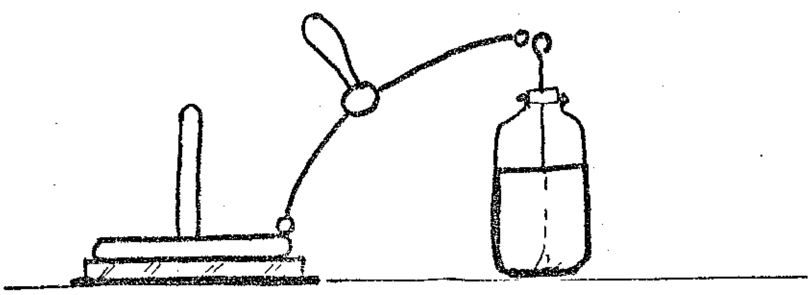
3. Sometimes a noticeable shock (or spark) is experienced when plate and base are connected (by hand); sometimes not. The conditions for the absence or presence of this effect should be explored.

4. How long does the electrophorus retain its power? This may be tested (a) with the plate in position, and (b) with the plate removed. How can the electrophorus be discharged, quickly?

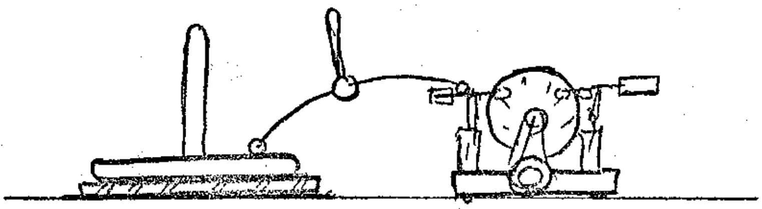
Condensing Action and the Condensing Electroscope

Simple apparatus required: Small Leyden jar, metal discs fitted with insulated handles, sheets of insulator, electroscope fitted with separable condenser.

1. Charge a small Leyden jar weakly; so that it does not produce visible (or audible) sparks. (A strongly charged jar may be partially discharged to achieve this result.) Now connect, momentarily, (use a wire with an insulated handle), the inner knob of the jar with the upper plate of the separable condenser. Remove this upper plate (by the insulated handle) and examine its state of electrification. Change the separation of the plates of the condenser by introducing various sheets of insulation (glass, dry cardboard, lucite, etc.) and repeat the experiment.



2. Charge the condenser by means of a slowly operated electric machine. Remove the contacts, and separate the



condenser. Examine the upper plate for electrification. Compare this with the direct electrification of the upper plate (supported on a large insulating block of material or suspended by an insulating thread) under similar circumstances.

3. Charge the insulated plate of the condensing electroscope (with upper plate removed), so that there is a moderate deflection of the electroscope. Slowly bring the grounded upper plate towards the insulated one. Observe and explain the change in the electroscope deflection. (Notice that the electroscope stem, the leaf and the plate connected to it are insulated, so that no charge can leave or enter. Check this by removing the grounded plate!) What differences are there if the previously grounded cover plate is also insulated? Cover the insulated plate with an additional sheet of insulating material, and repeat the above observations. In what sense is this experiment the converse of A.2?

4. Using the condensing electroscope (which is simply an electroscope combined with the separable condenser), or a separate electroscope and condenser, examine various rubbed materials for signs of weak electrification. Examine particular large objects (why is this important?), eg. a large insulated metal sphere rubbed lightly by hand, or a Leyden jar that has, apparently, been "completely" discharged.

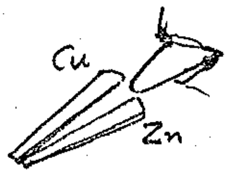
5. Charge the "plate" of the electrophorus moderately. Test its charge with an electroscope. Place the plate flat (a) on a poorly insulating surface (ordinary wooden table-top usually suitable) for a few seconds. Re-examine the plate for charge. Now repeat the experiment, but this time rest the plate on its side (b). This experiment may be tried with different table-top materials.

Compare your own experiments and observations with those of

Volta (c.f. pp. 7, 8 ; and § 24-27 and 35-43, in Volta's Paper, Ref.V.3).

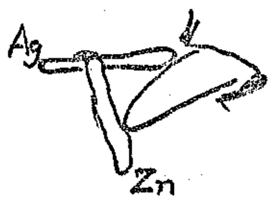
B. Experiments with Physiological Detectors

1. Sulzer's Observation:



Two strips of dissimilar metals make contact at one end; the other ends make contact with the tip of the tongue. Observe the effects with various pairs of metals - zinc, copper, silver, tin, iron, etc. Make up a "matrix" showing semi-quantitatively the magnitude of the effect for different pairs. Is there any discoverable effect with like metals?

