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LAW, DESCRIPTION AND HYPOTHESIS IN THE ELECTRICAL SCIENCE[1]

YOUR invitation to deliver the first Steinmetz lecture I consider a very great honor. The late Doctor Steinmetz was a dear friend of mine. I met him in Yonkers in 1889, and from that time on until his death we were tied to each other by bonds of personal sympathy and scientific interest, which was a source of uninterrupted pleasure to both of us.

This lecture is an attempt to describe briefly how Faraday and Maxwell, starting from definite laws which were discovered by experiment, created the modern electromagnetic theory by a prophetic use of description and hypothesis and how this theory furnishes the foundation of the science of electrical engineering. Our knowledge of electrical phenomena began its career as a science when it started to build upon a foundation of a quantitative law. Coulomb's law marks, therefore, the beginning of the electrical science. It says that two electrical point charges in a vacuum act upon each other with a mechanical force which is equal to the product of the two charges divided by the square of the distance between them.

In its mathematical form Coulomb's law is identical with Newton's law of gravitational action. Many theorems which the mathematical physicists of the eighteenth and the beginning of the nineteenth century had developed in their analysis of gravitational fields of force were, apparently, directly applicable to the analysis of electrical fields. This was very fortunate, because it attracted some of the best mathematical minds of those days to the electrical science. This raised its standing among the sciences which it badly needed.

Newton's great essay, "Principia Philosophiae Naturalis," published in the beginning of the eighteenth century, created a new school of natural philosophers which dominated during the eighteenth century the scientific mental attitude of the world. No natural philosopher of those days could expect to attract serious attention who departed from the rigorously mathematical methods of this school. Even so great a natural philosopher as Benjamin Franklin may be said to have been snubbed by the Royal Society, when it refused to publish in its transactions Franklin's communications describing his electrical experiments. These experiments, suggested by and clustering around

[1] The first Steinmetz lecture delivered on May 8, 1925, before the Schenectady section of the American Institute of Electrical Engineers.

Leyden jar discharges, had no obvious connection with the Newtonian school of natural philosophy of the eighteenth century and, therefore, the Royal Society failed to recognize their full significance. One may imagine how welcome Coulomb's law was to some natural philosophers of the eighteenth century, to whom Newton's Principia was as final as the book of Genesis is to some people of our own generation.

Faraday was the first to point out a fundamental difference between Newton's law of gravitational action and Coulomb's law of electrical action. The action of a gravitational mass upon another gravitational mass is not influenced by the medium separating the two, but the action of an electrical charge upon another electrical charge is influenced very much by the medium separating the two. Coulomb's law, unaided by other considerations, was unable to explain this difference. Additional knowledge was needed which Coulomb did not possess. Faraday was the first to enter into these considerations, and his first guide may be said to have been a hypothesis which maintained that all electrical charges trace their origin to the molecules and atoms of material bodies, which in their normal state contain, according to Franklin, the same amounts of positive and negative charges. This hypothesis of the atomic origin of electrical charges was undoubtedly suggested by Faraday's classical studies of the behavior of electrolytes, which revealed a new truth, namely, that a definite electrical charge is attached to each valency of atoms. The granular structure of ordinary electrical charges and the whole modern electron theory was first foreshadowed in these experiments. But how did this hypothesis affect Coulomb's law of force between Coulomb charges which are surrounded by a material medium?

Consider the insulators. The hypothesis suggested that in an insulator each molecule contains a definite quantity of positive and an equal quantity of negative charge which can be separated from each other by the action of an external electrical force impressed upon them, but that the distance of separation can not exceed the dimensions of the molecule. Adopting this picture of the electrical structure and behavior of insulators there was readily deduced a modified form of Coulomb's law of force between charges separated by an insulating medium, and this modified form of Coulomb's law says: *The force between two point charges in an iusulating material medium is equal to that in a vacuum divided by a constant, called the specific inductive capacity of the material medium.*

But experiment told us that the hypothesis mentioned above concerning the process of separating molecular charges and everything inferred from it can be only approximately true, because the specific inductive capacity of material insulators is usually neither constant nor does it always have a definite meaning. This law, therefore, could not be taken as our infallible guide in the study of the electrical fields of force in material insulators. The question arose then: Is there any other law to which we can appeal for guidance? Faraday's study of the electrical action of insulators, a subject to which Benjamin Franklin first drew attention, showed a way leading to the answer of this question. This study suggested one of the two great foundation pillars of the modern electromagnetic theory, which I venture to describe here briefly.

