THE SAGA OF THE VACUUM TUBE

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Part 2 of this authoritative series, shows the tremendous amount of preliminary work that led to the discoveries of the radio tube.

UP TO about 1800 the science of electricity was that of static electricity, the electricity which was developed in the electrical machine of that day, and stored in the Leyden jar.

Beginning at that time with the work of Galvani and Volta the emphasis in electrical research shifted to the field of galvanism and voltaic electricity. The technique of this work was essentially a technique of low impedances. We find little done during the next few decades which had any direct bearing on the field of thermionics. Not until the tools of voltaic electricity were developed and perfected, and high voltages and greater energies became available from the low impedance sources could any great amount of work be done in the high impedance field of thermionics.

The names of Galvani and Volta are inseparable in studying the development in this new field. The lives of these men are perfect contrasts in their approach to the study of this branch of science. Each man was a genius. As a result of their conflicting theories, there arose another of the controversies which provide such a wealth of material for the historian.

Luigi Galvani was an amateur in this field in the real sense of the word. He was a physician and anatomist by profession. His studies in the comparative anatomy of animals were responsible for his interest in electricity. A true scientist, his work was done with the utmost care. His powers of observation were so keenly developed that no detail passed unobserved or unrecorded. When he noted certain phenomena of animal electricity, he began to study the effects of electrical currents on animals. As a result of these experiments Galvani soon was convinced that muscular motion depended on electricity in the body.

At this critical time in his study the historical accident, which seemed to substantiate his theory conclusively, occurred. While we find several conflicting reports of exactly what took place, substantially the following occurred.

Galvani's wife, a well educated woman who was deeply interested in her husband's work, spent much time in his laboratory. When she became ill Galvani proceeded to prepare for her a soup of frogs which, according to the custom of the country, was considered a restorative. After he had skinned and cleaned the frogs he placed them on a table near an electrical machine. At that moment he was called away from the laboratory. While the machine was in action an attendant happened to touch, with a scalpel, the crural nerve of one of the frogs that was not far from the prime conductor of the machine. At the touch of the scalpel the frog kicked, and the kick of that dead frog changed the whole face of electrical science. When Galvani returned his wife called his attention to what had happened. It appeared to confirm his hypothesis and he proceeded to investigate the phenomenon at length.[38]

In the course of these investigations, Galvani attempted to determine what part, if any, atmosphere electricity played in this reaction. Accordingly he prepared some frog's legs, inserted brass hooks in the spinal marrow, and hung them on an iron trellis outdoors. He noted that under these conditions the frog's legs showed occasional convulsions even when the weather was fine, and the atmospheric electricity supposedly quiescent. In the course of his observations he happened to press the hooks against the iron trellis and found that the convulsions were produced whenever these dissimiliar metals were in contact. This was followed by many in-

