GEORGE FRANCIS FITZGERALD.

BY J. LARMOR.

THE eminent scientific man whose work we here propose to review was born in 1851, second son of William FitzGerald, a distinguished theologian and metaphysician, Bishop of Cork, and afterwards of Killaloe. His early education was conducted at home, in company with his brothers and sisters, under the tuition of a lady who was for many years a valued member of the household, a sister of the great mathematician and logician George Boole, who was professor in the Queen's College at Cork. He was good at all subjects requiring close observation from his earliest years. On passing to Trinity College, Dublin, at sixteen years of age, he soon made his way to the top in the classes of his year, obtaining his degree in 1871 at the head of the lists both in Mathematical and in Experimental Science. He became expert at gymnastic exercises and was for many years a fine racquet player; he also took a considerable part in the literary and social clubs of the College. His athletic skill was turned to account a few years ago in experimenting on the mechanics of flight.

The years from 1871 to 1877 were spent in reading with a view to the examination for Fellowship: vacancies were at that time very rare, but he was successful on his second time of trying. The course of study contained portions of the classical writings of Lagrange and Laplace, Hamilton and MacCullagh; and the close scrutiny of the modes of thought of masters such as these doubtless formed an admirable preparation for his subsequent scientific career. During this period he also made a formal study of metaphysics; he was much attracted by the idealism of his countryman, Bishop Berkeley, which kept cropping up in his discourses as the connecting link between material science and higher things, up to the end of his life. It formed one of the manifestations of a poetic and deeply religious temperament.

For some years after obtaining Fellowship, he served with great success as a College tutor ; his side was very popular, so that it was always full a long time in advance ; and his services were in great demand as a director of the social and athletic organizations of the College. He gave up tutorial work on being elected in 1881 to the Chair of Natural and Experimental Philosophy, which he retained until his death last February. The care of a laboratory not adequately endowed, and a large amount of teaching of elementary classes, took up most of his time ; what remained was much broken up in acting as Examiner in Physics in other Universities, and as referee of scientific memoirs for learned Societies, in copious correspondence with scientific friends who were sure of obtaining acute and stimulating opinions on all knotty points submitted to him, and in the discharge of public duties which of late years had been increasing largely in extent and importance. Yet he found time to become one of the most learned men of the day in all branches of physical science, both theoretical and applied, and to leave his mark on the scientific progress of his age.

The physical problem attacked in his first published paper (*Roy. Soc. Proc.*, 1876) was the then recently announced Kerr effect, the displacement of the plane of polarization of light on reflection from a magnet. By an argument based on general considerations, he connects this phenomenon with the double refraction indicated by the different velocities of propagation of right- and left-handed circular vibrations in magnetized media, as Stokes and Kelvin had already independently suggested. The details of the argument are corrected in the papers next following ; but by a rough numerical estimate he shows, as Kundt experimentally verified some years after, that the Faraday rotatory power in traversing a film of magnetized iron must be very great, and that the effect similar to Kerr's which must exist on reflection from a naturally rotatory substance such as quartz would be actually inappreciable. By neat and simple appliances he repeats Kerr's experiment : he moreover finds that the polarization really becomes elliptic, so that there is a phase-difference involved in addition to the rotation : in further confirmation that the effect is due to the magnetized substance and not to the field he finds that it is entirely cut off when a film of gold-leaf is spread over the reflecting

pole of the magnet. At first he thought that this elliptic polarization was directly involved in the double refraction; but in the next memoir he recognized that the difference of phase must arise, like the elliptic polarization of ordinary metallic reflection, "from the efficient reflecting surface being of some depth."

The subject of the connection of light with magnetism was thus opened out, as a necessary preliminary to a more definite treatment of this problem of magnetic reflection; and, being led thereby into Maxwell's electric theory, he follows it up two years later in a memoir "On the electro-magnetic theory of the reflection and refraction of Light" (*Phil. Trans.*, 1880, pp. 691-711) presented to the Royal Society at the end of 1878, which constitutes his most complete formal treatise. Maxwell in his memoirs on electrodynamics, and particularly in the definitive exposition published in *Phil. Trans.*, 1865, had shown that the hypothesis that light consists of electric waves gives a straightforward account of the mode of its propagation in crystals, and one which is free from the difficulties attaching to the existing mechanical theories; yet he had not made any explicit application to the dynamical laws of reflection. It was left for Helmholtz to make the remark in 1870, in a footnote to his first formal memoir on the theory of electrodynamics (*Gesamm. Abhandl.*: i, p. 558) that in this respect also Maxwell's theory leads directly to the observed results by supplying the appropriate boundary conditions at the transition between the official media, whereas it had proved to be impossible legitimately to adjust any definite mechanical theory so as to admit those conditions. This statement was confirmed in a detailed formal investigation published by H. A. Lorentz in 1877. The subject of reflection is not noticed by Maxwell either in the *Phil. Trans.* memoir of 1865 or in his treatise which appeared in 1873, two years after the date of Helmholtz's memoir. It seems possible, from various incidental remarks, that he was then content with the evidence afforded by the correspondence of the velocity of electric propagation in a vacuum with that of light; and that numerical discrepancies, such as that between the index of refraction in transparent bodies and the value of the square root of the specific inductive capacity, and the fact that metallic sheets are less opaque than their conductivities ap-