Faraday's method of representing graphically the field of force of electrical charges is well known, and it finds its simplest illustration in the well-known conical tubes of force drawn from a point charge as vertex and expanding into all space. We are also familiar with Faraday's tubes[2] of force for any distribution of electrical charges. Faraday's pictorial method of describing the field of force leads to the same numerical results as Coulomb's law when the surrounding medium is free space without any material bodies in it. When, however, the surrounding medium contains material insulators then Coulomb's law offers small assistance in our study when these insulators have a variable specific inductive capacity and deviate otherwise from the characteristics of an ideal dielectric. It will be pointed out below that there are electric and magnetic fields which are not due to charges and in which Coulomb's law is altogether inapplicable. Faraday's picture of the field in terms of the tubes of force suggested to Maxwell a new law of force which is broader than Coulomb's law both in its meaning and its applicability.

Faraday's ideas concerning the physical character of the tubes of force were a guide to Maxwell, whose earliest studies of electrical phenomena, while still an undergraduate at the University of Cambridge, related to Faraday's "Physical Lines of Force." In these early studies Maxwell made wonderful attempts to show by imaginative description and ingenious mechanical models what he saw in Faraday's tubes. But all these things were only a temporary scaffolding around a new structure which Maxwell was building. When the structure was finished the scaffolding disappeared and what do we see to-day? I shall try to answer this question. In Maxwell's mind, just as in the mind of Faraday, the tubes of force were not mere geometrical pictures but represented physical entities capable of actions and reactions. Each volume element of a tube of electric force is according to Faraday and Maxwell the seat of an electrical re-

2 The term "tubes" is preferable here to "lines" because it brings out clearly the three-dimensional character of these structures.

action against the change of its density, that is, of the number of tubes per unit area. When the surrounding medium is a vacuum or an ideal insulator, that is, a dielectric with a constant specific inductive capacity, then the numerical value of this reaction can be calculated. According to Maxwell's hypothesis, the electrical reaction in this case per unit length and unit cross-section of the tube is equal to the density of the tubes in the direction in which the reaction is considered, divided by the specific inductive capacity. The hypothetical reaction had a most significant corollary; it located the energy of the field in the volume elements of the tubes of force and assigned to each element, per unit of volume, an amount proportional to the square of the density of the tubes of force at that volume element. Dynamically, therefore, there is a perfect resemblance between the field of electrical reactions in ideal insulators and the field of elastic reactions in the interior of an elastically strained body which obeys the so-called Hooke's law.

According to this view, the charges transmit their action through the volume elements of the tubes against the reaction of the tubes. *When the field of electrical force is in equilibrium then the external actions coming from the electrical charges and the internal electrical reactions of the tubes are equal and opposite to each other at every point of space.*

This form of statement is suggested by Newtonian dynamics and furnishes a law which conforms to Newton's third axiom. It is different from Coulomb's law in form and meaning, and it holds good no matter how the impressed electrical forces are generated or what the physical character of the material insulators is upon which these forces are impressed. It is obtained from the hypothesis that the tubes of force are physical entities which react against a change of their density. There is nothing in Coulomb's law which suggests this hypothesis and there can not be, because this law suggests nothing concerning the velocity or the mechanism of transmission of force between electrical charges, whereas a reacting tube of force was suggested to Faraday and to Maxwell by the intuition that electrical actions are transmitted through the tubes of force with a finite and definite velocity which depends upon the dynamical properties, that is, upon the reactions, of the tubes. The tubes of force attached to electrical charges or otherwise generated are, according to this hypothesis, the transmitting mechanism reacting in every one of its elements by reactions which in the case of the vacuum and of ideal dielectrics are identical in form with the elastic reactions of an ideal elastic body. This view of the field of electrical force is one of the foundation pillars of the Faraday-Maxwell electromagnetic theory. I shall next describe briefly the second foundation pillar of this theory.