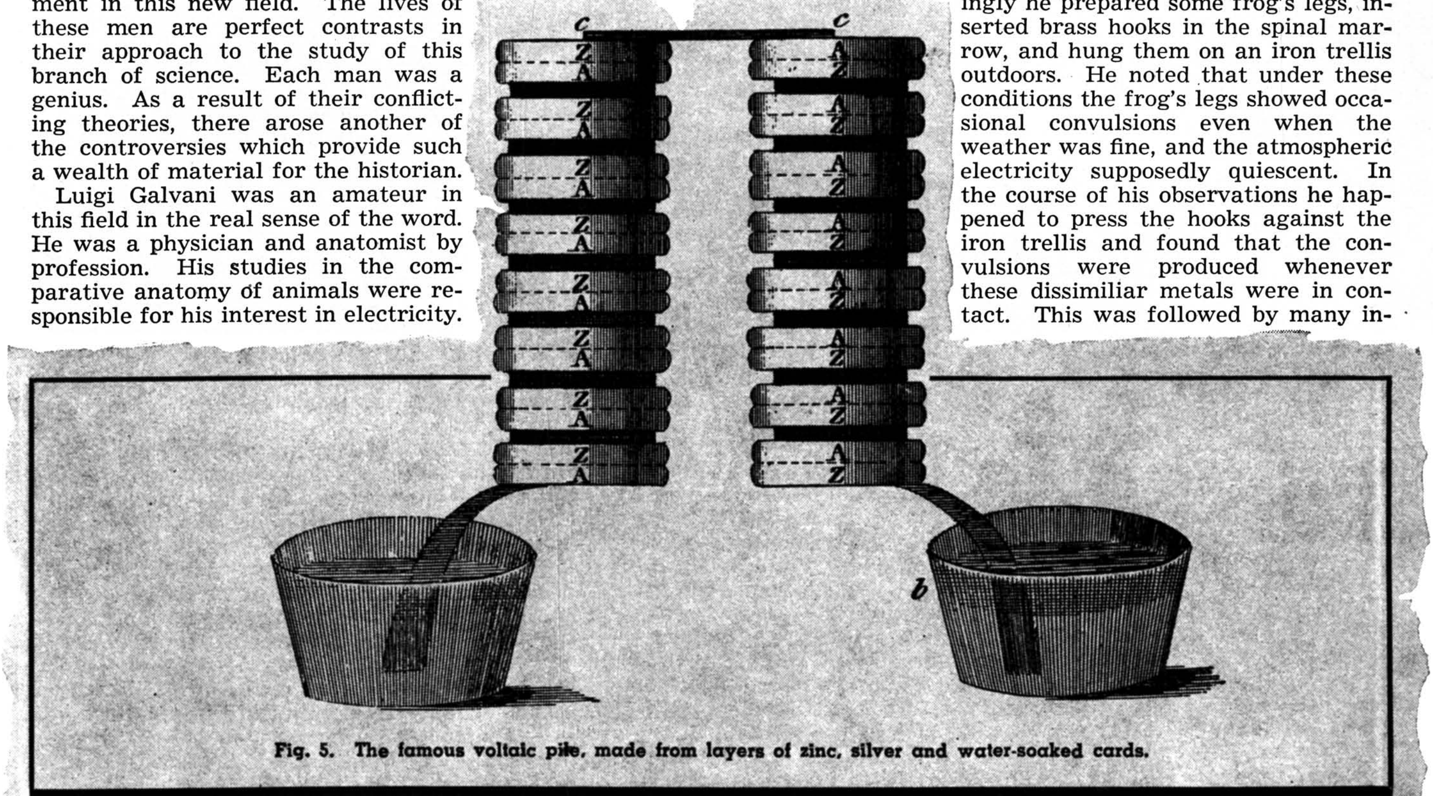

Fig. 5. The famous voltaic pile, made from layers of zinc, silver and water-soaked cards.

genious and clever experiments. His explanation of these results was that the electricity was due to the animal organism.

Similar observations had been made many years before by a Dutch naturalist Jan Swammerdam. In a book[36] published in 1737-8 experiments which he made in 1658 were described. During these experiments he obtained muscular contractions in frog's legs by means of combinations of silver and copper wires connected with the ends of the nerve. Also in a book[37] published in 1767 Johann Georg Sulzer had recorded the "galvanic taste" obtained by putting his tongue between two plates, one of silver and the other of lead, connected together by a wire.

After some years of investigation Galvani published an account of his work. No sooner did it appear than the philosophers in different parts of Europe entered with eagerness into the examination of this action—some to confirm, others to challenge.