2. Volta's Modifications of Sulzer's Experiment:



(i)

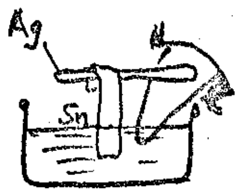
(i) Place a strip of tin or zinc in contact with the tip of the tongue; touch this with a silver "spoon"; bring the other end of the spoon in contact with the tongue further back. Then reverse the roles of the silver and the tin/zinc.

(ii) Instead of direct contact between silver and tin, make contact to the tongue through a beaker of water (or some aqueous solution).

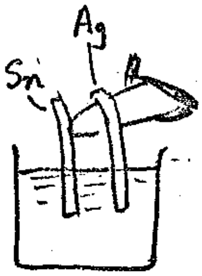
(iii) Compare the effects in the following two cases:

(a) Silver and tin strips both in contact with the tongue and each (separately) dip into water.

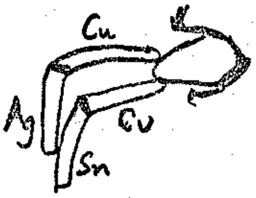
(b) The connection between the tongue and the silver and tin strips is made by the same metal (e.g. copper strips).



(ii)



(a)

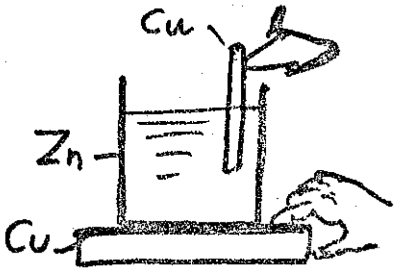


(b)

(iii)

(iv) Place a zinc cup on a clean copper plate. Make contact between the water (or solution) in the cup and the tongue with a copper wire. Then make contact with (moist) hand and the copper plate. Examine various modifications: changing and interchanging metals.

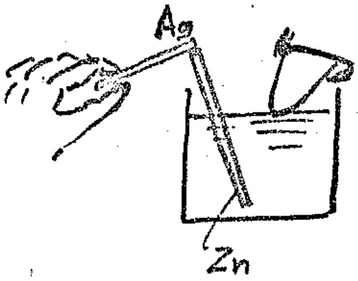
(v) Make contact between tongue and water (in glass beaker). Place a zinc strip in the beaker and make contact between zinc and a silver strip held in a moist hand.



(iv)

Two or more people can perform an extended version of this, and also the previous experiment. One person makes contact, via tongue, with the liquid, the other holds the silver. The two join (moist) hands.

Attempt to identify the essential conditions for producing the characteristic sensation in the tongue. Is there more than one recognizable sensation? How does the sensation depend on the duration of contact? Is a "closed circuit" necessary? If so, identify it in each case. Does breaking the circuit produce effects comparable to closing it? Do the responses differ with different parts of the tongue touched?



(v)

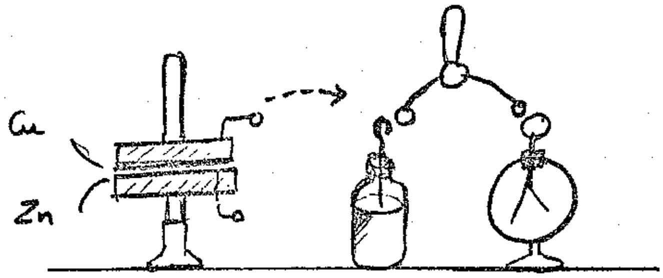
With the moist lip in contact with the rim of a copper (zinc, tin, ect.) cup, make contact between the tip of the tongue and the aqueous solution in the cup. Compare the sensation with those in B.2. Can the physical phenomena in the two sorts of experiments be related? (The phenomena here are familiar as a metallic taste of an (aqueous) liquid when drunk directly from a metal container.)

(vi)

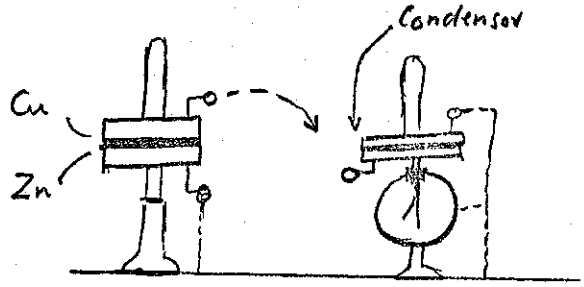
3. One end of a thin strip of tin is placed (carefully!) near the (moist) corner of the eye. A strip of copper (or silver) is held between the lips. The free ends of the two metallic strips are brought into memen-tary contact. Are the sensations of both sight and taste stimulated? Are they simultaneous? In all the above experiments, different metals and their permutations may be tried. In all cases where there is bi-metallic contact, the effect of inserting a third, different metal, e.g. zinc — silver replaced by: zinc — tin — silver, can be examined.

