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TENDENCIES OF MODERN ELECTRICAL RESEARCH.

MODERN electrical research may be divided into two principal groups. Faraday's discoveries in electro-chemistry form the central part of the first group. The characteristic feature of the second group is Faraday's view of electro-magnetic phenomena, the view, namely, that electric and magnetic forces between material bodies act contiguously, that is from point to point through the intervening medium, the lumeniferous ether. These two groups are the foundation pillars which support the splendid edifice of the modern science of electricity. Faraday laid its foundation and he also raised the most essential parts of its splendid structure. But this structure bears to-day so many marks of the genius of Maxwell, Thomson, Helmholtz and Hertz that in our admiration for the exquisite detail which we owe to these great followers of Faraday we often forget the original design and the designer. Even so eminent a mathematical physicist as Poincaré can write profound mathematical treatises on modern electro-magnetic theory with scarcely a mention of Faraday's name.

A broad view of the tendencies of modern electrical research is obtained by comparing the fundamental concepts concerning electric and magnetic phenomena which pre-

*An address delivered before the New York Academy of Sciences, April 28, 1895.

vail to-day to the fundamental concepts which prevailed during the period preceding Faraday. One of the most striking results which this comparison brings out is the evolutionary development of new mental concepts in the science of electricity, going on hand in hand with the accumulation of new physical facts. Faraday was a rare combination of the discoverer and the philosopher, capable of interpreting his experimental discoveries in terms of broader concepts suggested by these discoveries, enriching thus both our knowledge with new physical facts and also our mode of scientific reasoning concerning these facts with new mental concepts.

The concepts which Faraday first introduced into the Science of Electricity form the characteristic elements of the tendencies of modern electrical research. A discussion of these tendencies means, therefore, a careful analysis of these modern concepts.

The two principal elements in our ideas of physical phenomena are necessarily substance and force, that is the seat of phenomena and the agent to whose activity the phenomena are due. It is evident, therefore, that our ideas of electric and magnetic phenomena are, in a certain sense, the same to-day as they were a hundred years ago: that is, they are ideas of the electric and of the magnetic forces, and of the substances in which these forces display their activity. But although these ideas relate to the same concepts, their form to-day is vastly different from the form which they had a hundred years ago; and obviously so, because our ideas concerning forces and substances in general are much broader now than they were then.

The prototypes of our ideas of forces and substances are of course our mental concepts of mechanical force and of ponderable matter, and the Science of Mechanics is, therefore, the foundation of all exact physical sciences. The Science of Electricity is in more than one sense an extension of the Science of Mechanics, or rather of Dynamics. To this, the oldest and formally most perfect of all exact physical sciences, the Science of Electricity owes its terminology, its definiteness, and its elevation to the level of an exact science. Necessarily so, for the most satisfactory quantitative measure of any accidental quality of matter, like electrification or magnetization, is the mechanical force which accompanies this quality. Thus the history of the Science of Electricity as an exact Science dates from Cavendish's Coulomb's and Ampère's discoveries of the law of mechanical force between electrified or magnetized substances, and between conductors carrying electric currents. The concept of force is to-day and it always was the inseparable bond of union between these two sciences. But just as the history of Mechanics is simply a record of the evolutionary development of our ideas of mechanical force, similarly the history of the Science of Electricity is the history of the continuous expansion of our views concerning electric and magnetic forces. It is owing to this expansion that an apparent emancipation of the younger science from the older has taken place.

We are becoming more and more familiar with the modern division of the Science of Physics into *Physics of Ether* and *Physics of Ponderable Matter*. A closer examination of this modern division of Physics brings us face to face with one of the most important modern scientific doctrines. This doctrine, broadly considered, states that just as the Science of Mechanics is the foundation of physics of ponderable matter, so the Science of Electricity is on the eve of becoming, if it has not already become, the foundation of Physics of Ether. The existence of this doctrine is the most forcible expression of the tendencies of modern electrical research. Such a division is not only permissible and convenient, but even indispensable, if it is the result of our conviction that the most essential elements of electric and magnetic phenomena, that is, electric and magnetic forces and the substances which are the seat of activity of these forces, cannot be described completely in terms of the concepts of dynamics of ponderable matter. We acknowledge that such is our conviction as soon as we admit that the electric and magnetic forces are manifestations of the various states of a substance which is not ordinary matter and which, therefore, does not form a part of that past experience of ours which led to the formulation of the fundamental axioms of Dynamics. Modern electrical research believes in the existence of a substance which has the relation just mentioned to the electric and magnetic forces, and it has succeeded in identifying this substance with the lumeniferous ether; it sanctions, therefore, a temporary division of Dynamics into *Dynamics of Ponderable Matter* and *Dynamics of Ether*.

In order to approach this subject more closely, it is necessary now to state briefly how our present ideas of electric and magnetic forces developed gradually out of our ideas of ordinary mechanical forces. This is, in my opinion, the most efficient method of distinguishing between the essential and the non-essential elements of Physics of Ether. Without this distinction there is no reliable way of assigning the proper weight to the various features of the tendencies of modern electrical research.

MODERN DYNAMICS AND THE DOCTRINE OF DIRECT ACTION AT A DISTANCE.

Pressures and tensions are the oldest and most intelligible pictures of our ideas of the concept force. But there was a time when these pictures seemed to give us but one phase of this mental concept. They failed to explain the motion of machines and of projectiles, although it was recognized long before the Science of Statics had reached its stage of perfection in which we find it nearly three hundred years ago, that in these phenomena force was an essential element. It should also be observed that there was a time when the action of a mechanical force between bodies that had no visible material connection was not suspected. Thus Thales, of Miletus, believed to have detected in the attraction of a piece of amber when electrified by friction the presence of an awakened universal soul. The attraction of a loadstone gave rise to most remarkable superstitions. Even Gilbert, the foremost physician and physicist of the Elizabethan age, suspected in the attractions and repulsions between magnets the manifestations of an occult virtue, and whenever he attempted to explain this virtue he necessarily dragged in his ideas of force as illustrated by pressures and tensions in material bodies. 'Horror vacui' and the tendency of bodies to seek their proper place were for nearly two thousand years the only explanations of the action of gravitating force. The modern concept of force as a concise statement of a law of motion was first introduced into the Science of Mechanics by the genius of Galileo Galilei in the seventeenth century. This new, so-called dynamical concept of force, discovered by Galileo as a result of his experiments on the motion of a freely falling body is really nothing more nor less than a concise statement that a freely falling body increases its vertical velocity uniformly with the time of descent, and that, therefore, we can say: the gravitational force acting upon it is constant. Lagrange speaks as follows of this discovery: "It forms to-day the permanent and the most essential part of the glory of this great man. His discoveries of the satellites of Jupiter, of the phases of Venus, of sunspots, and so forth, required telescopes and patience only; but it was a stroke of extraordinary genius to disentangle a law of nature from the phenomena which men always had before their eyes, but whose explanation had nevertheless always escaped the inquiry of the philosopher."

