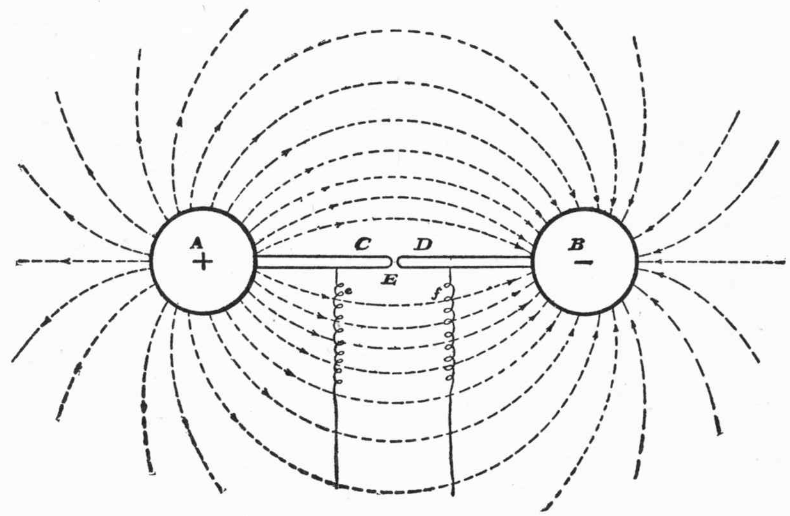
electrical oscillations. He then described in his inimitable way a preliminary report which Hertz had sent him, pointing out, in a most lucid manner, the bearing of these experiments upon the Faraday-Maxwell electromagnetic theory, and affirming that these experiments furnished a complete experimental verification of that remarkable theory. Everybody present was thrilled, particularly when Helmholtz closed with a eulogy of his beloved pupil, Hertz, and with a congratulation to German science upon the good fortune of adding another "beautiful leaf to its laurel wreath." That thrill soon reached the physicists in every physical laboratory in the world; and for a number of years after that memorable announcement most investigators in physics were busy repeating the beautiful Hertzian experiments. The radio of to-day is an offshoot of those experiments.

This is no place to go into a detailed description of what Hertz did. The fundamental idea underlying his beautiful research and its relation to the Faraday-Maxwell far-reaching electromagnetic theory can be described in very simple terms. The wonderful achievements of radio broadcasting alone, to say nothing of other much more important achievements, demand this description. That idea, like the tiny seed hidden in a beautiful flower, lay hidden in Faraday's visions and in Maxwell's wonderful, but, to most ordinary mortals, enigmatic interpretation of them. Hertz, guided by his great teacher, Helmholtz, caught the hidden seed and out of it grew a physical embodiment of the Faraday-Maxwell theory, represented by ideally simple apparatus, operating in an ideally simple way. The apparatus and its operation are now the heart and soul of a new art, the radio art, a beautiful daughter of the beautiful mother, the Faraday-Maxwell electromagnetic science. The following description of Hertz's apparatus and of its operation was the theme of popular lectures and of many conversations

which I had with my friends who were not physicists by profession. It represents quite closely the simple picture which I carried away in my mind from that memorable meeting of the Berlin Physical Society thirty-six years ago.

Two equal metal spheres *A* and *B*, each twelve inches in diameter, and each carrying copper rods *C* and *D*, are placed as indicated in the diagram given here. At *E* is an opening of about three-tenths



THE HERTZIAN OSCILLATOR

of an inch in length, the so-called *air-gap*. By means of two wires *e* and *f*, connected to an electrical machine, the spheres are charged, one receiving a positive electrical charge denoted by the (+) sign, and the other a negative one, denoted by the (−) sign. The air-gap *E* insulates one sphere from the other, and its function is to make it possible for the electrical machine to increase the two charges until a very high electrical tension is reached. When the electrical tension between the two charges, acting through the air-gap *E*, is sufficiently high, then the insulating power of the air-gap is overstrained and suddenly it breaks down and becomes conductive and permits the two charges to rush toward each other. The conductivity of the air-gap suspends the action of the charging machine. A large current passes then between the two spheres along the rods and through the air-gap E which is heated by the current to white heat. It becomes then a very good conductor and permits the charges to pass through it easily. The collapse of the air-gap is reported by the sharp crack of the electrical spark which is due to the very sudden heating and expansion of the air in the air-gap produced by the passage of the electrical current. It is a miniature lightning. The two charges reunite, the spheres are discharged, and after that the air-gap E recovers quickly from its breakdown and becomes an insulator again. The process is then repeated by the action of the machine and a rapid succession of sparks can be maintained, each one of them announcing by the crack of the spark the reunion of the charges that had been pulled apart and forced to the surfaces A and B by the action of the electrical generator.