C. Metallic Contact Electricity

1. Plates of different metals, with carefully smoothed, flat, clean surfaces and fitted with insulated hands are used. (Avoid any damage to the surfaces. Clean them with soft, slightly moist cloth, if necessary.) Pairs of plates can be brought in close contact (some slight cohesion will be felt) and then briskly separated. Firmly support and ground one plate. Bring another plate of different metal into contact with it, then remove. Now bring the (upper) plate into contact with the knob of a small Leyden jar. Repeat the process several times. Check the Leyden jar for charge with the electroscope. (Either a simple or condensing electroscope may be used.) Establish an adequately sensitive procedure for investigating the charging quantitatively.



2. This same investigation can be made without the Leyden jar. The condensing electroscope can serve as its own Leyden jar. (How?)

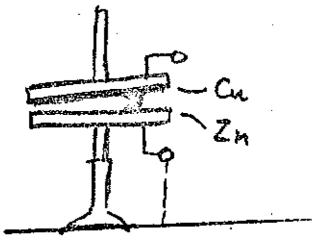


With the procedure in C.1 or C.2, measure the relative degree of electrification for different pairs of metals. The result can be exhibited in tabular form - or better in a two-dimensional "matrix". (c.f. B. 1 above)

3. Repeat the "experimentum crucis" of Volta: that the <u>sign</u> of electrification (plus = vitreous, or minus = resinous) is reversed when the roles of two metals in contact are interchanged.

4. Examine how the extent of the electrification depends on the closeness of the contact: e.g., if the contact is made along one edge only; or the separation is not made "squarely", but so that one point or edge breaks contact last.

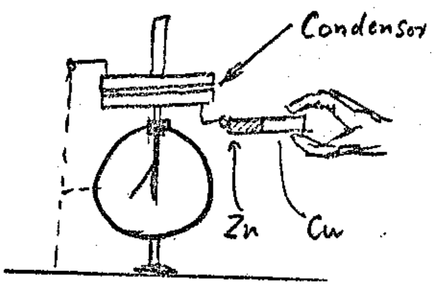
5. What happens when a drop of water is placed on one plate, so that on separation the final contact is through the water?



Compare your findings and interpretations with Volta's! In what respects are these experiments, C.1 - C.5, <u>essentially</u> different from B.1 - B. 4 (and from Volta's experiments with dissected animals) ?

D. The Voltaic Pile

1. One side of a single zinc-copper or zinc-silver bi-metallic pair is "connected" with the insulated plate of a condensing electroscope by means of a moist conductor; the other side is connected to the ground via the (moist) hand and the body. Under favorable conditions the electrification may be observed. Observe its sign. Reverse the bi-metallic pair; observe the electrification and the sign again. Compare this experiment with C.5.

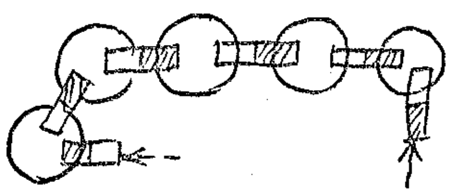


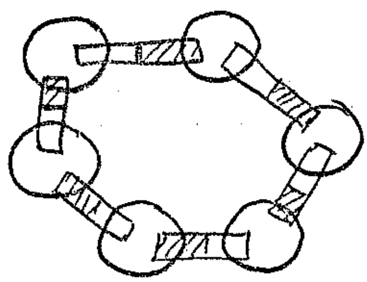
2. Assemble the pile, as described by Volta (c.f. Ref. v.9). Examine how the electric tension depends on the number of elements; and how the sign of the electricity depends on their ordering. Complete the Voltaic circuit of the pile by means of a poor conductor, (e.g., your body, or a damp strip of cloth), and when the circuit is completed re-examine the electrical properties of the pile. (Use the condensing electroscope.)

Compare this behavior with that of a charged Leyden jar.