By this discovery Galileo laid the foundation of the modern science of Dynamics. Newton completed the work so well begun; the result is summed up in the three Axioms or Laws of Motion.

Newton's discovery of the law of universal gravitation furnished a splendid illustration of the dynamical concept of force. Newton also supplemented his physical discoveries by a mathematical discovery of equal magnitude. I mean the discovery of the infinitesimal calculus. It enabled him to express the new idea of force by a mathematical formula of rare simplicity, for nothing could be simpler than the formula which states that the flux or rate of change of momentum equals the moving force. This simplicity gave to the dynamical idea of force a fresh and almost irresistible charm. The Newtonian force considered formally is a mathematical symbol, a rate of variation, or, as the mathematician calls it, a differential coefficient, and this symbol considered physically conveys to our mind nothing more than simply a description of the instantaneous state of motion. It matters little what the mechanism is by means of which the moving body receives the impulses of the force. Newton's Dynamics did not explain the mechanism by means of which material bodies gravitate toward each other, nor did it suggest any immediate need for such an explanation. The hypothesis of direct action at a distance worked just as well as any other hypothesis, and it had the advantage of settling aimless discussions quickly when the Science of Dynamics was too busy with numerous important problems awaiting solution to waste its time on needless speculation; and, besides, there were really none but purely metaphysical arguments that could be brought in the case of gravitational force against this hypothesis of direct action at a distance.

But, unfortunately, that which at one time was looked upon as a convenient hypothesis threatened to become a fixed scientific creed. Newton's dynamics considered force in its aspect of a law of motion expressible by a simple mathematical symbol and nothing else; but just as the Greek mind saw an active divinity in every physical phenomenon, and Thales ascribed the electrical attraction of amber to the manifestation of a universal soul, and Gilbert perceived the activity of an occult virtue in a magnet, so the so-called Newtonian school ascribed an objectively active existence to the law of gravitation and called it the force of gravitation. Even more than that. To Newton the force of gravitation was something merely descriptive; to the Newtonian school of mathematical physicists it was an attribute of matter that had an objectively active existence in consequence of which matter could act upon matter directly at a distance. "It is true," says Maxwell,* "that at one time those who speculated as to the causes of physical phenomena were in the habit of accounting for each kind of action at a distance by means of a special ætherial fluid, whose function and property it was to produce these actions. They filled all space three and four times over with ethers of different kinds, the properties of which were invented merely to save appearances, so that more rational enquirers were willing rather to accept not only Newton's definite law of attraction at a distance, but even the dogma of Cotes, that action at a distance is one of the primary properties of matter, and that no explanation can be more intelligible than this fact. Hence the undulatory theory of light has met with much opposition directed not against its failure to explain phe-

* Treatise on Elec. and Mag., 2d ed., p. 448.

nomena, but against its assumption of the existence of a medium in which light is propagated." The mathematical formula which describes the law of action at a distance of a force like gravitation, electric and magnetic attractions and repulsions was, in the opinion of most mathematical physicists of the last century, the most essential element of and the ultimate goal in our knowledge of this physical concept. For if the direct action at a distance doctrine be accepted what else remains there to enquire into? How much of this scientific creed received a direct support from Newton personally is difficult to tell. One thing is certain; he gave no support to the beautiful undulatory theory of light originated by his friends, Hooke and Huyghens, and it is interesting to observe here that it was owing to the intellectual rebellion of those very men who supported the undulatory theory of light of Hooke and Huyghens against Newton's corpuscular theory that the belief in direct action at a distance began to lose ground.

UNDULATORY THEORY OF LIGHT AND THE DOCTRINE OF DIRECT ACTION AT A DISTANCE.

There is one aspect of the Undulatory Theory of Light which, in my opinion, deserves much more attention than is generally devoted to it. This theory gave expression to a current of thought which ran diametrically opposite to the direct action at a distance doctrine of the Newtonian school. For we should observe here that the development of Newtonian dynamics of rigid bodies was accompanied by a steady though somewhat less rapid progress of the dynamics of compressible and incompressible fluids and of compressible solids, that is the Sciences of Hydrodynamics and of Elasticity. Now, Hydrodydamics and Elasticity consider more particularly the modern extension of our original statical concept of force, that is, force considered as a pressure, a tension, or as a stress of any kind in a continuous materia system in which each part, no matter how small, is capable of a relative displacement with respect to the adjacent parts, each such displacement being accompanied by an elastic reaction having a perfectly definite relation to the displacement. This relation cannot be found by abstract reasoning based on the concepts of Statics or on those contained in the Newtonian axioms, but must be determined by actual experiment. Observe now that Hooke, one of the earliest investigators in this experimental field, was one of the founders of the Undulatory Theory of Light. Hydrodynamics and Elasticity containing as they do an additional experimental element mark an advance in our physical knowledge of force and substance over that contained in the Newtonian axioms. The most important element in this advance is the recognition of the very important physical fact that matter is capable of propagating force between the various parts of a continuous material system with a perfectly definite velocity and in a perfectly definite manner, both the velocity and the form of propagation, *that is, the form of the wave*, depending not only on the distribution of the masses of the system, but also on the elastic property of each elementary mass. Hence, whereas the so-called Newtonian school of physicists, influenced by the many unsuccessful attempts to explain gravitational force by mechanical hypotheses, considered force principally in its formal or mathematical aspect and also in aspect of an objectively active property of matter, capable of acting directly at the distance, there was another school of physicists, with Hooke and Huyghens at its head, who focused their attention upon just the opposite aspect of force, that is, force considered as a state of stress, and hence incapable of being communicated from one body to another, unless there is a material connection between them. It is this view of force which led to the formulation of the Wave Theory of Light; it is also this view of force which gives us the nearest physical picture of the modern view of electric and magnetic forces. But the view of electric and magnetic forces which prevailed during the last century and during the first part of this century was that which accorded with the scientific credo of the Newtonian school. This is easily accounted for. The successful solution of many most remarkable dynamical problems, like the theory of tides, the figure of the earth, the problem of planetary perturbations, etc., commanded most profound attention. They were just so many signal triumphs of Newtonian dynamics and of the Newtonian school. No one dared to doubt the infallibility of anything that *seemed* to have even the remotest connection with Newton's philosophy. The laws of action of Electric and Magnetic forces, that is, the laws of Cavendish, Coulomb and Ampère, all followed the rule of the inverse square of distance and resembled, therefore, Newton's law of gravitation in a most remarkable manner. It is, therefore, not at all surprising that the doctrine of direct action at a distance, which *seemed* to have done so much good in the theory of gravitation, should have been transferred bodily into Science of Electricity and Magnetism.