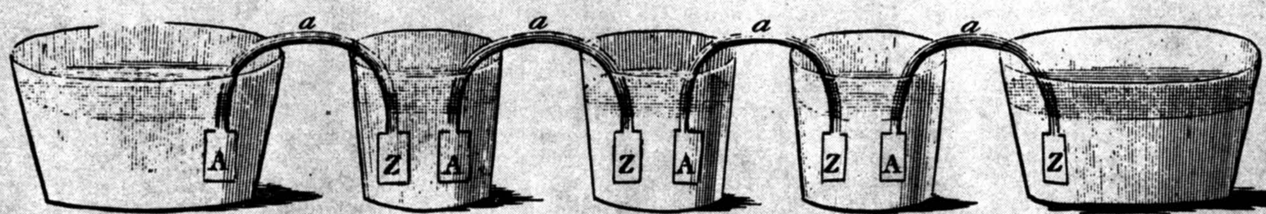

Fig. 6. Volta's revised voltaic pile (battery), called the "couronne des tasses."

Among those who did not accept Galvani's explanation was Alessandro Volta, of the University of Padua. In the relations of Galvani and Volta we see another excellent example of the combination of the amateur and the trained scientist—the value of the unchanneled thinker whose observations and discoveries open new doors for the mind of the trained scientist to enter. Volta, being Professor of Natural Philosophy at the University, was such a trained scientist. In fact he was the first of the scientists to confine his activities to that branch of physics dealing with electricity. Of necessity he was interested in allied subjects, but he devoted his life to the specialized field of electricity. Volta knew his theory. For this reason the great French scientist, Arago, said "There is not a single one of the discoveries of Professor Volta which can be said to be the result of chance. Every instrument with which he has enriched science existed in principle in his imagination before an artisan began to put it into material shape."[40]

Volta having read of the work of Galvani, repeated the experiments with his usual precision. Knowing his theory he could not accept Galvani's explanation of the twitching nerves in the frog's legs. He combined his observations with his experience and theory, and possibly with the experiences of Swammerdam and Sulzer in mind, he finally concluded that the nerve was merely a wet conductor between two pieces of metal, dissimiliar in nature, causing a flow of electricity which produced the reaction that Galvani had observed.

Volta communicated the results of his discoveries to the Royal Society of London, at the end of 1792, in the form of letters to Tiberius Cavallo.[41] He gave an excellent account of Galvani's discovery and added many experiments and observations of his own. In these letters he successfully laid down the basis for the theory of voltaic electricity.

Volta continued to actively investigate these phenomena and perfect his theory. He wisely concluded that, although the effect of one pair of plates or wires was small, it could be multiplied indefinitely by a plurality of such devices. He accordingly obtained a number of silver coins and pieces of zinc of similar dimensions; disposed them in pairs, and placed between adjacent pairs a card soaked in water. Thus came into being the famous *voltaic pile,* the first galvanic battery. See Figure 5. The effect of the combination fully justified his expectations. He found that electric shocks could be obtained from the pile as long as the pasteboard between the metals remained moist. These shocks were of the same kind as those produced by the electric machine.

Volta afterwards constructed another apparatus, or rather arranged the elements of the pile in a different fashion. It consisted of a set of small glasses, placed adjacent, and containing water or some saline solution. A number of metallic loops, with one end of zinc and the other of copper or silver, were inserted in the glasses in a uniform order, each glass having the zinc leg of one loop and the copper or silver leg of another loop, immersed in the liquid. Volta called this arrangement the "couronne des tasses" in his description of it in a letter to the Royal Society.[42] This arrangement is also shown in Figure 6.

Volta seems to have completely overlooked the changes which took place in the solution in the cups.

With the work of Volta electricity ceased to function as a series of jolts, and began to flow smoothly and controllably from pole to pole. A new day had dawned.

No sooner was the discovery of the voltaic pile announced than the English experimentalists began to use it, and almost immediately made some interesting and important observations. William Nicholson and Anthony Carlisle,[43] while conducting some of their experiments, made part of the circuit, connecting the extremities of the pile, of water. They noticed that gas was evolved where the connecting wires came into contact with the liquid. Subsequently the apparatus was arranged so that the gases given off from the two electrodes were kept separate, and it was found that (1) they consisted of oxygen and hydrogen and (2) that they were generated in the proportions that they occur in water.