3. Verify that the simple bi-metallic element A-B produces the same effects as the compound element A-B.

4. Set up the "crown-of-cups" using ordinary water in the beakers. Examine the electric properties for different pairs of points, (a) with the circuit "open"; (b) with a closed circuit. Can you detect the physiological effects (say, in your fingers) of this electrical system? Does the effect depend on the manner of making contact with the fingers? Do the effects persist? (Here again compare with the corresponding effects from a charged Leyden


(a)


(b)

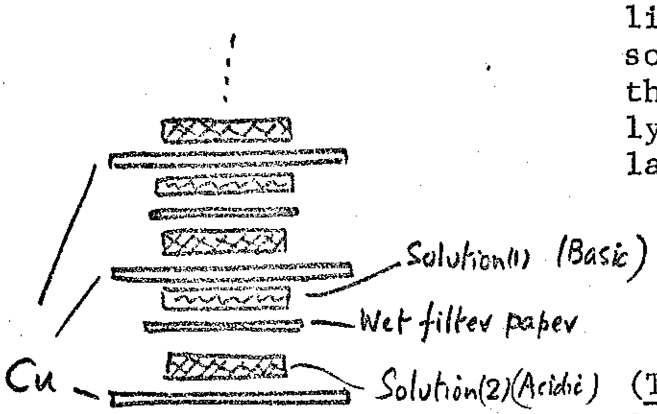
jar. A Leyden jar can be charged by contact for a very short time - say 1/20 sec. - with the pile. The shock discharge of the Leyden jar may then be compared with the sensation from the pile itself.)

5. With a sizeable - at least 20 - ring of cups filled with ordinary water, observe both the electrometer response and the physiological effects. Now add a little common salt (or vinegar or other solute) to each cup. Does either of the two effects change? What does this suggest about the importance of chemical processes?

E. Other Piles

1. Secondary Pile. Construct a pseudo-pile similar to Volta's but with only one sort of metallic element (e.g., copper) and moist pads soaked in brine. Discharge some electricity (e.g., by means of a normal Voltaic pile or a large Leyden jar) through this "pseudo-pile". Now examine its electrical properties. Check the sign of any detectable electricity. Repeat, with the connection to the Voltaic Pile (and therefore the direction of the electric current) reversed. Can these results be interpreted by Volta's theory of the pile?

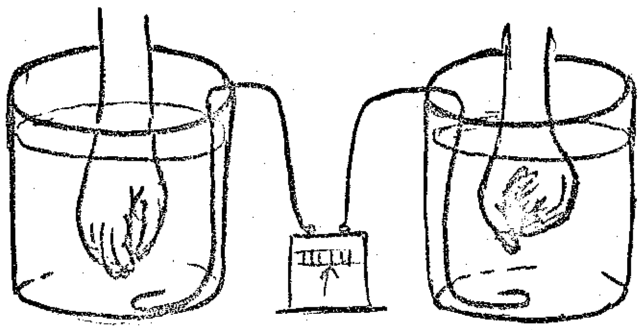
2. Humphrey Davy's Voltaic Cell or Pile. This is constructed with a single type metallic element (e.g., copper) and two sorts of moist conductor. To keep the two moist conductors separately intact, they are separated by a layer of "ordinary" water. Thus:



(Take care handling the solutions - especially the nitric acid.)

F. An Illustration of "Animal Electricity"

Two large beakers are filled with ordinary tap water, a copper lead from each is connected to a sensitive galvanometer. The water in the two beakers should be at the same temperature, the system symetrical as possible. Loosely closed hand is placed on each beaker. One or other hand is then clenched tightly. The electrical effects accompanying the muscular action should be systematically detectable. Checks to be made to establish as far as possible that no other asymmetries are responsible for observed effects.



The experiments A-D are by no means exhaustive of the sort Volta made. Many variations and additions will no doubt suggest themselves in the course of your own investigation.

Apparatus

Most of the "instruments" can be constructed using simple artifacts familiar to us*, just as Volta used the familiar artifacts of his day! Modern plastics make the problem of good insulators an easy one to solve; but sometimes they can be too good! (Great care is sometimes needed to avoid inadvertent charging of insulators, especially in the use of the condensing electroscope). In the spirit of Volta's experiment, a great variety of materials should be available and tested for their electrical properties.

(*aluminum foil, scotch tape, colloidal graphite, plastics, plastic containers, etc. etc.)

1. Electrophorus

This is most simply made from a shallow, flat aluminum dish, some 6" diameter, in which a plate of lucite (¼" thick) fits snugly. The dish itself is fitted on its underside with another insulating plate of lucite. With this arrangement the operations can be studied with the dish either grounded or insulated. If the insulators are shaped so as to provide a short extension handle, (see Fig. 1, p. 63) then the charges on all the parts of the electrophorus can be examined. The (upper) "plate" of the electrophorus is most simply made from hard-wood painted with conducting graphite, and then smoothed over (this avoids sharp, discharging edges), and fitted with a lucite handle. Electrical connections can be made to the small brass knob.