But the victory of the Undulatory Theory of Light, revived by Young and Fresnel, over the corpuscular theory lessened considerably the confidence in Newton's unquestioned authority and in the correctness of the doctrines of the so-called Newtonian school. Besides, this Undulatory Theory brought into conspicuous prominence a new form of matter which was independent of that mysterious attribute, the gravitating force that acts directly at a distance; a substance permeating all space, even the innermost interstices of ponderable matter, and capable of transmitting actions between material bodies with enormous velocity. Add to this the invention of the steam engine and the discovery of the galvanic cell, the operations of which had no apparent immediate connection with any formal laws of Newton's dynamics or with Coulomb's and Ampère's distance laws of electric and magnetic force and the scientific atmosphere at the beginning of this century will appear to us in its true light, that is, full of indications that the arrival of a new physical truth was near, a truth which was not explicitly stated in Newton's dynamics and which to be fully appreciated by the human mind needed a new physical concept there, the concept of *energy*. The age which saw the arrival of the Undulatory Theory of Light and of the Principle of Conservation of Energy was worthy of the honor of being the age in which Faraday lived.

FARADAY'S RESEARCHES.

When Faraday entered the field of electrical research, that which he found there worthy of the name of an exact science were Coulomb's, Cavendish's and Ampère's laws of force of inverse square. The method of analyzing electric and magnetic phenomena which prevailed at that time is well illustrated in Poisson's theory of induced magnetism, "who," and here I quote Maxwell, "by following the path pointed out by Newton and making the forces which act between bodies the principal object of study, founded the mathematical theories of electric and magnetic forces."

The field of Electrical Science, view it as you may, was narrow when Faraday entered it. Besides, the old superstition of direct action at a distance surrounded it on every side like a Chinese wall. There seemed to be no exit, no communication with the outside world of science where Faraday saw wide fields of activity opened up by the Undulatory Theory of Light and the Principle of Conservation of Energy, with both of which his mind was thoroughly imbued. Electric and magnetic attractions and repulsions between material bodies, induced electrifications and magnetizations and the manner in which these actions between material bodies were modified by a change of the medium separating them—all these phenomena could not fail to reveal to a bold investigator of Nature's hidden laws, like Faraday, that the law of inverse square is by no means the final goal of inquiry concerning electric and magnetic forces. The many failures to pass beyond that goal in the case of gravitational force did not discourage him.

It is far beyond the limits of this brief discussion to give an adequate review of Faraday's epoch making discoveries by means of which the Electrical Science was liberated from its hopeless prison of direct action at a distance theories and started on its new and eventful career. Suffice it to mention briefly the main features only of these discoveries, in order to bring out as forcibly as I can their bearing upon the tendencies of modern electrical research.* Faraday's discoveries are generally known to-day through the technical applications of the fundamental principles which were first established by these discoveries. The dynamo and the motor, the telegraph and the telephone, the induction coil and the modern transformer, all these great inventions, in fact, the whole science of electromagnetic induction, both pure and applied, are only single illustrations of the wide range which is covered by these discoveries. But it is no more than just to mention here that in the region of electromagnetic induction a very fair, if not an equal, share of the glory of original discovery belongs to our own countryman, illustrious Joseph Henry.

*The substance of the following summary of Faraday's discoveries and their aim was given by the author in 1894 in the Electrical World in a series of articles entitled 'The Faraday-Maxwell-Hertzian epoch.'

Faraday can well afford to share these honors with so great a physicist. For it adds to his greatness to have it recorded in the annals of science that the supreme effort in the life work of so great a physicist as Joseph Henry was the first step only in the long series of Faraday's far-reaching discoveries. The phenomena of electro-magnetic induction seem to have absorbed the smallest part of Faraday's attention during the earliest period of his electrical researches, and the question which presents itself to every thoughtful student of Faraday's 'Experimental Researches' is: What called Faraday away so soon from this important and promising field? For who does not feel that the pleasure one gets from reading Faraday's masterly story of his discoveries in electro-magnetic induction, given in the first part of Volume I. of his 'Researches,' ends much too soon? I even venture to suggest that many a one among the students of Faraday, whose taste runs more in the direction of estimating the value of a new discovery by the immediate practical application to which it can be put, has undoubtedly bemoaned the fact that Faraday allowed himself to be drawn away so soon from his researches in electro-magnetic induction to matters so abstract as electro-chemistry, electric discharges through gases, specific inductive capacity of dielectrics, magneto-crystallic action, magnetic properties of flames and gases, action of magnetism on light, etc.

But a careful review of Faraday's long series of researches suggests a very intimate connection between the numerous and apparently independent parts of that series. They are all just so many tributary streams which flow into the same main current of thought. This current starts from the phenomena of electro-magnetic induction. The tributary streams make it stronger and stronger. It grows wider and wider, and finally as if expanding beyond the limits of our mental vision disappears in the dim regions, which, according to Faraday's surmises, connect the phenomena of light, electricity, and magnetism. The phenomena of electro-magnetic induction inspired the prophetic mind of Faraday with the belief that there must be an invisible mechanism connecting material bodies, and that it is the activity of this mechanism which makes us cognizant of the existence of electric and magnetic forces. He gave expression to this belief by introducing into his mode of thought and of description a new term, the term magnetic curves or lines of magnetic force. At first he gave us only their geometrical definition. "By magnetic curves," he added in a footnote, Volume I., page 32, "I mean the lines of magnetic force, however modified by juxtaposition of poles, which would be depicted by iron filings; of those to which a very small magnetic needle would form a tangent." But the intimate connection between the phenomena of electro-magnetic induction and these curves, or lines of magnetic force, convinced him that these curves had an actual physical existence and that they were not mere geometrical space relations, of which the iron filings give us a convenient material picture. He seemed to be aware that the nature of these new physical existences could not be revealed by a study of phenomena like those of electro-magnetic induction, as long as these phenomena could be observed in bodies of finite dimensions only, and this being the case then he would naturally expect that the road leading to the understanding of the lines of force was by way of the phenomena which can be traced with certainty to the ultimate elements of matter, to atoms and molecules. This would have been the voice then which called Faraday away from his researches in electromagnetic induction and bade him rise higher and higher until he reached heights so lofty that only a genius like that of Maxwell could reach him. This is, I venture to suggest, why Faraday's discoveries in electro-magnetic induction led him into researches of what may be called the atomic and molecular region of the science of electricity. From this point of view, the chronological order appears quite natural in which his researches in electrochemistry, voltaic electricity, specific inductive capacity of dielectrics, disruptive discharges through gases, animal electricity, action of magnets on light, on metals and their compounds, on gases, on crystals, etc., follow each other in rapid succession. The numerous discoveries revealed by these profound researches convinced the great philosopher that his work was in the right direction. With steady aim he forced his difficult journey ahead with giant strides. The most vigorous years of his life were consumed in gathering a vast amount of evidence with which to reveal before our eyes the physical nature of the lines of force, his first inspiration, and banish the old superstition of direct action at a distance. With renewed vigor he returned to this favorite subject toward the closing years of his life. His research 'On the Lines of Magnetic Force; Their Definite Character, and Their Distribution Within a Magnet and Through Space' (Philosophical Transactions, 1852, page 1), given in the twenty-eighth series of his 'Researches,' mark the beginning of the last epoch of his great work. It prepares us to enter into Faraday's innermost thoughts and see that inspiration and those visions which guided his steps for twenty years. The essays which now follow, 'On the Lines of Magnetic Force,' 'On the Physical Character of the Lines of Magnetic

Force,' 'On the Physical Lines of Magnetic Force,' 'Thoughts on Ray Vibrations,' etc., are just like the glow of an approaching sunrise. The fairyland of Faraday's vision begins to appear clearer and clearer in this gently rising light; but, alas! the cloud of old age hides away the beauties of the sunrise itself.