What has been said above about our knowledge of electrical phenomena is also true of our knowledge of magnetic phenomena. It started its career as a science when Coulomb's measurements succeeded in formulating a law of force between magnetic charges. Since this law is identical in form with that for electrical charges, and since the presence of material bodies affects similarly a magnetic field as the presence of material insulators affects an electrical field it is obvious that the Faraday-Maxwell intuitive philosophy leads here to the same results as in the case of electrical fields of force. Coulomb's law can, therefore, be replaced by a law which is identical in form with the law formulated above for electrical fields. It is as follows: *When the field of magnetic force is in equilibrium then the external magnetic actions and the internal reactions of the magnetic tubes of force are equal and opposite to each other at every point of space.* Description and hypothesis serve here the same object as in the case of the electric fields, namely, to point out that the magnetic tubes of force are the transmitting mechanism of the magnetic force and that the quantitative relation between the forces impressed upon the tubes and their reactions is one of the determining factors of the mode of propagation.

It is obvious that so far I have been endeavoring to show that Faraday's and Maxwell's views paved the way to the formulation of new concepts, the concepts of electrical and magnetic actions and reactions, which like ordinary material actions and reactions obey Newton's third law. These endeavors will be continued in what follows.

The law of equality between electrical and magnetic actions and the respective reactions in fields which are in static equilibrium can, obviously, tell nothing definite about the velocity of propagation. Reactions brought into play when this equilibrium is disturbed must be considered. Do they exist, and if so, do they show that the velocity of propagation of electrical force is the same as or different from that of the magnetic force? The electrical science prior to Oersted's and Faraday's discoveries could not have answered this question. These discoveries supplied the necessary knowledge. Broadly stated, they revealed the following new truth: Oersted discovered that electrical charges moving through conductors produce magnetic tubes of force which are interlinked with the conductors; Faraday discovered that magnetic charges and their tubes of force produce by their motion or variation electrical forces in conducting circuits which are interlinked with these tubes. This description of the discoveries intentionally emphasizes the two facts, namely, that Oersted made his discovery while experimenting with conduction currents, and that Faraday explored the electrical field in conducting wires, only, which are interlinked with the magnetic tubes of force. The laws resulting from these experiments, namely, Ampère's law and Faraday's law, were necessarily limited to the conditions of the experiments which led to their formulation. Neither one nor the other were sufficiently general to give direct information concerning the unknown reactions associated with the variable electric and magnetic tubes of force at any point of a dielectric. Oersted's and Faraday's experiments did not detect them, nor was it obvious how to detect them experimentally. New hypotheses were needed and Maxwell was the first to formulate them; they were as follows: First, a variation of the flux, that is, of the total number of electrical tubes of force through any area, is equivalent to the motion of electrical charges through that area; in other words, the so-called displacement current produces according to Maxwell the same magnetic effect as the conduction or convection current. Secondly, the variation of the flux of the tubes of magnetic force through any area produces an electromotive force around the boundary curve of this area which is independent of the material through which this boundary curve passes. These two hypotheses extended the meaning of the Ampère and of the Faraday law and gave them that symmetry which is expressed in the following statements:

The rate of variation of the electric flux through any area is equal to the magnetomotive force in the circuit which forms the boundary curve of that area.

The rate of variation of the magnetic flux through any area is equal to the electromotive force in the circuit which forms the boundary curve of that area.