peared to demand, suggested that a closer view of the vibrations of the material molecules and their interaction with the æther would have to be acquired before the dynamical problem of optical reflection became ripe for definite treatment. He was in fact in full possession as early as 1869, as Lord Rayleigh has recently shown, of the manner in which the phenomena of normal and anomalous dispersion are dominated by the influence of sympathetic vibrations in the molecules of the material medium. The analysis of this problem of optical reflection that was now independently developed by FitzGerald is of high import from the point of view of general electrodynamic theory. He first announces the proposition (most pointedly in the abstract of his memoir, *Roy. Soc. Proc.*, 1879) that by introducing a vector (ξ, η, ζ) representing the magnitude of the total disturbance of the element of æther (of whatever nature it may really be) of which the magnetic force constitutes the time-rate of growth or velocity, the electrodynamic scheme of Maxwell, for dielectric media of aeolotropic quality however general, can be immediately reduced to the standard form required by the principles of analytical dynamics; namely, the effective kinetic energy T and the potential energy W of the medium being given by the expressions¹

$$T = \frac{\mu}{8\pi} \int (\dot{\xi}^2 + \dot{\eta}^2 + \dot{\zeta}^2) d\tau$$

$$W = \frac{1}{2} \int U d\tau,$$

where $d\tau$ is an element of volume and U is a quadratic function of (f, g, h) characteristic of the material medium, (f, g, h) representing the curl of (ξ, η, ζ) , or

$$\left(\frac{d\zeta}{dy} - \frac{d\eta}{dz}, \frac{d\xi}{dz} - \frac{d\zeta}{dx}, \frac{d\eta}{dx} - \frac{d\xi}{dy} \right),$$

then the equations of electromotive propagation are obtained in the Lagrangian manner by annulling the variation of the action, that is from the *single relation*

$$\delta \int (T - W) dt = 0.$$

There are, however, other analytical expressions for T and W

¹ In case the medium is not homogeneous μ would be inside the integral.

which would lead to the same equations of bodily propagation, as witness the various elastic mechanical theories of light which give the correct laws of transmission; in fact by integration by parts we may express $T - W$ in the form of a new volume integral together with a surface integral extended over the boundary of the region considered, and of these only the former part is concerned in the formation of equations of propagation, though the latter is essential to the relation connecting stress and strain.

FitzGerald points out, following his countryman MacCullagh, and also Green in a different connection, that not merely the equations of bodily propagation, but the equations of transition expressing continuity of stress and displacement between the media at the reflecting interface, are definitely and consistently involved in this way of formulating the problem by a single equation, the surface integrals in the reduced variation of the action determining the latter relations. He then remarks that the electric theory, as thus expressed in terms of this magnetic displacement (ξ, η, ζ), is formally identical with MacCullagh's dynamical theory of crystalline reflection and refraction published thirty years before. The problem which MacCullagh then proposed to himself was to work backward from an analysis of the actual circumstances of crystalline reflection, as determined mainly through the experiments of Brewster and Seebeck, to a type of Lagrangian functions $T - W$ for the media of propagation which would correspond in their consequences with these very various test phenomena. It has always been admitted that he was entirely successful in this analytical quest: but he definitely proclaimed his inability to conceive of any kind of material elastic medium, as ordinarily understood, whose properties would be represented by the relations finally obtained. The fact that in any material medium, in which dynamical phenomena are determined entirely by interaction between internal stress and forces of the usual non-polar kind acting from a distance, there would on MacCullagh's scheme be an unbalanced torque on each element of volume, shows that a mechanical theory of this type can subsist only if there are polar forces (*e. g.*, *quasi-magnetic*) capable of compensating the torque, or if there is a kinetic reacting torque arising from gyrostatic rotations forming a part of the constitution of the medium. In later years

Lord Kelvin showed how to construct a cellular material system with gyrostats mounted in its elements, which would form an actual model of this rotationally elastic medium of MacCullagh. The hasty assumption that the analysis of the latter must necessarily be identical with the tentative mechanical theory of F. E. Neumann, because it gave the same results, had led to the real significance of MacCullagh's investigation being overlooked at the time; doubtless too it was felt the possibilities of purely mechanical media had not been exhausted. It was accordingly an advance of prime importance when FitzGerald pointed out in 1878 that the strain, of unknown nature but known relations, which MacCullagh's theory required, was precisely the one, equally unknown to our perceptions of sense, on which Maxwell's electro-optic theory is based; his memoir in fact terminates with the remark that Maxwell's theory, if it "induced us to emancipate our minds from the thralldom of a material ether, might possibly lead to most important results in the theoretic interpretation of nature."