2. Separable Condenser

This can be constructed in a similar manner to the upper plate of the electroscope. The lower surface should be carefully sandpapered to be quite flat before applying the graphite. The latter should likewise be polished flat and smooth. It is then coated with insulating varnish (e.g. Crylon): two coats, the second applied after the first is thoroughly dry.

Alternatively, a brass disc (~ 6" diameter), fitted with a lucite stem, and ground flat on emery cloth, may be used. Insulation can be provided either by varnishing, as above, or by carefully applying adjacent strips of scotch tape so as to cover the whole surface.

With either form of the (insulated) condenser plate, the "grounded" plate is simply a flat sheet of metal (e.g. aluminum) laid on a flat (conducting?) table. Alternatively a flat wooden surface, made conducting with graphite or with a layer of metal (aluminum) foil.

The insulation of the condenser plate should, of course, be tested before use, and periodically thereafter.

3. Leyden Jar

Excellent small Leyden jars (capacity ~100-1000 pf.) can be made from common plastic bottles: Outside covered, over lower part, with aluminum foil; central terminal fixed by passing through cork into water inside the bottle.

4. Electroscope

A simple, robust, well shielded "gold-leaf" electroscope (roughly equivalent to Volta's straw electroscope) is at the heart of many experiments. An aluminum-foil leaf ~ 1" long and 1/8" wide is typical. Careful mounting of the leaf is all important. A reasonably sensitive electroscope gives an easily observable deflection for a leaf-potential of ½ to 1 esu. (150-300 v) and has a capacity of 10 to 20 cm. (charge sensitivity ~ 10 esu or 3×10^{-9} coulomb)

For most of the experiments, and for adaptation as a condensing electroscope, the stem is fitted with a brass plate of ~ 3"-4" diameter. The whole assembly - leaf, stem, plate and insulator - can be mounted on the lid of a scrap "tin-can" (4" - 6" diameter X 6" high). Holes are cut away in the sides of the can to permit viewing and to admit light.

It is prudent to mount the whole electroscope on a solid block of wood, to provide a firm base (see Fig. 2, p. 64).

5. Dry Contacting Metals

Construction depends on materials available. About 12 square inches of flat surface is adequate. The following arrangement has been found suitable.

Metals in the form of thin sheets are carefully cemented onto hard wood blocks (4" X 4" X¾") which have been sand-papered flat. Electrical connection is made by spot-soldering a thin strip of copper to the inside of the metal sheet before mounting; and providing a shallow recess in the wood block in which the copper strip lies. The outer surface of the metal is grounded as smooth and flat as possible. Use fine emery paper on a flat surface.

An insulating lucite handle is fitted to the uncovered side of the wood block. This handle can also be used to mount the metals firmly (one metal is usually grounded). (See Fig. 3, p.65). As many different metals as possible (Cu, Zn, Sn, Fe, Ag ...) should be assembled in this way.

6. Piles

(a) A multi-element pile can be made very simply from small postage-stamp-size (1" X 1") discs of Cu and Zn cut from sheets (about 0.01" thick), and pieces of blotting paper, which should be slightly smaller (3/4" X 3/4"). The whole can be mounted within a frame formed by four lucite rods (10" X ¼" diameter) fixed in a wooden (well-varnished!!) base. A top disc of wood, with four appropriate holes for the rods, provides a means of compressing the pile (gently!) and keeping the lucite rods properly spaced. (Fig. 4, p. 64)

(b) Crown-of-Cups. Simplest arrangement: Each bi-metallic "element" comprises a strip of copper and one of zinc (each about 6" X 1") soldered together to form a compound strip about 11" long. These elements are then bent into U-shape. Small jars or beakers with weak salt solution provide the wet conductors.

Note:

Some of the above items can be bought commercially, ready made, from the usual suppliers. On the whole we have found homemade equipment better suited to the experiments described.

Materials:

(a) Varnish for Condensers: Crylon Crystal Clear Spray (#1301), Borden.

(b) Graphite: "Dag" dispersion #154.
Acheson Colloids Co.
Pt. Huron, Michigan
(Dilute with alcohol, wood spirits, etc.)