It was reserved for Maxwell to raise the lofty edifice from which we first obtained a clearer view of the wonderland of Faraday's vision.

I cannot do better than sum up this brief statement of the position which, in my opinion, Faraday occupies in the tendencies of modern electrical research, by quoting the following words of Hertz,* the most brilliant of all the pupils of Helmholtz, Maxwell and Faraday: "Faraday heard of the belief that electrification puts something into a body, but he saw that the changes produced were all external and none internal. Faraday was taught that forces jump through space, but he saw that these forces were influenced in the highest degree by the substances which filled the space. Faraday read that electricities certainly existed, but that their forces were a disputed question, and yet he saw that these forces produced tangible effects, although he could not perceive anything of the electrifications themselves. Hence, in his conception, the state of these things became reversed. The electric and the magnetic forces appeared to him as existing, as real, as tangible; electricity and magnetism were things whose existence might be a disputed question. The lines of force, as he called the forces considered as independent entities, stood before his mind's eye as conditions in and of the space, as stresses, as vortices, as fluxes, as something or another —he could not tell as what—but there they stood, influenced each other, they pushed the bodies and they pulled them, and they continued from point to point, conveying impulses to each other. The objection that nothing but absolute rest was possible in empty space he met with questions: Is space really empty? Does not light itself compel us to assume it as filled? Could not ether which conveys the waves of light become the seat of those changes which we recognize as electric and magnetic forces? Is it not even possible to imagine a relation between these changes and those waves of light? Why could not these waves of light be something like the oscillations of those lines of force?"

"So far did Faraday reach in his conceptions and his surmises. He could not prove them. He busily searched for evidences. The connection between light, electricity and magnetism was the favorite subject of his research. The beautiful connection which he found was not the one for which he looked. Only the highest old age put an end to his efforts."

* Vortrag, gehalten bei der 62. Versammlung deutscher Naturforscher und Aerzte zu Heidelberg am 20, September, 1889. Publ. by E. Strauss in Bonn.

MAXWELL'S INTERPRETATION OF FARADAY.

Faraday did not form a new school of physicists during his lifetime. His ideas were too original, his view of the electromagnetic phenomena was too different from the generally accepted view of his time, to gain him a large following even among his own countrymen. His generation recognized the value of his discoveries; it failed to appreciate the full meaning of the aims of his speculation. It was reserved for the next generation to grasp this meaning and to explain it in terms of the language of the existing theories. It was by no means an easy task for the next generation to perform. It required a peculiarly constituted mind, a mind combining in itself the qualities of a physical investigator and those of a mathematician. Maxwell was a true representative of this rare combination. When his attention was first drawn to Faraday's work he was fortunately still out of the hearing distance of the seductive voice of the old '-direct-action-at-a-distance-theories.' I say fortunately, for, as Hertz* observed once in his characteristic way, "he who once strayed into the magic circle of these remained a captive there." Maxwell was born in June, 1831. Faraday announced his first discovery in magneto-electric induction in November of the same year. William Thomson, now Lord Kelvin, was then only ten years old, "Before I began the study of electricity," says Maxwell,† "I resolved to read no mathematics on the subject till I had first read through Faraday's 'Experimental Researches on Electricity.' I was aware that there was supposed to be a difference between Faraday's way of conceiving phenomena and that of the mathematicians, so that neither he nor they were satisfied with each other's language. I had also the conviction that this discrepancy did not arise from either party being wrong. I was first convinced of this by Sir William Thomson, to whose advice and assistance, as well as to his published papers, I owe most of what I have learned on the subject."

Maxwell was barely twenty when he first took up the study of Faraday. Sir William Thomson was twenty-four when he first announced, in 1845, in a paper 'On the Elementary Laws of Statical Electricity' (papers on 'Electrostatics and Magnetism,' Article II.), his strong inclination toward the view of Faraday. But Thomson played at that time too prominent a part in the establishment of the Principle of Conservation of Energy and the Mechanical Theory of Heat to allow Faraday's splendid discoveries to occupy his attention completely. Maxwell threw his whole young heart and soul into the study of Faraday's 'Experimental Researches.' It was only a year after he took his degree at Cambridge when his first essay 'On Faraday's Lines of Force'* appeared. This essay and his second essay on the same subject, 'Physical Lines of Force,'† are the forerunners of his great memoir 'On a Dynamical Theory of the Electromagnetic Field.'‡ In his 'Treatise on Electricity and Magnetism'§ the views elaborated in these essays are presented in a somewhat different form and compared to the views of some of the older theories. 'The lines of force,' quoting the words of Hertz, 'as Faraday called the forces considered as independent entities stood before his mind's eye as conditions in and of the space, as stresses, as vortices, as fluxes, as something or another * * .' The first problem, therefore, which confronted Maxwell in his undertaking to express Faraday's views in terms of the terminology of the accepted mathematical theories at that time was evidently this: What is the physical constitution of the medium whose conditions of stress and of motion manifest themselves as electric and magnetic forces, that is, as lines or tubes of electric and of magnetic force? The first and the second essay give strikingly original mechanical pictures illustrating the properties of the medium which will fulfill most of the essential requirements. It would lead us too far to enter into a discussion of the beautiful mechanical models which represent Maxwell's earliest attempts to explain Faraday's view of the activities going on in an electromagnetic field. A popular account of this phase of Maxwell's work will be found

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†Treatise on Electricity and Magnetism; preface, p. ix.

* Cambridge Phil. Transact., Dec. 10, 1855.

† Philosoph. Mag., March, April and May, 1861; Jan., Feb. 1862.

‡ Royal Soc. Transact., Oct., 1864.

§ Clarendon Press, Oxford, 1873.

in Prof. O. Lodge's charming book on 'Modern Views of Electricity.'* Suffice it to state that these mechanical models were temporary structures only, as it were, mere scaffolding, which Maxwell tore down as soon as the building which he started to raise reached its completion.†

In the third essay the description of the physical properties of the medium is not so specific as in the first two. The mechanical models are replaced by broad mechanical hypotheses.

"It appears, therefore," says Maxwell, in the introduction to the famous third essay, "that certain phenomena in electricity and magnetism lead to the same conclusion as those of optics, namely, that there is an ætherial medium pervading all bodies, and modified only in degree by their presence; that the parts of this medium are capable of being set in motion by electric currents and magnets; that this motion is communicated from one part of the medium to another, by forces arising from the connections of those parts; that, under the action of these forces, there is a certain yielding depending on the elasticity of these connections, and that, therefore, energy in two different forms may exist in the medium, the one form being the actual energy of motion of its parts, and the other being the potential energy stored up in the connections, in virtue of their elasticity."