About this time the relation in which the voltaic pile stood with reference to the Leyden jar and the electrical machine began to be perceived. In the Leyden jar a quantity of electricity under high tension is accumulated on the surface of the glass, and is held there in equilibrium. When communication is established between the two surfaces an almost instantaneous discharge takes place, and equilibrium is soon reestablished. A sudden, instantaneous, and violent effect is produced in whatever bodies are exposed to this electrical discharge in transit. The Leyden jar is a high voltage storer of electricity, quickly discharged. The voltaic pile, by contrast, is a generator of electricity in a continued current. It discharges not suddenly, but with a moderate, continued, controllable action. It is a comparatively low internal resistance device.

The experiments of Nicholson and Carlisle attracted the attention of Sir Humphrey (then Mr.) Davy, who was at that time starting the labors in chemical science which were later to surround his name with so much lustre. He repeated[44] their experiments and found that no decomposition could be obtained when the water was pure, i.e. that conduction depended on the presence of some impurity in the water. He continued his experiments and later demonstrated to the *Royal Society* that other substances than

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water (such as the fixed alkalis) could be decomposed in the same way, and thus laid the foundations of the science of electrochemistry.

In 1806, Paul Erman of Berlin wrote an elaborate memoir[45] on the conducting power of different bodies, which was awarded the prize of the *French Academy.* In this memoir we find the first mention of the action of flames in connection with the phenomena of voltaic electricity. He divided all bodies into five classes; perfect conductors, perfect non-conductors, imperfect conductors, positive conductors, and negative conductors. The nature of the first three classes requires no explanation; the fourth and fifth classes of bodies act as perfect conductors when applied to either of the two poles separately, but when placed between them, insulate either the positive or negative pole respectively and do not form a communication between them. The flame of a spirit lamp is described as a positive conductor; if it be applied to each pole separately it conducts the electricity; but if placed between the two poles it will not form a communication between them in consequence of its insulating the negative electricity. Although flame is a conductor, it does not conduct as perfectly as the metals. Flame is, however, a very different substance according to the body from which it is procured. The above observation refers to the flame of a hydrocarbon. The flame of sulphur insulates both the poles; that of phosphorus insulates the positive and conducts the negative.

William T. Brande, in 1814, reexamined Erman's work[46] and performed additional experiments with flames. He attempted to explain Erman's results on the basis of Davy's electrochemical theory. He postulated that some chemical bodies were naturally positive and some negative, and that they would be attracted toward the negative and positive poles of the pile respectively. Brande found that the flame of a hydrocarbon was attracted to the negative; and the flame of phosphorus which would contain a quantity of phosphoric acid, was attracted toward the positive. Here the bodies seemed to follow the then known laws of electrochemical attraction.

Meantime experimenters were improving on the voltaic pile and developing other forms of primary batteries. The evolution of this device, from the time of Volta to the present day, would fill volumes, hence we can only touch on it briefly.

In 1803, Hachette and Desormes substituted[47] starch for the liquid in the common voltaic pile, and in 1809 J. De Luc invented[48] the so called "dry pile," consisting of a column of alternate disks of paper gilt on one side, and zinc. This was not in reality *dry;* the paper imbibed and retained moisture enough to activate the pile. These modifications all produced a device which gave a high voltage but which had a high internal resistance.