(c) Cement: for metal-wood
Welwood Contact Cement #107
(Welwood, Michigan)

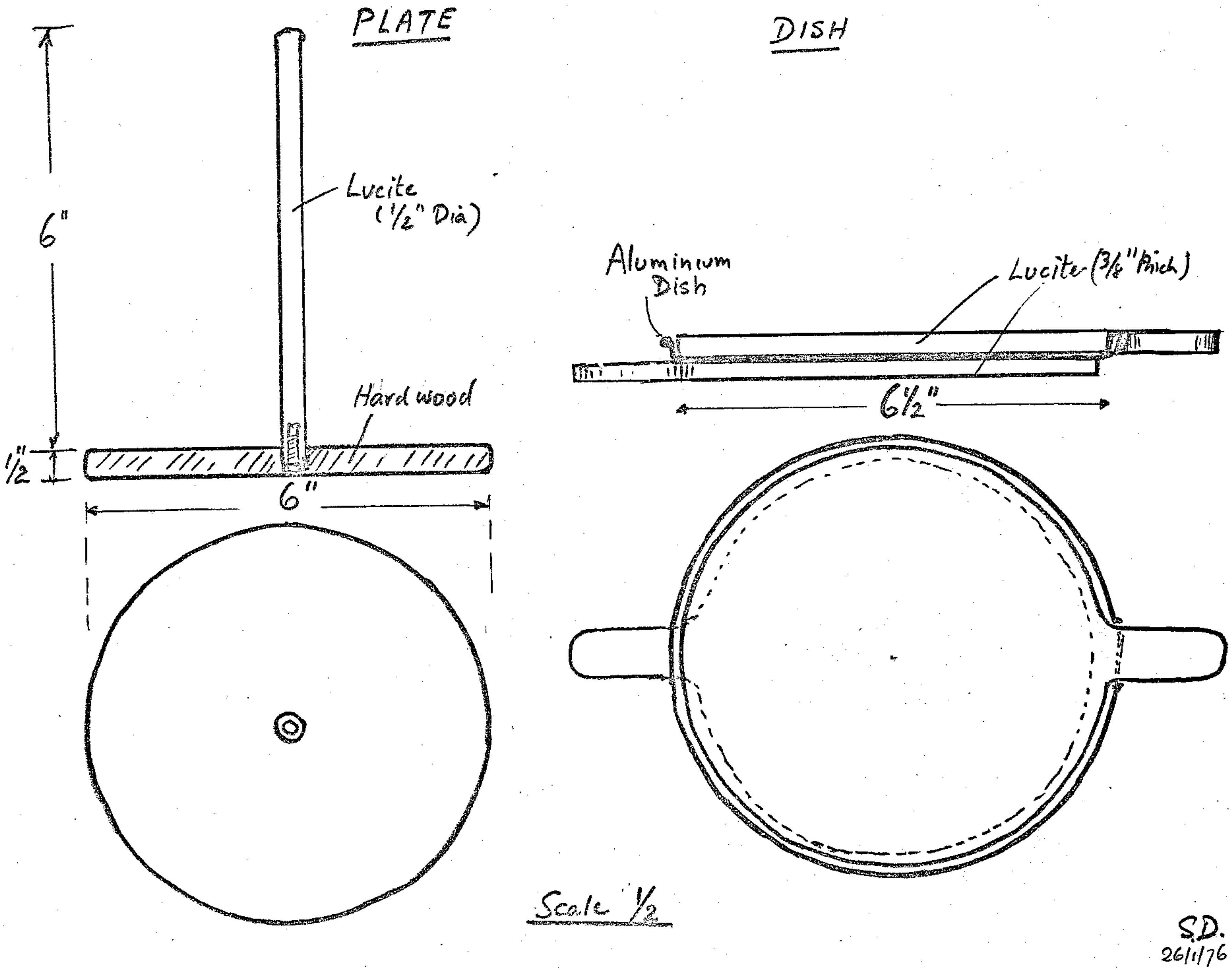


PLATE
DISH
6"
Lucite
(1/2" Dia)
Hard wood
1/2"
6"
Aluminium
Dish
Lucite (3/8" thick)
6 1/2"
Scale 1/2
S.D.
26/1/76