All this was known long before Hertz. The first experiment of this kind I saw in Panchevo in my boyhood days, when my Slovenian teacher Kos explained to me the theory of lightning according to the views of Benjamin Franklin, a theory which clashed with the St. Elijah legend of Idvor and nearly proved me guilty of heresy. But there was something in these electrical discharges that Benjamin Franklin did not know, and that knowledge was first suggested by another great American scientist, a scientist even greater than Benjamin Franklin was in his day.

As far back as 1842 our own Joseph Henry performed experiments similar to those performed by Hertz, and he inferred, prophetically, that the discharge was oscillatory. Nobody ever suggested this idea before, but Henry's experiments permitted such an inference. Its oscillatory character was then demonstrated mathematically in 1853 by Professor William Thomson of Glasgow, and his calculation was proved to be correct by many experimental tests covering a period of over twenty-five years, and thus the electrical oscillator, similar to the one employed by Hertz, became a well-known apparatus.

What, then, was the novel element in the Hertzian work? It was, broadly speaking, his demonstration that the space surrounding the oscillator (the spheres with their rods) participates in the electrical oscillations in perfect agreement with the Faraday-Maxwell theory; a participation which was foreign to all previous electrical theories. In other words, he detected in the old electrical-oscillation experiments a new action, never detected nor even dreamed of before. He discovered the electrical waves in the space outside of the oscillator. Remembering the impression which Helmholtz's lecture on Faraday made upon my mind, I was certain at that time that nobody in Continental Europe but one of Helmholtz's pupils like Hertz could have predicted that there was in these well-known electrical oscillations a new action, an action demanded by the Faraday-Maxwell theory. A simple analogy will, I trust, help much to illustrate the new action which Hertz expected when he started out to search for an experimental test of the modern electromagnetic theory. No scientific expedition ever started out in search of scientific treasures and returned with a richer load.

Here is the analogy:

If by the force of our fingers we deflect the ends of the prongs of a tuning-fork and then let go, the prongs will return to their normal position after performing a number of vibrations of gradually diminishing amplitude. The state of rest is reached when the energy of bending, produced by the work of our fingers, has been expended, partly in overcoming the internal friction in the tuning-fork, partly in overcoming the reactions of the surrounding medium, the air; this last effect results in sound-waves which are radiated off into space. The stiffness and the mass of the prongs of the fork determine the period of vibration, that is, the pitch of the fork.

I confess that in the course of my life since my Berlin days I afforded considerable amusement to my friends whenever I tried to explain to them the Hertzian experiments by appealing to what I considered a well-known action of the tuning-fork. Some of them objected on the ground that this action is just as difficult to understand as the action of the Hertzian oscillator. I met this objection by describing to them the action of the reed in Serbian bagpipes which I watched when I was a boy, and understood sufficiently well to recognize later in the action of the tuning-fork a performance similar to that of the reed in the Serbian bagpipes. I understood the tuning-fork because I understood the reed. An educated American, I claimed, should find no difficulty in understanding the action of a simple mechanism which an uneducated Serbian peasant boy understood.

The Hertzian electrical oscillator, described above, acts like the tuning-fork. The process of pulling apart the two charges, the positive from the negative, and of forcing them to the surface of the spheres by the action of the electrical machine, is a parallel to the process of deflecting by the pressure of our fingers the prongs of the tuning-fork from their normal position. In one case the tuning-fork by its elastic stiffness reacts against the bending of the prongs. In the electrical case the electrical lines of force in the space surrounding the oscillator react against the action of the machine which crowds them into this space by stretching and compressing them. This is the picture of the action of the lines of force which Faraday gave me on the island of Arran, but I did not understand it. In the picture the dotted curves are the Faraday lines of force and the arrow-heads indicate the direction of the electrical force. The Hertzian oscillator, and what Helmholtz had told me before, made Faraday's language and thoughts much more intelligible. The work done by the machine is all expended upon the stretching and compressing of the lines of force into the space outside of the spheres, that is, upon the *electrification of that space.*