The first statement represents Maxwell's generalization of Ampère's law, and the second that of Faraday's law. Mathematical physicists call them Maxwell's field equations. This name does not convey clearly their physical meaning, nor does it express fully their historical significance. Prior to the time of Oersted and Faraday there were only a few, rather feeble, processes of generating and impressing upon material bodies electric and magnetic forces; frictional machines, galvanic cells, action of permanent magnets, etc. . . . Ampère's and Faraday's generalized laws describe new processes of generating and impressing magnetic and electric forces upon *any part of space*. They might be called Maxwell's laws of electrodynamic generation, or briefly *Maxwell's laws*, the rest of the proposed title being understood. These laws give the total sum of the electric and magnetic forces impressed by those processes upon any circuit; the energy principle tells us that this sum is equal to the sum of the electric and of the magnetic reactions in the circuit. The parcelling out of the total impressed forces thus generated among the volume elements of the circuit and the character of the reactions of each volume element must be determined by the character of each problem and by the physical properties of each volume element of the circuit. Circuits in ideal isotropic dielectrics present the simplest illustration of the general procedure, and this was the subject which Maxwell considered first. In this case the reaction per unit cross-section and unit length of the circuit is, as already pointed out, equal to the ratio of the flux density to the specific inductive capacity, or permeability, respectively, and this reaction must be equal to the force generated by the variable fluxes and impressed per unit length of the circuit. This leads to a reciprocal relation between the electric and magnetic reactions in variable fields which in an isotropic dielectric exhibits a process of propagation identical in form with that obtained by Newtonian dynamics for the actions and reactions in an isotropic, incompressible, elastic medium. Maxwell's greatest achievement is, in my opinion, his introduction into the electrical science of new concepts, electric and magnetic actions and reactions, which obey the same laws as the corresponding concepts in Newtonian dynamics. But it should be observed here that Maxwell's success was due to Faraday's suggestive description of the electric and magnetic fields in terms of tubes of force and to the intuition which created the epoch-making hypotheses endowing these tubes with dynamical attributes formerly belonging to material substances only. These hypotheses demanded experimental verification; Hertz seized the opportunity and furnished the epoch-making demonstration of the correctness of Maxwell's hypotheses.

The propagation of force through an ideal elastic solid makes the velocity of propagation depend upon two constants only, the density and the elastic constant. The first determines the inertia reaction and the second the elastic reaction per unit volume of the solid. Similarly in the propagation of the electric force through the electric and magnetic tubes of force in an ideal dielectric the velocity of propagation depends upon two constants only; the specific inductive capacity of the tubes and their magnetic permeability. One determines the reaction of the electrical tubes of force, and the other the reaction of the magnetic tubes. These reaction constants determine the velocity of propagation through the electric and magnetic tubes in the same manner as density and elastic constant determine the velocity of propagation through ideal elastic bodies. The question arises, which of the two reaction constants of Faraday's tubes corresponds to the density and which to the elastic constant of material bodies? In other words, which of the two constants is characteristic of the inertia reaction of the tubes?

The generalized laws of Ampère and of Faraday, which I call the Maxwell laws, suggest a permissible answer to this question. They indicate a scheme which demands one fundamental flux, the electric flux, called here the primary flux. A variation or velocity of motion of the electric flux generates, according to the first Maxwell law, magnetic forces and corresponding magnetic fluxes which in an isotropic dielectric are proportional to the impressed magnetic forces, the factor of proportionality being the magnetic permeability of the tubes of the magnetic field. If, therefore, we consider the magnetic flux of the field, thus generated, as the momentum of the varying or moving electric flux, since it is proportional to its rate of variation or velocity of motion, then the electrical field generated, according to the second Maxwell law, by the variation of the magnetic flux will be due to the change of this momentum. According to this scheme the permeability constant in the electromagnetic theory would correspond to density in the theory of propagation through elastic solids.