This paragraph contains the keynote of the essay. Its meaning may be illustrated in a simple manner, as follows: Consider a charged Leyden jar. Its energy is potential and stored up in a sort of elastic deformation of the dielectric, principally in that part of the dielectric which separates the metallic plates of the jar. Connect the two plates by a conducting wire; a current is set up and a magnetic field accompanying this current appears. Magnetic force is due, according to Maxwell's mechanical hypotheses, to some kind of motion in the medium, and, therefore, the appearance of the magnetic field means that the discharging process in the jar consists in a transformation of the potential energy of the charge into kinetic energy of the magnetic field. At the moment when the jar is completely discharged, all the potential energy of the charge, except that part which has been transformed into heat in the conducting wire, appears as kinetic, that is, as magnetic energy of the field. From that moment on, this kinetic energy begins to diminish, because, owing to the peculiar connection of the conducting wire to the moving parts of the medium, the current in it will persist and charge the jar in the opposite sense, which means a retransformation of the magnetic energy of the field into the potential energy of the charged jar, and so on. These cyclic transformations continue until the total initial energy of the charged jar is transformed into heat in the conducting parts of the system. *We have electric oscillations.* These oscillations were observed by Joseph Henry, nearly twenty years before Maxwell wrote his famous third essay; Sir William Thomson discussed their theory in 1853, and Feddersen subjected this theory to crucial experimental tests from 1857 to 1862. But that which, in the estimation of the tendencies of modern electrical research, is the most essential element in our physical view of these oscillatory phenomena is entirely absent from these early investigations. Maxwell, guided by the visions of Faraday, was the first to introduce this element. It is this. If the forces of the electromagnetic field are due, as Maxwell assumed and illustrated by mechanical models, to the reactions of the moving parts of the field, elastically connected to each other, then, since these reactions must necessarily consume time in passing from any part of the field to any

* Published by Macmillan & Co.

† Treatise, Vol. 2, p. 427, 2d. ed.

other, it is evident that in the case of the oscillatory discharge of the Leyden jar, which we have just considered, the oscillatory current in the conducting wire must be accompanied by oscillatory variations of the electric and magnetic force at every point of the field, and that these oscillatory variations are propagated *with a finite velocity and in complete accordance with the laws of propagation of waves through an elastic solid.*

This is the new element which Maxwell introduced into our view of the oscillatory phenomena of electromagnetism, and it is the very heart and soul of the modern electromagnetic theory. Suppose now that these variations are very rapid, and that by a suitable detector of the electric or of the magnetic force we actually detect these waves and measure their length, then the ratio between this length and the period of oscillation will give us the velocity of propagation. Maxwell predicted that this velocity is the same as that of light of the same wave length, but he never told us how to produce these waves nor how to measure their length. In fact, he never mentioned a word about the oscillatory discharges of a Leyden jar, and without a complete understanding of these there *seemed* to be no way of getting at Maxwell's full meaning.

Referring to the theory of these oscillations Mr. O. Heaviside remarks: "It had been given by Sir W. Thompson in 1853, but it is a singular circumstance that this very remarkable and instructive phenomenon should not be so much as mentioned in the whole of Maxwell's treatise, though it is scarcely possible that he was unacquainted with it; if, for no other reason, because it is so *simple* a deduction from his equations. I lay stress on the word simple, because it is not to be supposed that Maxwell was fully acquainted with the whole of the consequences of his important scheme." (Electr. Papers, Vol. II., p. 83). The omission is certainly puzzling, but it can hardly be assumed to furnish any evidence, as Mr. Heaviside seems to infer, that Maxwell was not fully acquainted with the whole of the consequences of his theory. For when one sees as clearly as Maxwell certainly did that the waves of light are the same thing as the electric waves, accompanying the oscillations of a Leyden jar discharge, he can well afford to ignore these and pass on without delay to the discussion of the luminous waves considered as electric waves. This was the ultimate aim of what Mr. Heaviside calls Maxwell's 'important scheme.' From a practical, and what one might call a business point of view, it must, of course, be admitted that Maxwell would have promoted much more rapidly his 'important scheme' if he had elucidated it first by the oscillations of a Leyden jar discharge, and this omission is, in a sense, a mark of incompleteness in Maxwell's presentation of Faraday's view of electromagnetic phenomena.

This unfinished part of Maxwell's monumental work remained practically just as Maxwell left it for over twenty years until, in 1887, the genius of Hertz, of Karlsruhe, completed the magnificent structure in a manner quite worthy its original designer. The existence of electric waves accompanying a Leyden jar discharge and their finite velocity of propagation, equal to the velocity of light, was demonstrated by Hertz in a series of brilliant experiments whose parallel one would seek in vain outside of Faraday's 'Experimental Researches.' They revealed to us for the first time the whole view of the electro-magnetic phenomena as they appeared to Faraday and Maxwell; they convinced us that the doctrine of direct action at a distance has no place in these phenomena; and they also inspired us with a hope that our view of the phenomena of gravitation may, perhaps, some day be liberated from the narrow prison walls of this persistent doctrine.

Hertz's contribution to Maxwell's work

did much to make that work what Maxwell intended it to be, that is, an interpretation of Faraday. "If by anything I have written," says Maxwell, "I may assist any student in understanding Faraday's modes of thought and expression, I shall regard it as the accomplishment of one of my principal aims—to communicate to others the same delight which I have found myself in reading Faraday's *Researches*." It is in this sense only that the Hertzian experiments mark a completion of what Maxwell had apparently left undone. They enable us to understand more clearly Faraday's modes of thought and expression, because they supplied the force and the vigor of living experiment where many a physicist saw formerly nothing but the inhospitable realms of what, to many of us, appear as dead symbols only of Maxwell's intricate mathematical analysis; and, above all, they revealed to us the beautiful simplicity of the loftiest among the many lofty conceptions of Maxwell's electro-magnetic theory, that is the 'Electro-magnetic Theory of Light.'

"The connection between light, electricity, and magnetism," says Hertz, "was the favorite subject of his (Faraday's) research." The same statement applies to Maxwell. *The Electro-magnetic Theory of Light is the crowning effort of his immortal work.* The fundamental idea in Maxwell's many-sided view of the phenomena of electricity and magnetism is undoubtedly the idea that the same fundamental laws govern the phenomena of electricity, magnetism and light. To formulate these laws was the ultimate problem of his great work, and when he found its solution it mattered little whether he could or could not devise a logically clear and consecutive course of analysis which would lead others to the same result. Hence the complaint on the part of mathematical physicists,* trained in the school of Euclid, Newton and Ampère, because they miss in Maxwell that perspicuity and logical sequency which we all admire so much in the writings of the mathematical school of the last century. The fundamental laws of Maxwell's electro-magnetic theory, capable, as they are, of explaining not only the phenomena of electricity and magnetism, but also the phenomena of light—these laws are the building which Maxwell proposed to raise on the foundation of Faraday's discoveries and conceptions, the various mechanical hypotheses, on the other hand, concerning the physical properties of the medium which enabled him to carry out his plan in accordance with a predetermined design—these hypotheses are mere scaffolding, which can and must now be taken away if it obstructs our view of the finished building.