Compare now the motion of the tuning-fork, after the pressure of the fingers has been removed, to the electrical motion when the air-gap has broken down and the action of the electrical generator suspended. The prongs are driven back to their normal position by the elastic reaction due to the bending; but when they reach that position they are moving with a certain velocity, and their momentum carries them beyond that position; they move on until the energy of the moving mass has been expended in the work of bending the prongs in the direction opposite to that of the original bending. The prongs begin then to move back in the opposite direction, starting the second cycle of motion. The same line of reasoning will carry us into the third and fourth and every succeeding cycle of motion. It is obvious that these cycles will follow each other during equal intervals of time, which gives a definite pitch to the tuning-fork. A periodic motion of this type is called an oscillation or vibration; and it is clear that it is a periodic transformation of the energy of elastic bending into energy of motion of the mass of the prongs including the surrounding air, and vice versa. The motion is finally reduced to rest when the energy of

bending, produced at the start by the work of the fingers, has been used up. The question, what has become of that energy? is very important in this connection. The answer is: It is used up partly in overcoming internal friction and *partly in overcoming the reactions of the surrounding air, which result in sound-waves.* A sound-wave is a short name describing the physical fact that in the air there are compressions and dilatations alternating at periodically recurring intervals. The production of sound-waves in the air is a proof that the air in the space surrounding the tuning-fork participates in the motions of the tuning-fork.

A perfectly analogous experiment was performed by Hertz with his electrical oscillator, and his principal object was to find whether the electrical field, that is, the electrified space surrounding the oscillator, reacted as did the air driven by the vibrating tuning-fork; if it did it would develop electrical waves. If these electrical waves actually existed, what did Hertz expect them to be? In the description of the oscillator and of its action, given above, two things only were mentioned: the action of the electrical machine which charges the oscillator and the reaction of the lines of force against the tensions and pressures which crowd them into the surrounding space. The electrical waves can, therefore, be nothing else than periodic variations of the tensions and pressures in the lines of force, that is to say, periodic variations in the destiny of the lines of force in the space surrounding the oscillator. This was what Hertz had found.

The breakdown of the air-gap in the electrical oscillator and the consequent suspension of the action of the electrical generator is analogous to the removing of the pressure of the fingers from the prongs of the tuning-fork. The electrical charges on the spheres with the lines of force attached to them, strained by tensions and compressions, are released, and they move toward each other through the conducting air-gap. Just as the prongs of the tuning-fork, after the pressure of the fingers has been removed, cannot remain in the strained position in which they have been bent, so the electrical lines of force, after the insulating air-gap has broken down and the action of the machine been suspended, cannot remain in the position to which they are stretched; they contract, and hence their positive terminals on one sphere and the negative on the other move toward each other. The motion of the strained lines of force with their terminals, the charges on the spheres, has a momentum. Maxwell was the first to show that the momentum of the moving electrical lines of force is equal to the number of magnetic lines of force which, according to Oerstedt's discovery, are produced by the motion of the electrical lines of force.

The motion of the electrical lines of force has not only momentum but also energy. Employing Faraday's mode of expression we can say that the electrical energy of the stretched electrical lines of force is thus transformed into energy of the electrical motions. This is perfectly analogous to the passage of the elastic energy of the bent prongs of the tuning-fork into the energy of motion of the moving mass of these prongs. Again, just as the momentum of the moving mass of the tuning-fork bends the prongs in the opposite direction and continues this bending until that motion has disappeared, so the momentum of the moving electrical lines of force will stretch again the electrical lines of force and continue this stretching until the energy of motion has disappeared, when the two spheres are charged again, but in the direction which is opposite to that in the beginning. A new cycle of electrical motion is then started again by the stretched electrical lines of force, repeating itself in an oscillatory fashion until the original electrical energy, produced by the charging electrical machine, has disappeared.

But where has the energy gone? This question is just as important in this case as it was in the case of the tuning-fork. The old electrical theories answered this question one way, and Maxwell, inspired by Faraday, answered it in another. The old theories maintained that there is no other electrical motion except the motion of the charges along the conducting surface of the spheres and the rods. They paid no attention to the motion of the lines of force, because they knew nothing about them. Their vision did not see the lines themselves but only their terminals, the charges. Hence, according to the old theories, all of the energy imparted by the machine is transformed into heat in the conducting parts of the oscillator.