Electron physics supports this scheme. It traces the origin of all magnetic forces of magnets to the orbital motions of electrons. This reminds us of the old Ampèrean conception. Magnetic tubes of force associated with so-called permanent magnets are, according to electron physics, the result of the motion of electric tubes of force attached to electrons. Maxwell always associated with magnetic tubes of force the momentum of some electric motions. What Faraday called the electrotonic state he called the electrokinetic momentum of a circuit, that is, the magnetic flux interlinked with the circuit. The reactions of varying magnetic tubes of force are, therefore, inertia reactions and their reaction constant, the permeability, should, as already pointed out, be considered as corresponding to the density of elastic solids, whereas the reciprocal of their specific inductive capacity corresponds to the elastic constant. Faraday's tubes of force in free space have, in electromagnetic units, a permeability equal to unity and, measured in the same system of units, an exceedingly small specific inductive capacity. They behave, therefore, like incompressible elastic bodies of moderate density but of very high elastic constant for shearing strains. It is equal to 9×10^{20}. Hence the great velocity of propagation of electromagnetic disturbances through tubes of force in free space, as experimentally verified by Hertz.

Electrical propagation through ideal dielectrics, including the vacuum, demands, according to the above picture, nothing more than Faraday tubes of electric force capable of two distinct reactions, one an electrical reaction and the other a magnetic, that is an inertia, reaction. The tubes react like a material medium of reasonable density but of most extraordinary stiffness. But neither this similarity to material bodies nor anything else in our present knowledge of electrical phenomena justifies the hypothesis that they consist of a substance which has qualities of ordinary matter in bulk. One can not resist the temptation of asking the question: What are these tubes made of? I venture, therefore, to offer the following pardonable suggestion.

Our ideas of these tubes are associated with our concepts of electrical charges which are the terminals of the tubes when they have a terminal. In this we follow in the footsteps of Faraday. It is not an unreasonable hypothesis to assume that they are made of the same fundamental substance of which the electrical charges are made. The name "electricity" may, therefore, be reserved for that substance, whatever it may be, so that we may say: The medium which transmits electrical disturbances is "electricity," meaning thereby the substance out of which electrical tubes of force are made. Light is an electrical disturbance and it is, according to this view, transmitted by electricity. The concept suggested by the word "electricity" is much more definite than that suggested by the words "lumeniferous ether," because we associate with electricity two perfectly well-known and experimentally determinable reaction constants, that is, the reaction constants of the primary flux of force at rest and in motion. These are the only attributes that we can dynamically predicate of a material substance, hence the concept "electricity" is dynamically just as definite as the concept "material substance"; the concept "ether" is not.

Perhaps I have dwelt too much upon that part of the electromagnetic theory which is a little outside of the daily problems of the electrical engineer. Some people think that it is entirely outside of the theory which underlies electrical engineering problems. Permit me to show you, as briefly as I can, that this is not so, and that the same form of laws and the same dynamical methods apply to electrical engineering problems as to the problems discussed above. Electrical engineering problems deal with actions and reactions in electrical and magnetic circuits and so does the general electromagnetic theory. I have pointed out how starting with Coulomb's law a more general law was formulated for the field of force due to electrical or to magnetic charges at rest, the law of equality of actions and reaction in every volume element of the field in static equilibrium. The validity of this law was maintained for the dynamical equilibrium of variable fields when Ampère's and Faraday's laws were formulated by Maxwell in their most general form. The principle of conservation of energy demands that this law be always true irrespective of the physical character of the circuit or of the process of generating the impressed forces. This furnishes then the most fundamental basis in theoretical electrical engineering. It may be stated as follows:

In every circuit or part of a circuit the algebraic *sum of electrical reactions is equal to the algebraic sum of the impressed electric actions.*

Omit the words "electrical" from this statement and you have the most fundamental law in Newton's dynamics, showing that "electricity" obeys the same fundamental law which ponderable matter obeys.