Other considerations may be mentioned in illustration of the significance of FitzGerald's mode of considering the subject. In the statement of electrodynamic theory elaborated by Heaviside and by Hertz, which has been widely accepted as a powerful aid to concise formulation and development, the main feature has been the elimination of the potential functions of the vector electric current and the scalar electric distribution, that were introduced in the course of Maxwell's analysis: in FitzGerald's dynamical procedure, from the basis of the principle of Least Action, no such potentials occur. Indeed Maxwell had himself pointed out (*Phil. Trans.*, 1868) that the equations of electric propagation were most compactly expressed (when their theoretical basis was not in question) by the pair of circuital relations between the fundamental vectors which result from the elimination of these potentials. In FitzGerald's analyses the relation in which the interfacial conditions stand to these bodily relations is moreover directly involved. The problem as treated by him was however limited expressly to the case of transparent media, in which there are no wandering electric charges. The natural way to extend his method to the more general questions in which charges are in finite translatory motion, either from conduction or by convec-

tion of the material system, is to retain his specification of $T-W$ for the free æther, but to introduce into the process of variation the conditions imposed by the presence of these electrons ; in the reduction of this more general problem to differential analysis suitable for material media treated as continuous, the employment of Maxwell's potentials can hardly be evaded.

The other general remark is that, in the question as to whether Maxwell's electrodynamic scheme is sufficiently wide to cover the facts, it would have been possible to reason from the optical problem of crystalline propagation already fully analyzed by Green, Neumann, and MacCullagh, in the light of the very various and easily executed optical experiments, to the more general electric problem in which crucial experiment was for a long time almost unattainably difficult. There was fair ground for the inference from MacCullagh's analysis that his scheme was the unique one of dynamical type that could lead to the laws of crystalline reflection : no demonstration of this was indeed given, but the variety of experimental laws to which the solution had to conform created a presumption almost equivalent to proof. That scheme might be made more general by assumption of effective compressibility of the medium, *i. e.*, convergence of the magnetic vector in the electric interpretation, thereby introducing compressible waves ; these would however travel by themselves in entire independence of the transverse waves. But a scheme such as Helmholtz's, which introduced to any sensible extent compressible waves interacting with the transverse ones, would in so far come into conflict with the optical evidence. This question whether Helmholtz's proposed generalization of Maxwell's theory had any actual basis remained a main problem of theoretical electrodynamics until the discovery of electric radiation by Hertz : it has now been tacitly dropped, not so much on account of any specific experiment in disproof, as through the conviction, created by the ever-widening range of correspondence between electric and optical radiations, that these are the same thing at bottom. Towards this conviction the illustrative experiments of FitzGerald and his pupils had their share in contributing. It does not appear that he ever paid much attention to the Helmholtz theory : it reposed really on ideas involving action at a distance, and from the optical point of view which we

have here attempted to sketch there was no need for its wider generality.

The extension of this theory of optical reflection to the magneto-optic problem was effected by FitzGerald by introducing, after Maxwell, terms into the function $T-W$ so as to represent interaction between the imposed magnetic field and the optical vibrations in the medium. He finds, however, that the interfacial conditions in the dynamical problem could not now be satisfied by means of transverse waves alone: and, reserving the theoretical difficulty thence arising, he completes the analysis without introducing compressible waves by neglecting the condition involving the normal disturbance, as Fresnel had done under similar circumstances. This gives him a magneto-optic effect resembling in details, as regards intensity, the description published by Kerr in the same year, but without changes of phase.

Finally it is pointed out that this is only a first approximation to an exact theory, on account of the metallic character of the reflector being ignored, and of the difficulty above mentioned—the question of phase in particular awaiting a more comprehensive theory in which the relation of matter to æther would be more exactly expressed. The difficulty has since been removed by considering the effect of the imposed magnetic field to be a structural modification in the material medium, rather than a fundamental change in the dynamical relations between the electric vectors; and FitzGerald's analytical work still remains applicable. The extension of the metallic media is now formally made, as Ohm's law indicates, by taking the refractive index to be a complex quantity: with this generalization the analysis has been extended by various writers including Lorentz, Goldhammer, and Drude, but most completely by Leatham¹ and by Wind,² and shown to embrace satisfactorily all the mass of detail that has been brought out in recent years in experimental magneto-optic investigations.

While these developments were proceeding, FitzGerald was also taking a close interest, stimulated in part by his uncle, Dr. Johnstone Stoney, in the theory of the Crookes radiometer, then coming

¹ Phil. Trans., 1897.