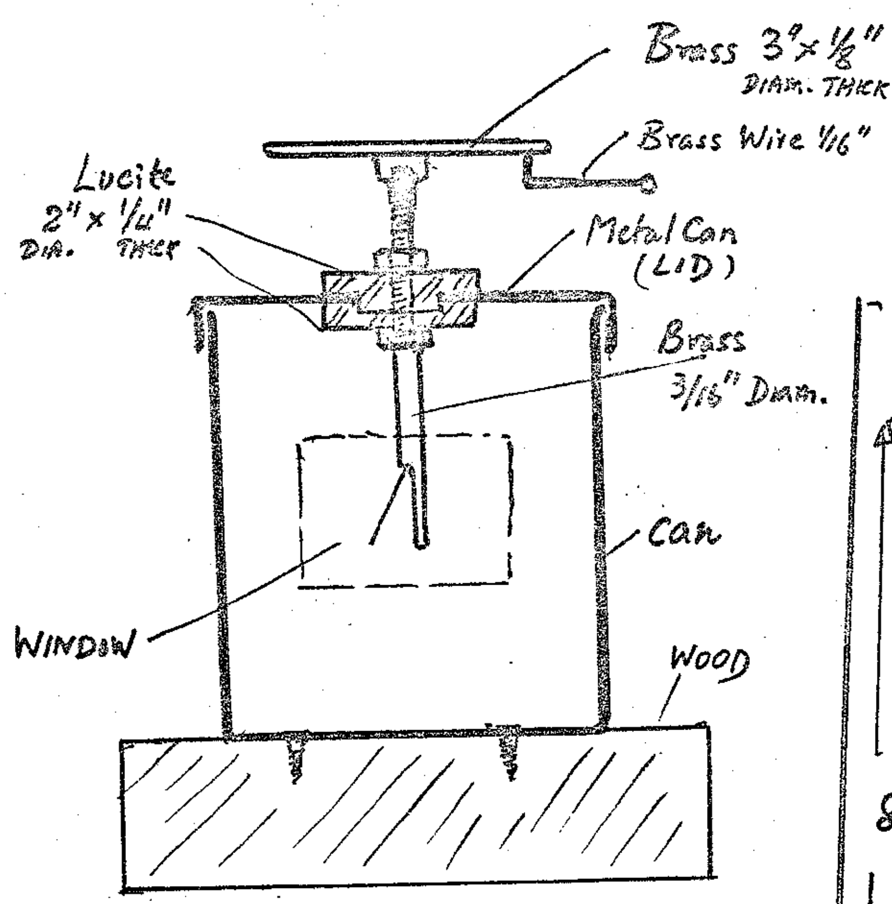
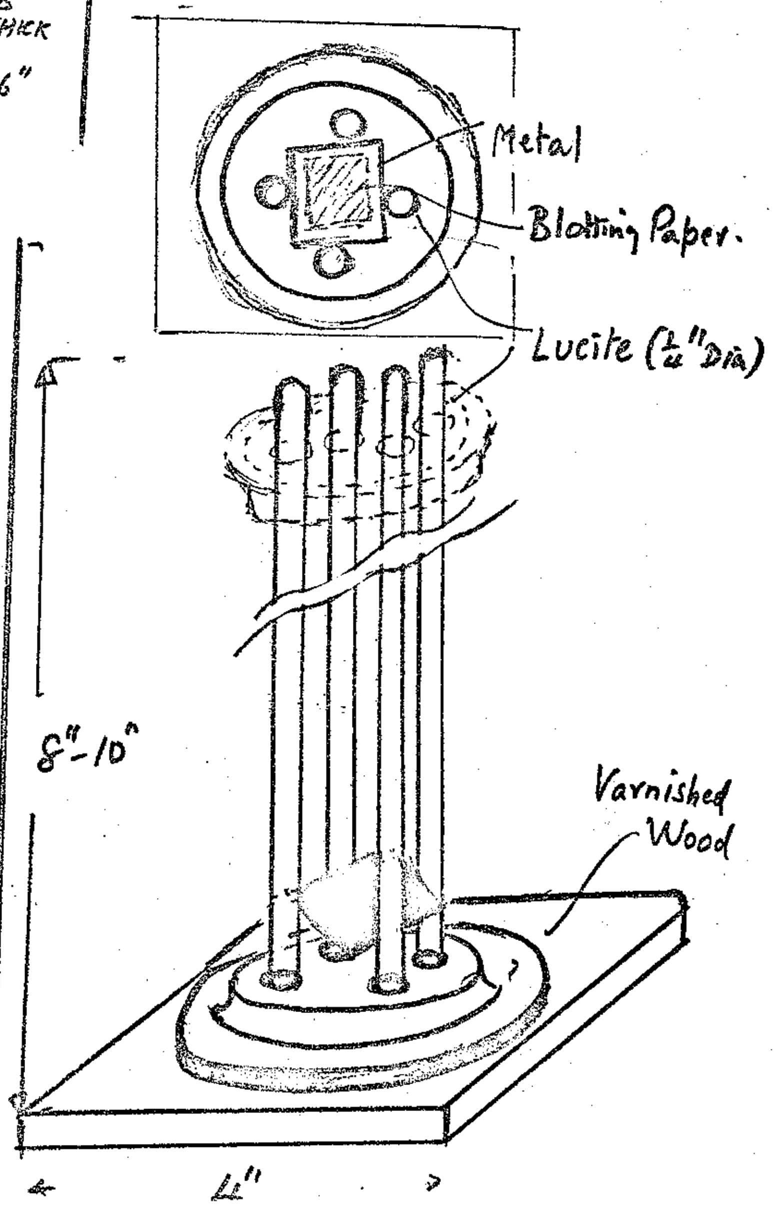