Take for an illustration an electrical circuit in which we have a constant electromotive force, generated by a voltaic cell and a constant current flowing through a conducting wire. Consider any two points on the wire. Heat is generated in the wire between these two points and, therefore, there must be an electrical reaction in the wire between these two points. Heat is the result of the work done against this reaction by the impressed electrical force transmitted by the battery. This reaction may be called a *resistance reaction,* whereas the impressed action is the difference of potential between these two points. The law of equality of action and reaction says: The resistance reaction is equal to the difference of potential. This relation is independent of the so-called "Ohm's Law." When, however, the wire is maintained at constant temperature then its resistance reaction is found by experiment to be proportional to the current; this empirically established characteristic of most metal wires is called Ohm's law. It really is not a law any more than Joule's rule for the rate of heat generation by a current flowing through a metal wire. Both are accurate empirical descriptions of a physical characteristic of most metal wires. It is occasionally stated, with some show of disappointment, that the flow of current through a gas does not obey Ohm's law, which really means that the resistance reaction is not proportional to the current, and that it can not be described as simply as the resistance reaction of a metal wire. That a conducting gas should react differently than a conducting metal wire should not surprise anybody; but it seems that it does.

Consider, as another simple illustration, a toroidal magnetic circuit consisting of several different radial sections of different kinds of steel separated from each other by small air gaps and magnetized by a current flowing through turns of wire wound around the toroid. The total magnetomotive force generated by the current is given by Ampère's law. Each part of the magnetic circuit receives its definite share of the total magnetomotive force; this share is the magnetizing force impressed upon that part of the circuit. In each part of the magnetic circuit the impressed magnetizing force is equal to the magnetic reaction of that part, so that according to the fundamental law the sum of the magnetic reactions is equal to the total impressed magnetic actions, which is the magnetomotive force. This is the fundamental law, whereas the usual method of calculating, roughly, the magnetic flux from impressed magnetizing forces and reluctances by making use of a new kind of Ohm's law for the magnetic circuit is, in my opinion, a misleading use of the word law. This spurious Ohm's law is abandoned, of course, as soon as we attempt to devise an experimental method for measuring hysteresis losses during a complete cycle of magnetization, but we do not abandon the dynamical law that in every part of the magnetic circuit the magnetizing force is equal to the magnetic reaction. On the contrary, we could not interpret without it the hysteresis losses during cyclic magnetizations.

When in a network of linear conductors alternating current generators are located at various points of the network, the current distribution in the network can be calculated by setting up equations for each circuit, which state the fundamental dynamical law that in each circuit the algebraic sum of electrical reactions is equal to the algebraic sum of impressed electromotive forces, generated by the alternators. To call these equations mathematical expressions of a Kirchhoff law, as some do, is unpardonable abuse of language. Kirchhoff gave the *rule* that for any circuit in a network of metallic wire conductors in which there are sources of constant electromotive force the algebraic sum of the electromotive forces is equal to the algebraic sum of the products of current and Ohmic resistance; but he never suspected that this is a special case of the fundamental dynamical law given above.

It is true that in 1858 Kirchhoff, in his analysis of electrical propagation along an overhead telegraph wire, stated correctly the relation between the electrical reactions at any element of the wire, and in this statement he was guided by Thomson's discussion of electrical propagation over a submarine cable. But neither Thomson nor Kirchhoff were aware of the general law, stated above. Maxwell's electromagnetic theory had not yet been published, and prior to that publication the general law implicitly contained in this theory, and which is to-day the foundation of electrical engineering, could not be formulated.

The several simple examples cited above suffice to illustrate clearly that electrical engineering problems, on their purely scientific side, are formulated in the same way as the problems in the general electromagnetic theory. Their solutions are obtained by the application of the same form of the fundamental laws employing the same methods of reasoning and the same terminology which Newton had formulated when he created the science of dynamics. The possibility of describing electrical phenomena in terms of Newton's concepts and language is one of the greatest achievements of Faraday and Maxwell. Law, description and hypothesis were never employed with greater effect than by the genius of these great prophets of the electrical science.

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