Mr. John G. Children worked along somewhat different lines. Starting with Volta's "couronne des tasses" he increased the size of the elements, in order (as we now see it) to increase the current or quantity output. He first constructed a battery of twenty cells, with plates four feet by two feet, the cells being filled with a mixture of dilute nitric and sulphuric acids, with which battery he performed numerous experiments. He next made a battery of two hundred pairs of plates, each two inches square. From the experiments he performed with these batteries he deduced[49] that the *intensity* of the electricity is increased with the number of cells and the *quantity* with the extent of the metallic plates. He subsequently built[50] another battery of twenty-one cells, with plates six feet by two feet eight inches in size. This battery was first used in July 1813. Later a battery of two hundred cells, with multiple plates per cell, was installed at the Royal Institution. With the ouput of this battery many substances were fused and the electric arc between charcoal points was publicly demonstrated. This arc, or "arch," was described as follows by one of the historians of that day:[51]

"A singularly beautiful effect was produced by placing pieces of charcoal at the two ends of the wires in the interrupted circuit; when they were brought within the thirtieth or fortieth part of an inch of each other, a bright spark was produced, above half the volume of the charcoal, which was rather more than an inch long, became ignited to whiteness; and by withdrawing the points from each other, a constant discharge took place through the heated air, in a space equal to at least four inches, producing a most brilliant arch of light, this light constituted the sphere of activity of the instrument."

From this demonstration came the subsequent development of the arc lamp as a commercial source of light. Since it was so brilliant later scientists attacked the problem of making the unit smaller, that is, of "subdividing the electric light." This eventually led to the development of the incandescent lamp, and the modern vacuum tube. But this was far in the future, and the development of the tools with which it was finally accomplished went on.

The functioning of these early batteries was none too good, especially those containing acid electrolytes. Investigation by de La Rive showed[52] that this was due in part to "local action" caused by impurities in the electrode material, especially in the zinc electrode. Kemp,[53] followed by Sturgeon,[54] drew attention to the fact that this action could be reduced by amalgamating the zinc plates. In 1836 came the Daniell cell,[55] and in 1839 the Grove.[56] These were the first cells to use depolarizers in a practical way. The principles underlying depolarization had previously been recognized[57] by Becquerel, who also described cells similar to the Daniell, which however were not very much used. The Smee cell appeared in 1840 and the Bunsen cell in 1841.[58] This Bunsen cell was a modification of the Grove. The bichromate type cell usually referred to as the Bunsen cell did not appear until 1875.[59]

We have followed the development of the battery. While our source of electrical energy was growing from the abrupt discharge of the Leyden jar to the steady unidirectional flow of electric current, fortunately for us the age-old question of the relationship of electricity and magnetism still held the attention of some scientists. To these men the voltaic pile and its successors opened a new avenue of investigation. As we look into this phase of electrical research we shall see how their patience was rewarded.

In 1820 Hans Christian Oersted of Denmark, after spending thirteen years seeking some evidence of a physical interaction between magnetism and electricity, was suddenly rewarded for his perseverance. In this year he announced[60] to the world his discovery of the magnetic effect of the electric current. This discovery caused unqualified astonishment throughout Europe; more especially since all previous attempts to connect electricity and magnetism had proved unavailing. As might be expected, the experimental resources of every laboratory were brought to bear on the pursuit of the consequences of this newly-enunciated relation, so long suspected. The inquiry was taken up by Ampere, Arago, Biot, Savary, and Savart in France; Davy, Cummings and Faraday in England; de La Rive, Berbelius, Seebeck, Schweigger, Nobili, and others elsewhere in Europe.

Within less than three months after Oersted's announcement, Andre Marie Ampere communicated[61] the first of a series of Classic memoires on the subject of electromagnetism to the *French Academy.* In these memoires Ampere gave a far more complete exposition of Oersted's discovery than Oersted himself had done. He gave a definite rule concerning the direction in which the magnetic needle deflected when influenced by the passage of the electric current in a nearby wire. This is still known as *Ampere's Rule.* He disclosed the attraction and repulsion of parallel wires carrying electric currents, and proved that the force between them was directly proportional to the product of the currents and inversely proportional to the square of the distance between them. It was Ampere who decided that the direction of the current is the direction in which we imagine the positive electricity to move, and who introduced the term "galvanometer" to describe a current measurer which worked by means of the magnetic effect as it appeared.