² Archives néerlandaises, 1897; or PHYSICAL REVIEW, Vol. VI.

into shape ; this he studied in its connection with the cognate subject of the constitution of the gaseous layer which supports a liquid in the spheroidal state without contact with the hot slab, and the state of stress that is as a consequence involved in it. In an elegant subsidiary investigation (March, 1888), of the state of internal pressure in a gas, arising from supposed presence of some co-ordination in the directions of motion of the molecules, he finds that when the directions are simply related to a single axis an internal stress of the Maxwell electrostatic type results ; in the general case the stress is not specially conditioned. This result is to be expected when we reflect that it can be proved that the Maxwell type of stress is the only one, symmetrical with respect to an axis, that can maintain itself in equilibrium. In FitzGerald's point of view the normal pressure on the warm side of a vane of a radiometer may differ from that on a perpendicular cold side because the stress in the gaseous medium is not isotropic ; how far this mode of representation is consistent with the more complete analysis of internal stress in gases due to temperature-gradient, by O. Reynolds and by Maxwell, has been a subject of controversy.

In 1881 a new departure was initiated in theoretical electrodynamics by J. J. Thomson, in an investigation with the aim of determining directly the effects produced by moving charged bodies, by means of Maxwell's equations of the electric field combined with the appropriate conditions at the surfaces of the moving conductors. The question is whether the hypothesis that the moving charge acts after the manner of a current-element is an independent assumption, or how far it is already implied in Maxwell's scheme of the electric field. Neglecting the self-induction of the æthereal displacement-currents surrounding a moving charged sphere, that is, assuming instantaneous transmission of effects, it was shown that the continual adjustment of the electric force in the field, so as to be normal to the conducting surface as it moved through space, entailed a magnetic field of the type demanded. Thus if the charged body carries its electric field along with it, the same as if it were at rest, that convection creates the magnetic field aforesaid. At speeds comparable with the velocity of radiation, the result of taking account of this finite velocity of the electrodynamic transmission is that the

electric field thus convected, when the steady state of motion has become fully established, is somewhat flattened equatorially, and the magnetic field is correspondingly changed : but ordinary electrodynamics based on the convection of electrons can safely leave such extreme cases aside. An important result in this paper was the remark that this field of magnetic (kinetic) energy carried along by an electron involves an addition to its effective mass ; the question has in fact more recently been propounded whether all inertia of matter may not be of cognate type. The paper took its rise from the magnetic deflection of the cathode stream in a vacuum tube, as described by Crookes ; and, when some of the analytical computations had been corrected by Heaviside, this memoir of Thomson's constituted the beginnings of what has now become the basis of electrodynamic theory. It is interesting also to observe in it the suggestion that the nearly abrupt changes in the magnetic field arising from the sudden stoppage of the cathode particles may be responsible for the phosphorescence excited by them in the glass: how much more they are actually responsible for was revealed years after through an accidental observation of Röntgen's. In a critical paper FitzGerald had something to add : he pointed out that as the spherical conductor of finite size, to which the analysis related, moved along, the field of æthereal displacement is suppressed in the space that the sphere comes to occupy and is instantaneously established in the space it leaves behind : these changes constitute impulsive displacement-currents : when their vector potential is added to that of the displacement-currents of the field, the result does not give the correct magnetic force—it gives in fact none at all—the current of convection of each superficial element of the charge on the sphere has to be included as well. Thomson, without explicitly including the latter, had done what comes to the same thing by addition of a term required to make the vector potential circuital, thereby implying that the æthereal current must be supplemented so as to make it everywhere circuital also. Thus on closer examination, each portion of the electric charge is found to act independently, and so far from our being able to exclude the electric charge from view by merging it in interfacial conditions, it turns out that its convection is the very cause of the phenomena of the electric

field. When considered from the point of view of the æther, the hypothesis that the total current is circuital, which lies at the very root of Maxwell's theory, involves and is equivalent to the magnetic influence of moving charges, which was verified experimentally before this time by Rowland but has recently again been challenged on experimental grounds. Following out the same train of thought, FitzGerald soon after introduced order into an obscure passage in Maxwell's exposition by inserting the term representing the current due to the convection of charged bodies, which had been overlooked.

In 1882 he contributed three papers to the Royal Dublin Society on the conditions necessary to excite electric radiation; at first he was led into inconsistencies by some confusion between the true exciting cause of the radiation existing in the radiating matter alone and the displacement currents in the surrounding æther to which Maxwell formally ascribes like properties. But he gradually gained firm footing and began to think of the vector potential as something *propagated in time* from the true electric sources, yet remaining essentially the same function which Maxwell treated as an *instantaneous* potential of the true currents and the fictitious æthereal currents taken together. He concludes that the production of radiation by electrical means is possible, that "the interactions between the molecules of matter and the æther are of the same character as the electromagnetic actions with which we are acquainted," and at this early date he goes on to express the opinion that the discharge of a condenser arranged so as to have very little inductance in the discharging circuit may be made to send out actual electric radiation of manageable wave-length.