It is well to quote here several passages from an essay in which Hertz discussed this matter in his characteristically profound way.* "And now, to be more precise, what is it that we call the Faraday-Maxwell theory?" * * * * "Many a man has thrown himself with zeal into the study of Maxwell's work, and even when he has not stumbled upon unwonted mathematical difficulties has nevertheless been compelled to abandon the hope of forming for himself an altogether consistent conception of Maxwell's ideas. I have fared no better myself. Notwithstanding the greatest admiration for Maxwell's mathematical conceptions, I have not always felt quite certain of having grasped the physical significance of his statements." * * * * "To the question, 'what is Maxwell's theory?' I know of no shorter or more definite answer than the

* The French school of the mathematical physicists seems to be especially displeased. One has only to refer to the writings of Poincaré, Bertrand, Duhem, etc., to prove the correctness of this statement.

* Electric Waves, translation by D. E. Jones, p. 20, B. Theoretical.

following: Maxwell's theory is Maxwell's system of equations.* Every theory which leads to the same system of equations, and therefore comprises the same possible phenomena, I would consider as being a form or special case of Maxwell's theory. * * * *" Boltzman, one of Maxwell's most sincere admirers, introduces his lectures on Maxwell's electro-magnetic theory † with the following verse from Goethe's Faust, which he paraphrased evidently with the intention of describing the desperate state of his mind:

> So soll ich denn mit saurem Schweiss
> Euch lehren, was ich selbst nicht weiss.

MAXWELL'S ELECTRO-MAGNETIC THEORY OF LIGHT.

These statements, coming, as they do, from so high authorities, do not seem to present a cheerful outlook to those who, like myself, take upon themselves the burden of the ponderous task of popularizing Maxwell's electro-magnetic theory. But the outlook is really not quite as gloomy as it appears at first glance, provided, of course, that one limits himself to the essential parts of Maxwell's story and leaves out the ornamental detail. In other words, the story of what Maxwell actually accomplished can be told in a few and simple words; what he probably attempted to do, but did not accomplish, is a different matter and does not concern us at present. Maxwell's electromagnetic theory in its simple form and divested of all unnecessary hypotheses can be described briefly as the extension of the meaning of certain well established experimental facts. To state these facts it is well to consider briefly the following well-known experiments:

First: Connect two metal plates, facing each other and forming an electric condenser, to the poles of a galvanic cell. A transient current takes place whose value can be determined experimentally. Experiment tells us that this transient current is proportional to the electromotive force of the cell, so that n equal cells in series will produce n times the transient or integral current. Having charged the condenser we disconnect the cells and then join the plates by a conducting wire and discharge; the integral discharge current is just as large as the charging current, but in *opposite* direction. A charged condenser is, therefore, the seat of an electromotive force acting in opposite sense to the charging electromotive force. The old view maintained that this electromotive force is due to the accumulated electricities in the plates; the Faraday-Maxwell view denies this and maintains that the electromotive force is due to an action of the dielectric separating the plates. According to the old theories the current is a process confined to the conducting parts; in our present case, for instance, it is along the conducting wire and stops at the boundary separating the condenser plates from the dielectric. According to the Faraday-Maxwell view this process continues through the dielectric, and whereas it generates heat in the conducting parts it stores up energy in the dielectric just as a compression stores up energy in the body which is being compressed. The charging cell supplies the action and the dielectric reacts; *the work against this reaction is the energy of the charged condenser, which is, therefore, in the dielectric and not on the surface of the plates, as the old theories supposed.* The charging process or current continues until the electromotive reaction of the dielectric is equal to the electromotive force of the cell, and since the integral current is proportional to the electromotive force of the charging cell it follows that the electromotive reaction of a charged condenser is also proportional to

* What Hertz calls 'Maxwell's system of equations' means the same thing as the expression 'fundamental laws,' mentioned above.

† Vorlesungen über Maxwell's Theorie, etc., publ. by Barth, Leipzig.

this integral current. Whatever is true of the condenser as a whole is true of any elementary part of the dielectric. Hence, whenever a current passes through any part of a dielectric it produces there a change of state which we call polarization and a consequent electromotive reaction which is proportional to the total current that has passed through. This total current Maxwell calls total electric displacement, selecting this name evidently for the purpose of bringing out the strong resemblance of the relation just described to the relation between the elastic compression of a material body and the elastic reaction produced thereby. The electric displacement depends also on the nature of the dielectric. Thus, the integral current between the same plates and acted upon by the same cell will be greater if the plates are separated by glass than if the intervening space is a perfect vacuum. The ratio between the two is the specific inductive capacity of the glass. This constant is within wide limits independent of the charging electromotive force and it corresponds to the elastic constant in elasticity. We have, therefore, summing up these relations, the following law of electric displacement or flux :

"Intensity of electromotive reaction in any direction equals the intensity of electric flux in that direction divided by the specific inductive capacity."

Second : A magnetized bar of iron is magnetically polarized just as the dielectric separating the plates of a charged condenser is electrically polarized. The resemblance between the two states is complete. We can speak, therefore, of a magnetic flux or displacement, just as we speak of an electric displacement, and experiment tells us that the first follows the same formal law as the second, viz :

Intensity of magneto-motive reaction in any direction equals the intensity of magnetic flux in that direction divided by the magnetic specific inductive capacity or permeability.

It should be observed that no assumption is made that these two physical constants of the medium are the same in every direction. In an allotropic substance they can, and generally will, be different in different directions.

The last law is not rigidly true for conductors of high permeability like iron, nickel, cobalt, bismuth, when the magnetizing force is high. The same limitaation exists in the deformation of elastic bodies when the deformation passes beyond the elastic limit. It is not a serious limitation as long as we keep, as we necessarily do in experimental investigations of electric oscillations, within the limits of what may be called the elastic limit of electrification and magnetization.

These two laws describe one of the two essential elements in our modern view of the electric and the magnetic force, that is the view of these forces considered as reactions of the dielectric against the continuance of an abnormal condition produced in consequence of a certain process, called in one case the electric and in the other the magnetic current, having taken place there. These reactions suffice to explain the attractions and repulsions between electrified and magnetized substances, which now appear not as direct actions at a distance, but as a consequence of a definite distribution of reactions in the dielectric separating the bodies under consideration. These laws of electric and magnetic flux occupy in the modern electro-magnetic theory the same position and have the same physical significance as the laws of elasticity in mechanics of a material body. This very important element, we may call it the statical element, our modern view of the electric and magnetic force was first clearly brought out by Maxwell. His failure to illustrate it in a completely satisfactory manner by a mechanical model is of no material consequence as far as the correctness of the laws of flux and the definiteness of our ideas of this *statical element* of electric and magnetic force is concerned.