While Galvani and Volta supplied the means for this development Oersted pointed out the main road to the application, and Ampere gave this application a fixed form, which is serviceable today. Later Faraday added to it something new and important both in form and matter.

Ampere succeeded because of his analytical mind and fertile imagination. Up to his time even the idea of the electric current was undefined. It was difficult for the philosophers to grasp exactly what happened when the wire was connected to the voltaic pile. We find that Volta used the term "courant electrique"[62] and Gray had previously spoken of the flow of electricity. Ampere decided, in 1820, to call the whole process in the discharge wire an *electric current,* and the direction of the current to be defined as the direction in which we imagine the positive electricity to move. This gave a pattern and terms to the study of electricity. We can understand the importance and significance of this when we note that even Oersted referred to the phenomenon as an "electric conflict" in the title of the book which announced his discovery.

Ampere was the first to make a clear distinction between *electric tension* and *electric current.* He realized that the phenomenon of electric tension existed in the voltaic pile before the circuit was closed, and could be measured by the electrometer, while that of electric current was absent until the circuit was closed. He felt that the current could best be measured by its magnetic effects.

Ampere was also the first to distinguish between *electrostatics* (the science of stationary electricity), and *electrodynamics* (the science of moving electricity). He also named these two branches of the science.

The names of Ampere and Oersted became linked for all time with the study of the mutual effects of electricity and magnetism. Oersted appears to have been the pure scientist. Apparently he gave no thought to the possible practical applications of his discovery. This was in line with his statement before the *University of Copenhagen* in 1814 that "The real laborer in the scientific field chooses knowledge as his highest aim." Oersted appreciated the utilitarian in science, but it took a flash of the genius of Ampere to see the practical application of Oersted's discovery. He thought immediately in terms of an electric telegraph. Ampere was not only a scientist but also an engineer.

Claude Servais Matthias Pouillet, in 1837, developed [63, 64] the sine and tangent galvanometers, which were later improved by Helmholtz. These were all moving magnet type of instruments. The first elementary form of the moving coil type was devised[65] by Sturgeon in 1824, and termed by him an "electrodynamoscope," improved by others until in 1882 it was modified by d'Arsonval to use a mirror and beam of light as a pointer. This instrument has ever since been known by his name.

The development of the tools proceeded. Sources of controllable energy and better instruments and methods of measurement became available. Along with them grew knowledge of the phenomena. Sir Humphrey Davy, as has been previously stated, laid the foundations of electrochemistry. His work was supplemented by that of Guyton-Morveau, Berzelius, and others. This work was rounded out by that of Michael Faraday, of whom we shall speak later.

With the discoveries, clear terminology, and clear cut laws established by Ampere we might think that the next link, Ohm's Law, would be readily seized upon by the scientists. This was far from what actually happened. As Ampere disclosed his findings the philosophers followed him step by step. They found that they could repeat the experiments, but their cold reception of Ohm's Law shortly after showed that, with the exception of Davy, the electrical scientists did not really understand what Ampere was doing. Both Ampere and Davy had conceived the idea of the *resistance* of a conductor. They noted that the strength of the current depended upon the nature of the circuit.

It was Georg Simon Ohm who found the answer to the questions raised concerning the work of Davy and Ampere. Though he had none of the recently developed tools to work with he cleverly improvised apparatus which would give the desired effect. After deep study and repeated experiments he settled forever the question of this distribution of the electromotive force in the circuit and also the strength of the current. So comprehensive was his knowledge of the phenomena that he was able to enunciate,[66] in 1827, the law which bears his name, and which is the keystone of all work in direct current engineering. This was done in a book in which was stated that the current in a circuit was directly proportional to the electromotive force and to the cross-section of the conductor, and inversely proportional to the length of the conductor. His book was ignored. Instead of fame and fortune, it brought its author misery and contempt. Not until 1841 was the importance of this work recognized, when the Royal Society awarded to Ohm the Copley Medal.