Following up this train of ideas he published towards the end of 1883 an investigation of the intensity of radiation that would be electrically obtainable. His radiator was an alternating electric current traversing a small circuit, or, as he afterwards described it, a vibrating magnetic doublet, in contrast with the later electric doublets of Hertz. In this brief, but for the time very remarkable paper, he starts with an expression for the vector potential A as *propagated* from the true current $i_0 f(t)$ in the linear circuit, namely the vector formula:

$$A = \mu i_0 \int \frac{f(t - r/c)}{r} ds;$$

then calculating the kinetic energy by the formula

$$T = \frac{1}{2} \int (Fu + Gv + Hw) d\tau,$$

where (u, v, w) is now total current, and $d\tau$ an element of volume, he finds that in the spherical shell between radii R and $R + \delta R$, this involves an amount of energy which is proportional to δR simply and another amount which also varies as R^{-2} . The latter part he identifies as belonging to the "forced displacement-currents" around the vibrator, which start the radiated displacement-currents of which the former term represents the energy. The energy thus radiated per second comes out as

$$\frac{8}{3} \pi^4 (i_0 A)^2 \frac{\mu}{c^3 T}.$$

where A is the area of circuit, T the period of the simple harmonic alternations of the current, and c the velocity of light. He points out that all of this formula except the numerical factor could have been obtained from the theory of dimensions alone, assuming of course the existence of clear ideas of the process involved. This radiated energy is very small in amount except for high frequencies; with 10^7 alterations of the current per second it amounts to $\frac{1}{10} (\iota_0 A)^2$ ergs per second. He suggests the possibility of estimating the magnetic moment of a gaseous molecule from the radiating power of the gas. He had here not quite got to the conception of identifying the source of radiation with the motions of the electrons in the molecule; Hertz afterwards approached closer when he took for his theoretical vibrator an alternating electric doublet instead of a magnetic one.

As everybody knows, the apotheosis of these studies of radiation, so clearly presented to the mental eye, came three years later in Hertz's detection of the phenomena which have now, in wireless telegraphs, become developed into a commonplace of civilization. Beyond all question the genius of Hertz deserved this success and he stands alone. But the tracing of the history of scientific thought

on the eve of a great advance is always fascinating and instructive. At the very time FitzGerald was formulating these profound yet direct views, or soon after, Oliver Lodge, his close friend and in a sense his pupil, was actually engaged in feeling out the nodes of the electric waves that ran along his discharge-circuits like sound-waves along pipes, and there can be little doubt that the goal of the experimental demonstration of Maxwell's theory would have been reached along this path, though not perhaps with the same directness as Hertz attained. Indeed it appeared that phenomena of the same kind as Hertz's had been noticed long before by Joseph Henry, and had suggested thoughts of propagation of electric influences ; now when we are instructed, the difficulty is so to speak to avoid them.

Referring again to this paper on the intensity of radiation, we see clearly emerging the conception of an electric source, and of the electric field as formulated in terms of vector and scalar potentials directly propagated from the sources. This is the idea which H. A. Lorentz developed into a general theory of electrodynamics in 1892, ten years afterwards. Its expression has attained to ultimate simplicity in the compact statement by Levi-Civita in 1897, that vector potential, varying as usual inversely as the distance, travels in time, with the velocity of radiation, from each element of true current, and static electric potential similarly travels from each element of electric charge, and that the electric force (on electricity at rest) and the magnetic force in the æther are expressed in terms of these potentials in Maxwell's manner. But this kind of vector potential is a difficult one for purposes of analysis of media treated as continuous, its value at a point at a distance τ from a source depending on the strength of the source not at that instant but at a previous time—previous by τ/c when the source is at rest. In practice Maxwell's original potentials are much more convenient : with him there is no finite propagation of potentials, their values depending on the strengths of the sources at the very instant considered, but to attain to this simplicity the change of so-called æthereal displacement must be treated as current in Maxwell's manner, as well as the convection of the charges ; it is only for the total current thus constituted that the simple laws of the early electro-

dynamics of Ampère and Faraday are strictly applicable. In 1893 the formal development of electro-dynamic theory from this point of view, inspired at the start by Fitzgerald's electric interpretation of MacCullagh's optical analysis, and by mechanical models based on Lord Kelvin's construction for a rotationally elastic medium, and resting directly on the broad dynamical basis of the principle of Least Action, was initiated in Great Britain, and was practically complete early in 1897, running parallel in the main results, though not in method or mode of development, with Lorentz's final presentation in his tract of date 1895. This mode of investigation immediately obtained the strong and active support of FitzGerald: the discovery by Zeeman and Lorentz in 1897 of the subdivision of the lines in a spectrum by a magnetic field afterwards provided the stimulus required to attract general attention to a theory whose logical processes were difficult and unfamiliar; so that this point of view is now universally prevalent, and is perhaps occasionally pushed to extremes that would have discredited it when in the purely theoretical stage. The distinction between the analytical potentials of Maxwell and the potentials that are actually propagated from true electric sources had been, as may be gathered from the account here given, fermenting in FitzGerald's mind, though it is only recently that it has emerged into the simplicity demanded for its general recognition: it appears from one of his last letters that it had been his intention to work the subject up, if time had allowed, into a paper for the British Association last September.