We now come to the second essential feature of Maxwell's theory. It deals with what may be called the dynamic element of our modern ideas concerning electric and magnetic force. Oersted discovered that a conductor which is the seat of that progressive process which we call an electric current is accompanied by magnetic forces which are present in every element of the space surrounding the conductor. Ampère formulated the law in accordance with which this force is distributed in space. This law can be stated broadly as follows:

The magneto-motive force around the boundary line of any elementary area is proportional to the electric current, or what is the same thing, to the rate of variation of the electric flux through that area.

This law is one of the fundamental laws of the Faraday-Maxwell theory, but although its form is essentially the same here as it was in the old theories its meaning is very much more comprehensive. In the old theory the magneto-motive force around the boundary of any elementary area through which no conduction current passes is *always* zero. According to the new view the current is not confined to conductors, but extends to the dielectric and its value through any elementary area is equal to the rate of variation of the electric flux or integral current through that area. The law of magneto-motive force just mentioned applies to this current just as well as it does to currents in conductors. Again, in the old theory the magnetic force accompanying an electric current was a direct action at a distance between the various elements of the conductor carrying the conduction current and a magnetic pole; according to the new theory the magnetic force at any point of the medium is the same in this case as in any other, that is, a magneto-motive reaction in the medium produced by the integral magnetic current, that is, by the magnetic flux or induction, which was set up in the medium while the electric currents in the various parts of the field increased from their zero value to the value which they have at the moment under consideration. It must be observed, however, that since in the law just mentioned the magnetic force figures as a *rate of change of the electric flux*, that this law presents to us the dynamic element of the magnetic force just as Newton's second law of motion presents to us the dynamic element of the mechanical force.

We proceed now to consider a similar aspect of the electric force. Any change in the electric currents brings with it a change in the integral magnetic currents in the various elements of the field, and hence it implies work against the magneto-motive reactions in those elements. Hence, every electro-motive action tending to change the electric currents in any part of the field experiences a reaction to which every element of the field contributes its definite share, just as a change in the motion of any part of a mechanism is accompanied by a reaction to which every other part contributes its definite amount. How does this reaction against a change of the electric current manifest itself? The answer to this momentous question was first given by Faraday when he discovered the magneto-electric induction. This discovery can be described as follows:

Consider a loop of a conducting wire and a magnet, in its vicinity. A change of relative position of the two produces a current in the loop. If the magnet is an electro-magnet, and if we keep the relative position unchanged and change the strength of the magnet, a current will also be induced in the loop. Again, leaving everything unchanged and changing the shape of the loop only a current will result. In each case the magnetic flux through any surface bounded by the loop is varied, and this variation of the flux produces, according to Faraday's researches, an electro-motive force in the loop. The law connecting the two may be stated as follows:

The electro-motive force around the boundary line of any elementary area is proportional to the magnetic current, or, what is the same thing, to the rate of variation of the magnetic flux through that area.

This law is the fundamental law of the Faraday-Maxwell theory which describes the dynamic element in our view of the electric force. Although the form of this law is essentially the same here as it was in the old theories its meaning is radically different. The old theories believed that unless the boundry line mentioned above consisted of a conductor, no electro-motive force around this boundry would be called into play by the variation of the magnetic flux. In the modern theory this limitation is removed. The current in the loop produced by the variation of the magnetic flux is an evidence that electomotive reactions are set up in the dielectric surrounding the loop, and this reaction manifests itself as a conduction current when the loop consists of a conducting material. Now an electro-motive reaction in the dielectric is impossible without a previous electric flux, hence every variation of the magnetic flux is accompanied by an electric flux, just as every variation of the electric flux is accompanied by a magnetic flux. The law connecting the variation of the flux of one type to the integral flux of the other type is formally the same in each case.

The question, How does the reaction of the magnetic field against a change of the current in any part of it manifest itself? is now easily answered. Evidently since this change of the current is accompanied by a proportional change of the magnetic flux in every part of the field the reaction will be an electro-motive reaction against the electro-motive force tending to produce this change in the current. It is evident also that the electro-motive reaction is proportional to the rate of change of the current; that is to say, the current seems to behave like a moving body in consequence of its inertia. For a moving body opposes an inertia reaction against every force tending to change its velocity, and this inertia reaction is, according to Newton's second axiom, equal to the rate of change of momentum. Hence the striking formal resemblance between the laws of electro-magnetic and magneto-electric induction and the laws of inertia reactions of a connected material system. This is the second essential feature of the modern electro-magnetic theory which Maxwell emphasized by his mechanical models, illustrating the actions going on in the electro-magnetic field.

Summing up the foregoing brief account of the Faraday-Maxwell theory, we can say that, broadly speaking, this theory rests on two laws: *a*. The law of flux. *b*. The law of the variation of the flux. These two laws are formally the same as they were in the old theory, but their meaning is radically different. This difference has been brought about by a substitution of a new view of the electric and of the magnetic force in place of the doctrine of direct action at a distance, the view, namely, that electric and magnetic forces at any point of space are reactions due to the physical state of the dielectric in that point. This state is completely determined by the fluxes in that point and the rates of variation of the fluxes in every point of the field.

The account of the ordinary electro-magnetic phenomena in which the electro-magnetic forces are either constant or slowly varyiny is practically the same in the two theories. The radical difference becomes apparent when these variations are rapid, for it is then only that the currents in the dielectric both the electric and the magnetic show their real power. Hertz was the first to show us how to produce these rapid changes by the disruptive discharge of a Leyden jar.

Maxwell's Electro-magnetic Theory of Light can now be easily stated. Formally it is the same as the Dynamic Theory. For this one starts from the hypothesis that light is a vibratory motion of a substance which is a particular form of matter of very small density and very high rigidity. The fundamental laws of the Dynamic Theory of Light are, therefore, Newton's axioms, particularly the second law of motion, and the law of elastic displacement. Now these two laws bear a perfect formal resemblance to the law of variation of flux and the law of flux respectively; it follows, therefore, that since these two theories start from the same formal laws they will, formally, account equally well for all the simpler phenomena of light.

It would lead us much beyond the already extensive limits of this discussion to dwell even briefly upon the superiority of the electro-magnetic theory over the other theories. I shall mention a few only of the most striking features of this comparison. First, it makes no hypothesis as to the material constitution of ether; the Dynamic Theory does this and fails to reconcile some of its hypotheses, as, for instance, the very high rigidity, with well-known physical facts. The only hypothesis which the electro-magnetic theory makes is that its two fundamental laws apply to ether as well as to any other dielectric. In fact, it defines the fundamental physical properties of ether by these two laws just as Mechanics defines the fundamental physical properties of matter by Newton's axioms and the law of elastic deformation. It is in this sense that Maxwell's electro-magnetic theory may be called the Dynamics of Ether and treated distinctly from Dynamics of ponderable matter. Second, the hypotheses of the electro-magnetic theory admit of a direct experimental test, those of the Dynamic Theory do not. The Hertzian experiments furnished this test for the electro-magnetic theory and verified its hypotheses. Third, the beautiful picture of the phenomena of dispersion and absorption of light which Helmholtz gives us in his extension of Maxwell's theory forms by reason of its elegant simplicity a striking contrast to the mechanical model of these phenomena which he gave us some twenty years ago. Consider as Helmholtz does the electro-magnetic forces that must be acting between the luminous wave and the definite electric charges which Faraday detected long ago in every valency of the atoms of ponderable matter, and the cloud of uncertainty and of ignorance which for a long time seemed to hang over the region of these most interesting phenomena of light clears away and leaves us rejoicing in the possession of new knowledge, more beautiful than anything that we have ever known before.