Michael Faraday was much more fortunate than Ohm in the matter of prompt recognition for his achievements. His early association with the great Davy placed him in a very advantageous position in announcing his discoveries to the scientific world. The searching mind of this great experimentalist was guided by his motto "It must be tried. Who knows what is possible?" He would spend years delving into the mysteries of science, making excursions into the unknown, with comprehension far beyond that of his contemporaries. And yet when a discovery was made, Faraday's explanation of it would be simple, concrete, and of such a nature as to add something practical to scientific knowledge.

Faraday had followed closely the work of Oersted and Ampere. They had obtained magnetism by means of electricity. He determined to investigate the possibilities of obtaining electricity from magnetism. As a result, mutual inductance, the phenomenon on which all transformer action is based, was discovered.[67] He was also the first to obtain continuous mechanical motion by electromagnetic means, and the first to use the terms "anode" and "cathode."

In 1838 Faraday observed that when an electric discharge is produced in rarefied air the negative electrode is covered with a glowing layer which is separated by a dark space from a glowing column extending from the positive electrode. Later this separation became known as the *Faraday dark space.* Subsequent investigation by Geissler, Plucker, Hittorf, and others, using higher vacua, but with cold electrodes, provided knowledge along the high voltage-vacuum path to the modern radio tube. Since we are confining ourselves to the approach along the high voltage-heat path (as previously stated), these phenomena will not be discussed. The student who wishes information along this line of research is advised to consult the work of Thomson,[68] Townsend,[69] and Loeb,[70] is which this branch of development is discussed at length.

Wilhelm Weber spent a long and industrious life adding to the knowledge of electricity. We have seen the work of brilliant men elsewhere in Europe making great strides in this field. Weber, to whom order was Heaven's first law, began his career by carefully studying what had been done by others. He summarized their work and proceeded to utilize the principles which they had enunciated. He devised more and better measuring instruments, which are the tools of the scientist. Among his achievements may be listed[71] the earth inductor and the electrodynamometer, the latter of which is the fundamental measuring instrument for all low frequency alternating current work. The accuracy of his measurements on newly discovered phenomena was such as to provide in the science of electricity a picture of harmony in which no gap remained. From the exact measurements of Weber stemmed the mathematical development of the electromagnetic theory, first worked out by James Clerk-Maxwell. Weber was also the first to define *unit current* and *unit tension.*

What was being done in America during these years of industrious investigation in Europe? Almost a century after Franklin we find the brilliance of another American star rising in the firmament of this science. Space does not permit us to go into detail concerning the work of the man after whom the unit of inductance was named. Suffice it to say that Joseph Henry constructed[72] the first electric motor embodying an electromagnet and a commutator. He discovered[73] the property of self-induction of an electric circuit, and produced currents in distant circuits by means of an oscillatory discharge.[74] It was from Henry that S. F. B. Morse learned how to make electromagnets for his telegraph. Henry also showed how to properly proportion the coils of a mutual inductance so as to give voltage step-up or step-down, which is to say that he began the work on transformer theory.

With the tools which had thus been developed by workers from all parts of the scientific world, let us see what progress was made in the science of thermionics.

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(To Be Continued)

U.H.F. Oscillators

(*Continued from page* 29)

tubes seem to have very little effect.

The screen grid acts as an effective shield, as mentioned previously, and must be hooked up as illustrated in Fig. 3. No R.F. chokes are to be used under any conditions in the filament or power leads, since at these frequencies the distributed capacity together with the inductance of such a choke would combine to give a parallel tuned circuit which would change the characteristics of the oscillator and possibly stop it from oscillating. Note remarks of this effect under discussion of coaxial tuner in "Ultra-High-Frequency Techniques" by the D. Van Nostrand Co.

Oscillator Calibration

Experimentally, this oscillator was first constructed on a breadboard, so that the component parts were readily available to change and experiment with. To check the frequencies at