FitzGerald's skill in intuitional construction was illustrated by a striking model of the functions of the æther, invented in 1885 in connection with the dynamical theory of his memoir on optical reflection. The problem was to form a simple representation of a medium possessing the rotational elasticity above described. He effected this, as regards two dimensions of space, by mounting a number of wheels freely on a board, and connecting adjacent ones in pairs in various ways by elastic bands stretched over them, so that, as the bands maintained a hold, the wheels became bound together into a single elastic system. Fixity of the centres of the wheels implied incompressibility of the medium. A rotation imparted to one of the wheels spread itself to the surrounding ones and at the same

time set up elastic stress in the bands : this stress represented a field of electric or æthereal polarity—the poles being the two sides of a band, one extended the other shortened. A rotational disturbance imposed at any place in such a medium was propagated with finite speed on account of the finite moments of inertia of the wheels : the kinetic energy of the revolving wheels represented the magnetic energy of the field, which was thus a direct consequence of the changing electric strain. In the state of equilibrium free from polarization the elastic bands were supposed to be free from strain. A region in which the wheels were loose represented a conductor. An intrinsic polarity may be introduced into this medium at any place by rotating one or more of the wheels there situated, making them slip underneath the bands that pass around them : when they are released there will be a permanent field of strain, *i. e.*, an electric field. The lines of electric polarity will be circles surrounding the place, which therefore is the analogue of a free magnetic pole ; an electron is not readily represented, nor therefore are electric currents which involve the transfer of charges through the medium. But we can have currents within a limited range ; if the region contains perfect conductors, slip is continually taking place at their surfaces when disturbances are going on in the medium ; this represents a current sheet around the surface of each conductor, which compensates the external disturbance and so avoids any penetration to the inside of the conductors. The model in fact illustrates the phenomena of dielectric propagation, which is necessarily of alternating character ; but it does not include the free mobility of electric charges which is involved in an ordinary current of conduction. By employing wheels with various orientations and replacing the elastic bands by hydraulic connections, the model is capable of extension to the three dimensions of space.

The converse of this plan, which took the kinetic (*i. e.*, magnetic) energy of the medium to be rotatory, gives the rotationally elastic medium of Rankine and Kelvin, with kinetic energy translatory, which can be practically illustrated only by complicated gyrostatic systems. But here electrons can be definitely created in the medium by supernatural operations involving a kind of knotting process, while free magnetic poles cannot exist ; and a true electric current

being a flux of electrons, the representation is complete. Not, however entirely complete; for the nature of the mobility through the medium of the core of the electron is unspecified, though when that is postulated the model shows how its surrounding electric field necessarily travels along with the core. The nature of the core itself involves the problem of the intimate intrinsic structure of the material atom: if that were explored there would be no secrets left in nature: in electro-dynamics and optics we may, therefore, be content to know the way in which an electric field travels through the æther without ever becoming disconnected from the unknown nucleus or electron to which it belongs. The science of physics is concerned only with the interactions between the atoms, which operate through the agency of the æther in which they definitely subsist; we may attain to clear views on that subject even though we be warned off the more obscure, perhaps unfathomable, problems of the intimate nature of matter itself and of the vital manifestations of which it can become the seat.

Examination of this very interesting paper will help to elucidate the fundamental part which intuition, working by means of models and analogies, can play in the formation of physical theory. According to Helmholtz this method of procedure has been characteristic of the British School. Its advantage is that correlations between directed physical quantities, which for their mathematical expression may require intricate formal operations, are made to run parallel with actual processes with which we are conversant from experience, so that they can be considerably developed without much trouble; the transition from analogy to theory then proceeds through logical analysis of these familiar processes, in the course of which ideas become generalized and in the end but little of the original analogy may remain. Notable examples are Cavendish's modes of thought which carried him some way into the nature of electrical phenomena more than a century ago, and the ideas of Faraday which formed the foundation of his own discoveries as well as the basis of the modern point of view. An intermediate link, between bare physical intuition and fully correlated theory, has been forged in the entirely new range of dynamical thought involved in Helmholtz's cardinal discovery that permanent vortex aggregates maintain their