"One cannot study this wonderful theory," says Hertz, "referring to Maxwell's Electro-magnetic Theory of Light," with out feeling from time to time that there resides in its mathematical fomulæ an independent life and an individual intelligence; that they are wiser than we are, wiser than their discoverer; that they give us more than was formerly put into them."

Boltzmann expresses the same sentiment as Hertz by placing the following verse from Goethe's Faust as the motto of the second volume of his lectures on Maxwell's electro-magnetic theory:

War es ein Gott der diese Zeichen schrieb,
Die mit geheimnissvoll verborg'nem Trieb
Die Kräfte der Natur um mich enthüllen
Und mir das Herz mit stiller Freude füllen.

The summary with which Hertz concluded his famous lecture 'On the Relation between Electricity and Light,' cited above, is the most comprehensive statement of the tendencies of modern electrical research that I know of. I shall, therefore, conclude my discussion with a translation of this summary, hoping that I have succeeded in paving the way to a clear understanding of the following comprehensive language of one of the most profound students of Faraday and Maxwell. Hertz speaks as follows:

"No longer do we see the flow of currents nor the heaping up of electricities in conductors. We only see the waves in air, passing through each other, dissolving and uniting, intensifying and neutralizing each other. Parting from the region of purely electric we arrive step by step to purely optic phenomena. We have crossed the pass; our path grows less steep and approaches a level. The union between light and electricity which the theory surmised, expected, predicted, has been accomplished, comprehensible by the senses, intelligible to our common intelligence. A broad veiw into both regions greets us at the highest point which we have reached, at the pass itself. The domain of optics is no longer limited to ether waves, the length of which is only a small fraction of a millimeter; it extends to waves which are measured by decimeters, meters, kilometers. But in spite of this extension, this domain appears to us, when viewed from here, as an appendix only to the domain of electricity. This last one gains the most. We see electricity in a thousand places where formerly we found no sure record of its presence. In every flame, in every luminous atom, we see an electric process. But even a non-luminous body, as long as it radiates heat, is the seat of electric impulses. Thus the domain of electricity is being extended over all nature. It approaches us personally; we learn that in reality we possess an electric organ, the eye. This is the view of the things below, the view of details. The view from this standpoint of the things above, the view of the lofty peaks, the general aims, is not less inviting. There lies directly before us the question concerning direct actions at a distance. Do they exist? Among the many which we believed to possess, one only remains, gravitation. Does this one also deceive us? The law, in accordance with which it acts, makes it suspicious. In another direction, not far away, is the question concerning the nature of electricity. It hides itself, when viewed from here, behind a more specific question concerning the nature of electric and magnetic forces in space, and directly alongside of this, rises the mighty chief problem concerning the nature, the properties of the medium which fills all space, the ether, its structure, its rest or motion, its infinite extension or its finite boundary. Stronger and stronger grows the appearance that this question towers way above all the others, that a knowledge of ether will reveal to us not only the nature of former imponderables, but also of old matter itself and its innermost properties, gravity and inertia. The quintessence of primeval physical doctrines is preserved in the words that 'all that is is made of water, of fire.' Physics of to-day approaches the question whether all that is is made of ether? These things are the ultimate aims of our Science, of Physics. They are, to continue our simile, the last ice-capped peaks of its highlands. Will it ever be granted to us to place our foot upon one of these peaks? Will that happen late? Can it be soon? We do not know it. But we have gained for further efforts a foothold which is a step higher than those which were used before; the path is not cut off by a steep mountain side; the ascent, at any rate the nearest visible part of it, presents a moderate incline only, and among the rocks there are narrow paths which lead on high; there are many zealous and skilled investigators; how can we but look hopefully ahead to the successes of future efforts?"

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*THE BERNE PHYSIOLOGICAL CONGRESS (II.).**

THURSDAY, September 12. Morning demomonstrations and papers (Chairmen, Profs. Dastre and Einthoven).

Prof. S. Arloing (Lyons) described experiments showing that the persistence of electric excitability of the peripheral ends of divided nerves was of long duration, although varying with the animal and nerve experimented on. The excitability of the spinal accessory and facial nerves lasted in dogs four to five days, in asses eight to ten days. In one case the peripheral end of a cat's sciatic was excitable after thirty-one days. The different kinds of nerve fibres in one nerve trunk have different rates of degeneration and their existence can be thus demonstrated; for instance, the vagus of some animals seven or eight days after section has lost its inhibitory action on the heart, and now produces acceleration on stimulation. In the case of an ass, stimulation of the peripheral end of the vagus produced standstill of the heart accompanied by a rise in blood pressure, which Prof. Arloing considered to be due to tetanus of the cardiac muscle. The graphic record of this experiment was shown.

Discussion by Prof. Schiff.

Dr. M. Arthus (Paris) discussed the action of lime salts in promoting the coagulation of the blood. He did not agree with the late Prof. Al. Schmidt that the action of the oxalates in preventing clotting was a specific one, independent of the precipitation of lime salts, as the same action was possessed by citrates and fluorides.

Discussion by Prof Kühne.

Prof. J. v. Kries (Freiburg) discussed the color-blindness, except for red, of eyes which have been long unexposed to light. He did not agree with Hering that this was due to the activity of the white-black substance alone, for he found the periphery of the retina one to two hundred times superior to the center, and held that the retinal rods by virtue of their visual purple possess the power of adaptation to darkness, while the cones distinguish colors.

Discussions by Profs. Grützner, Hensen, Pflüger (Berne) and Kühne.

Prof. A. Gamgee (Lausanne) described his investigation of the absorption bands in the outer violet and ultra-violet produced by haemoglobin and its derivatives, photographs of which were shown. The absorption bands of Turacin, the pigment containing copper obtained from the feathers of certain birds, were also described. Its ultra-violet absorption band is identical with that of reduced haemoglobin.

Discussion by Prof. Tschirch.

Prof. S. Epstein (Berne) gave an experimental demonstration of the increase in visual acuity caused by auditory impressions. He did not agree with the localization of the nervous process in the cerebral cortex, but held it to take place in the corpora quadrigemina, in which the auditory stimuli are reflected on to the optic nerves, these functioning as efferent as well as afferent nerves. In favor of this view he described an experiment in which faradisation of the cochlear nerve produced movements of the eyes and increased sensibility of the conjunctiva. Prof. Epstein also showed an improved perimeter to be used

*Continued from Vol. II., No. 50, p. 781. (December 13, 1895.)