Fig.2 ELECTROSCOPE

Scale approx 1/2

FRAME for PILE



S.D.
26-1-76

PLATES FOR DRY CONTACT

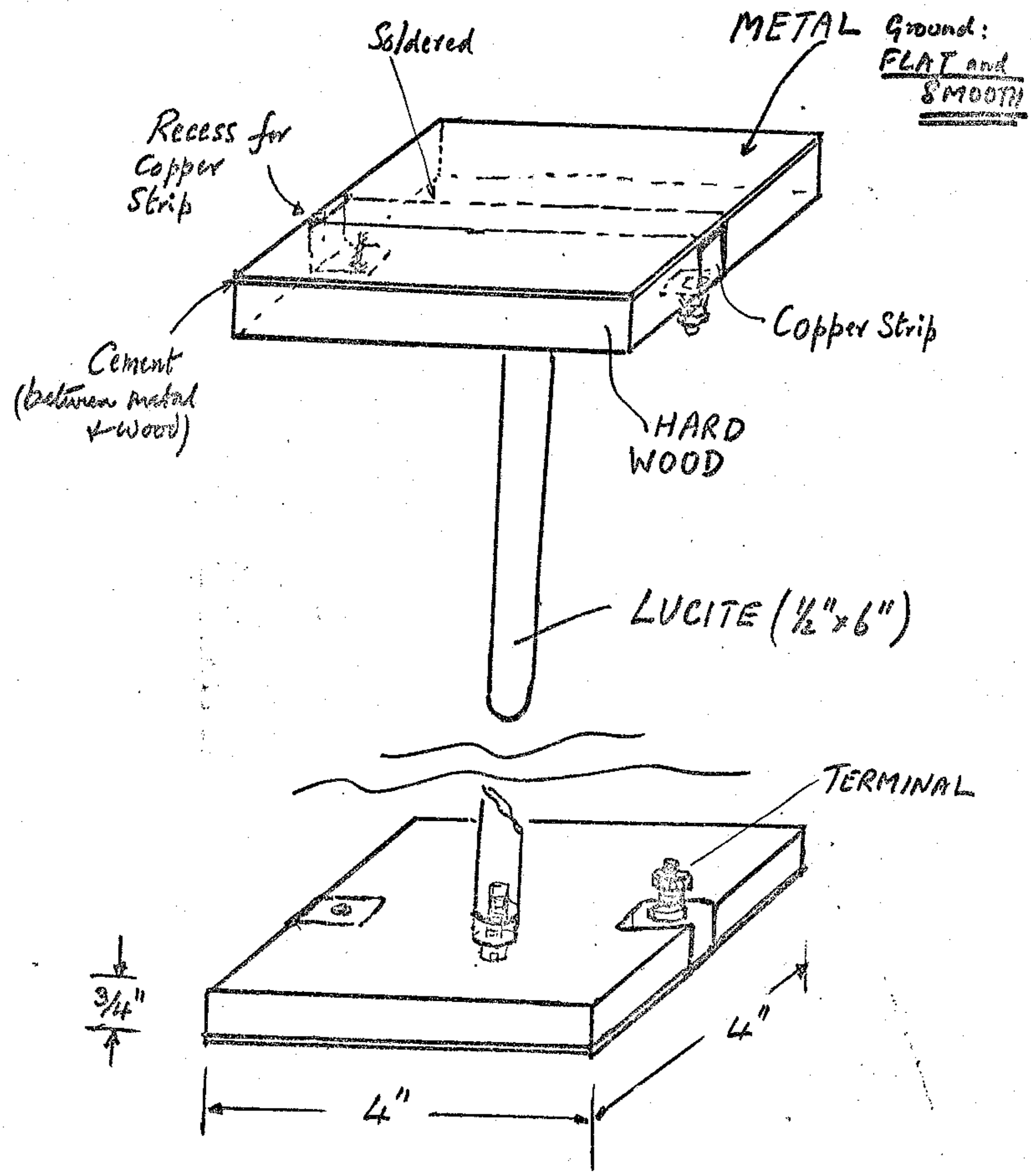


Fig. 3

Scale ~ ½

S.D.