existence (subject to the condition of stability) in a frictionless fluid medium, solely through the interaction of inertia and continuity of movement, that they in fact determine and in a sense control the entire motion of the medium to which they belong.¹ And, taking its rise from special problems of gyrostats and vortices and other steady motions, we now possess the simple and masterful generalization of the Lagrangian dynamics, foreshadowed by Kelvin and Maxwell, developed independently by Kelvin and Routh, and subsequently expounded by Helmholtz, in which the conserved momenta of permanent internal motions are considered to be a part of the constitution of the system just as much as the distribution of the masses and the geometrical configuration. So that while Lagrange and Hamilton were able to form a synthesis of the possible modes of motion of a purely dynamical system, specified as regards mass and configuration, by means of the single formula of Least Action, we are now able, as the result of a concentrated analysis, to express the laws of a dynamical phenomena that can arise in a general system more closely specified by mass and configuration and intrinsic momenta, and to lay down the limitations to which all such non-dissipative dynamical systems must conform. The question suggests itself whether, in face of so wide a synthesis, the *rôle* of analogies and models in the discovery of physical principles is not now ended: Helmholtz has in fact himself recorded that, in general physics, he found it easier to begin with wide formal relations into which the phenomena are to be fitted rather than to ascend through special analogies to more general views. Doubtless there are advances yet to come, which will arrange in still clearer and simpler order the general features of the phenomena that can arise in purely dynamical systems, and the essential limitations to which such systems are subject.

In 1882 in a paper on the electro-magnetic effects due to the motion of the Earth, FitzGerald examines the question how far Maxwell's scheme satisfies the very crucial test arising from the fact that we have here a velocity of 20 miles per second available for our

¹ For some years past FitzGerald was considerably occupied with difficult but very suggestive speculations, in part published, explaining the elasticity of the æther by a tangled structure of vortex filaments in a medium otherwise fluid.

observations.¹ In his treatise Maxwell had noticed, somewhat vaguely, that the general form of his electro-dynamic equations is not affected when the whole system is moving with uniform translatory velocity, if the axes of reference move along with the system and the optical consequences of this fact were doubtless present to his mind. If the æther were supposed to move along with the system this result would indeed be involved in the mere principles of relative motion. It is not true in any case for movements of rotation. In the present paper it is recognized that there would be an alteration in the force (of the second order however) acting between electric charges arising from their convection; for if they are convected alongside each other with the velocity of light their mutual attraction would disappear. But he now found from Maxwell's equations that there would be no effect produced on a moving magnet by any charges carried along with it, for there would be induced on its surface a charge which would exactly neutralize the magnetic influence of the moving external charges; and conversely there would be no force on the moving charges arising from currents or magnets which are carried along with them. In ignorance of this result, quite recently it has still been thought to be a difficulty in æther-theory, that no magnetic action of charges convected with the Earth's motion has been observed. In fact FitzGerald went about as far as possible at that early date: the complete analysis of convection involves separate treatment of the moving electricity and the stagnant æther, such as was developed first by Lorentz and then by Helmholtz and other writers ten years afterwards. Later on he was greatly interested in the discrepancy between Michelson's classical interference experiment, which suggested that the æther moved rigorously along with the earth, and the body of electric doctrine which almost demanded that it should be stagnant. He was the first to suggest the natural reconciliation, for which much theoretical evidence has since accrued—which is in fact a necessary consequence, if forces of cohesion are wholly or mainly electric—that motion through the

¹ Later he remarked the bearing of this velocity on any hypothesis that would make inertia a function of temperature; any such addition to mass would demand a large impulse in order to acquire for it the velocity of the Earth's motion.

æther affects the dimensions of solid molecular aggregations, but to an extent so minute as to be detectable only by most refined optical measurement.

There is a paper of this date on comets' tails. It is pointed out that Maxwell's pressure of radiation on cosmical dust, being proportional to the intensity of the radiation, is inversely as the square of the distance and so proportional to all distances to the gravitational attraction of the radiant body. For attraction thus to be changed into repulsion the mass must be very light, or its effective surface very great compared with its volume; the latter condition may be attained by external smallness of the particles. The more minute analysis that is now possible connects the repulsion directly with the reflection and absorption of the waves of radiant energy; in these processes a definite mechanical force is established whose reaction is on the surrounding æther and not on the radiant body. The validity of the principle of Least Action for the complex system æther *plus* matter implies that action and reaction are balanced for the two constituents taken together; but the pressure of radiation, now satisfactorily established on circumstantial and other evidence, shows, as Poincaré has recently admitted, that this balance cannot always be maintained for either constituent separately.

In recent years FitzGerald has taken a leading part in the critical discussions regarding the foundation of the laws of osmotic phenomena and electrolysis, and the ionization of solutions. Indeed this latter term, now universally adopted to distinguish the phenomena from ordinary dissociation, was originally due to his suggestion; last autumn, in a contribution to a British Association discussion, since abstracted *Nature*, he proposed the term electronization for the still different phenomena of molecular decomposition that are involved in the formation of the cathode streams in vacuum tubes. Some years ago he completed the work of Maxwell and Chrystal on the degree of validity of Ohm's law of conduction, by a minute test in electrolytes with powerful currents conducted through a small hole in a diaphragm; no deviation was detected, and the law possibly holds rigorously up to the point of rupture of the conducting medium.