Hertz was the first to prove that a part of the energy is radiated off into space, in a similar manner as the energy of a tuning-fork is radiated off in the form of sound waves. He detected in the space surrounding the oscillator the presence of electrical waves, that is, periodically recurring variations of the destiny of the electrical lines of force; he measured their length, and, having calculated the period of his oscillator, he divided the wave-length by the period and obtained the velocity of propagation. It came out, in his earliest experiments, roughly equal to the velocity of light, as the Faraday-Maxwell theory had predicted. The waves were reflected and refracted by insulators denser than air, and all these and other effects Hertz demonstrated to follow the laws which hold good for light, supporting admirably Maxwell's theory that light is an electromagnetic disturbance. Even this preliminary report which Hertz had sent to Helmholtz convinced everybody that the Faraday-Maxwell electromagnetic theory had triumphed, and that our knowledge of electromagnetic phenomena had been wonderfully extended. Subsequent experiments by Hertz and others added more and more laurels to this first victory.

That meeting of the Physical Society in Berlin was what I always considered the inauguration day of the electromagnetic theory. Prior to that day the theory existed in all its beautiful completeness, but it dwelt on high in the celestial heights of Faraday and Maxwell. Continental physicists needed the guidance of a Helmholtz to reach these heights. After that day it came down to earth and lived among mortal men and became part of their mode of thought. It was a heavenly gift which Hertz brought down to earth. Everybody was convinced that the science of light had become a part of the science of electricity.

This new knowledge was the second great revelation of the nineteenth century. The wonderful things which followed in its wake, even before the nineteenth century had closed, testify to the greatness of that revelation.

I have often asked myself the question, Why did not our Joseph Henry, who discovered the oscillatory electrical motions and operated with apparatus similar to that employed by Hertz, pursue his studies further than he did in 1842? and why did not Maxwell, the formulator of the modern electromagnetic science, perform those ideally simple experiments which Hertz performed? The knowledge of the electrical oscillator was the same in 1865 as in 1887, and Maxwell undoubtedly had that knowledge. History offers an answer to these questions and this answer throws a splendid light upon the character of these two great scientists.

Soon after 1842 Joseph Henry resigned his professorship at Princeton College, and bade good-by to his laboratory where he had made several of his splendid discoveries, and where in 1832 he had constructed and operated the first electromagnetic telegraph, one of the practical results of his great discoveries. This happened long before Morse had ever been heard of. Henry's fame among men of science was very great and promised to grow even greater if he continued his scientific researches. He was still in his prime, only a few years over forty. But a patriotic duty called him to Washington, where the Smithsonian Institution waited for his skilled hand to organize it and to defend it against the scheming politician. This duty tore him away from his beloved laboratory, and he spent the rest of his life, over thirty years, in Washington as secretary of the Smithsonian Institution, as originator of most of the national scientific bureaus of which this country is proud to-day. He was also the first president of the National Academy of Sciences, chartered by Congress in 1863, thanks to his efforts. Physical science under his leadership had rendered valuable service to the country during the Civil War, and the congressional charter to the National Academy of Sciences was a graceful recognition of this service. I have already pointed out Joseph Henry's splendid efforts for the advancement of scientific research in this country and shall return to it later. He was a great scientist, but he was also a great patriot; his country stood first and his own scientific achievements and fame stood second in his

heart. That, I am sure, was the reason why he did not pursue any further than he did his researches of electrical oscillations. I will mention here that one of the most gratifying results of my humble efforts was the naming of an electrical unit after his name. My colleague, the late Professor Francis Bacon Crocker of Columbia University, joined me most enthusiastically in these efforts; and the Electrical Congress in Chicago in 1893, at which Helmholtz presided, adopted the name Henry as the unit of electrical inductance; the unit Farad was named in honor of Faraday. No other electrical units are in more frequent use than the Farad and the Henry, particularly in the radio art. No other men contributed to this art as much as Faraday and Henry did.

Maxwell resigned his professorship at King's College, London, at the end of 1865, soon after he had communicated to the Royal Society his great *memoir* on the electromagnetic theory. The electromagnetic theory of light which, as I pointed out before, he had called "great guns" in a letter addressed to a friend, was the climax of it. He retired to his country place, Glenlair, in Scotland, and for five years he was free to devote his entire time to study and meditation. That was the highest joy of his life. But the Duke of Devonshire, a loyal Cambridge man, had presented the university with a goodly sum of money for the building and equipment of a physical laboratory. It was to be named the Cavendish laboratory, after Lord Cavendish, the Duke's illustrious ancestor, who had devoted his life to electrical science. This gift was the Duke's response to the Cambridge movement in favor of scientific research. Maxwell was called to Cambridge to become the director of the new laboratory, and he responded, knowing well that, from that moment on, most of his time would be devoted to organization and administration. Duty to his university, and to the cause of scientific research in Great Britain, stood higher