The displacement of the lines in a spectrum towards the red,

with increasing pressure of the surrounding gas, which was discovered and investigated by the Baltimore spectroscopists, he ascribed to increase of density of the surrounding matter rather than to pressure. Each molecule in the neighborhood contributes to reduce the effective elasticity of the vibrating æthereal system, in a way which when averaged up on a large scale shows itself as increase of the electric permittivity of the medium ; thus the presence of the molecule must increase all the periods of free vibration : in fact Wilsing and others have observed that when the spark is taken in dense liquid media the displacement becomes large and indefinite. He has also paid much attention to the Zeeman change produced by a magnetic field, and was the first to develop in a definite quantitative manner its relation to the Faraday magneto-optic effect.

This rapid review of the acquisition and settlement of a new region in physical science has been suggested by the recent departure from amongst us of one who by general acclaim of his fellows held the position of a leader in the enterprise. It has permitted us in a way to bring to a focus our estimate of FitzGerald's powers in the domain of physical thought. Looking back from our present position of vantage on his own published work,¹ which represented but a small portion of his scientific activity, the main feature is its tentative and pioneering character and the continuous effort towards general views ; we can see more in it than his contemporaries saw at the time, doubtless more even than he was clearly conscious of himself. Although an accomplished mathematician, he preferred to reason in terms of direct images of the phenomena, and to reserve algebraic representations for purposes of calculation ; he had early acquired the use of the quaternion analysis, and handled it with facility, and it was interesting to watch him getting to the bottom of a tangled scheme of physical relations by jotting down a few brief vector equations. The combined efforts of many men of genius are required to take full possession of a new territory ; the subject must be for a time in the air ; its ideas must be refined and polished by workers with various gifts, through the mutual attrition of apparently conflicting views, before the body of doctrine emerges

¹ It is expected that his scientific writings will shortly be republished in collected form.

in a compact and intuitive form ready to take its place as common knowledge in the scientific inheritance of mankind. Here and there giants stand out, a Maxwell or a Hertz, and by some special achievement fix the attention of their contemporaries, or sometimes it may be only of their successors. But the greater number of workers are soon merged in their generation; they have helped to mould the ideas which will be the starting-point of the next, and their place may be not the less important though no definite priorities are claimed for them, or specific discoveries attached to their names.

FitzGerald has died young, in the fiftieth year of his age, before any failure or loss of freshness had come over his mental powers. Important as have been his direct contributions to the intellectual progress of his generation, his influence over his fellows has been greater still. He was the ideal gentle knight, always more ready to afford what assistance he could to others than to proceed with his own speculations; even in his lifetime he has had his reward in becoming the trusted advisor and guide of some of the foremost scientific men of the age. His brilliant discourse to the Chemical Society of London in 1896 as the Helmholtz memorial lecture is remembered there as a classic. The impression produced by his loss may be judged from the affectionate appreciations collected recently in *Nature* (March 7) from Heaviside, Lodge, Ramsay, Perry and others of his scientific contemporaries. Here it will suffice to insert some reminiscences received more recently from Lord Kelvin.

“My first meeting with FitzGerald was when we were both guests of Dr. Traill of Trinity College, Dublin, at his country house near Bushmills, Co. Antrim, in the Easter vacation of 1883 or 1884 so far as I can remember, to visit the first electric railway of the British Empire, then recently opened between Portrush and the Giants' Causeway.

“Expecting to meet a mathematician of high order, a young and distinguished Fellow of Trinity College, I found much more than the great pleasure I anticipated. Mathematics and physics in abundance and of highly interesting quality we had, but in FitzGerald's personality there was a unique combination of which I never had experience before. His enthusiasm about water-power and electricity were delightful. We had many little and some con-

siderable troubles in reconciling steam and electric power ; and whenever a linesman or a dynamo-driver (a mechanic of species then new) or a fireman or an oiler was in trouble, FitzGerald was there helping him as a comrade and acting practically as if to the manner born and educated. Our happy three days together on that occasion gave me an epitome of FitzGerald, living in an atmosphere of the highest scientific and intellectual quality, but always a comrade with every fellow-worker of however humble quality ; just as I have known him ever since, and as he has been known for a quarter of a century to hosts of friends and brother workers in Ireland, England and Scotland.

“ My scientific sympathy and alliance with him have greatly ripened during the last six or seven years over the undulatory theory of light and the ether theory of electricity and magnetism ; and I feel keenly the scientific bereavement which his loss entailed on myself.

“ As for his whole life, it seems to me that no one ever attained more nearly than FitzGerald to the chief end of man as defined by the shorter catechism of the Church of Scotland, ‘ to glorify God and to enjoy Him for ever.’ ”