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THEORIES OF LIGHT[1]

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EARLY speculations as to how impressions were produced on the senses ascribed the sensations associated with the senses of taste and smell to the emanation of small particles of the substances involved, and ascribed the sensations associated with the sense of sound to undulations or pulses in the air. The sensations associated with the sense of sight were assumed by some philosophers to be produced in a manner similar to those belonging to the senses of taste and smell, while by others they were assumed to be produced in a manner similar to those of sound. In the first case they were assumed to be produced by emanations from the body seen, in the second case by undulations due to the body. Among the Greeks Empedocles was an exponent of the first view, while Aristotle supported the second view. It should be noted that different views were held by those who supported an emanation theory as to the nature of the emanation. Some held that the emanation consisted of small particles of matter, while others held that the emanation was something different from matter.

In the fifteenth and sixteenth centuries, when attention was being directed again to the study of natural phenomena, the two types of theory were revived. The form of the emanation theory which was adopted ultimately is that due to Newton, usually referred to as the corpuscular theory of light. In this theory light is regarded as consisting of very small particles of matter emitted by luminous bodies with the same velocity, the velocity of light. These light particles are supposed to be repelled or attracted by the molecules of material bodies according to some law de-

[1] Address of the president of Section A—Mathematical and Physical Sciences—British Association for the Advancement of Science, Aberdeen, September, 1934.

pending on the distance between them. It is further assumed that the law is such that the force can change from an attraction to a repulsion or from a repulsion to an attraction, that these forces are insensible at sensible distances, that the motion of a light particle satisfies the ordinary laws of dynamics, and that, as the light particle moves, it passes through states which have been termed "fits of easy transmission and easy reflection" by Newton, these states recurring periodically.

The form of the undulating theory which was adopted is due to Huygens. On this theory light consists of undulations propagated through an elastic medium which fills all space; it is assumed that the elasticity of this medium is different in different material bodies and different from its elasticity in free space, and that therefore the velocity of propagation of light in a material medium is different from its velocity of propagation in free space. It is a consequence of either theory that when all the media are isotropic $\Sigma\mu\varsigma$ along the path of a ray from one point to another point is stationary, and this relation is sufficient to give the results which are classed under the term of geometrical optics. The modification necessary in this result to make it applicable to the case of crystalline media was effected by Laplace, who made use of the corpuscular theory of light in his investigation and assumed that the velocity of the light particles in a crystalline medium depended on the direction. The same result was also derived from the undulatory theory.

At the end of the eighteenth century the corpuscular theory of light was the theory which was accepted generally; one of the main arguments against an undulatory theory was its failure to explain the formation of shadows. Early last century the principle of interference was put forward by Young to account for the formation of shadows on the undulatory theory, and somewhat later, though independently, Fresnel arrived at the same result. In 1816 Arago and Fresnel showed that light polarized in perpendicular planes did not interfere. It is not improbable that Fresnel had inferred already that the direction of the disturbance which constituted light was transverse to the direction of propagation, and that these experiments confirmed it, but he makes no reference to the principle of transversality in his writings for a considerable time. The earliest explicit reference to the principle I have been able to find is contained in a letter from Young to Arago written in January, 1817. Young had visited Arago after the experiments had been carried out in 1816 and discussed them with him, and he appears to have been the only one who saw the importance of Fresnel's inference and who agreed with it. In his essay on diffraction (1818) Fresnel does not refer to the principle; he uses Huygens' principle and the principle of interference to obtain his results, principles which are independent of the direction of the disturbance. After the publication of his essay on diffraction, Fresnel applied his law of transversality to the phenomena of polarization, the propagation of light in crystalline media and other problems. He obtained and verified by observation relations between the intensities of the incident, transmitted and reflected light, when light is incident on a surface which separates two isotropic transparent media, and these relations have ever since been regarded as conditions which any adequate theory of light must satisfy. This is also true of the results he obtained for the propagation of light in crystalline media. Fresnel's method of attack is to a great extent geometrical and independent of any hypothesis as to the nature of a medium.

The developments which had taken place in analytical mathematical methods beginning with the work of the Bernoullis on strings which led to Fourier's work and Lagrange's treatment of dynamical problems made it possible to submit the hypothesis that light is due to the vibrations of an elastic medium to a more rigorous analysis. The earliest investigation of this kind is due to Cauchy. In Cauchy's treatment the elastic medium is supposed to consist of small particles or molecules which act on each other, and the further hypothesis is made that the force between any two particles is along the line joining the two points which are taken to represent the two particles. As the same problem was discussed by Green in a more general way in 1837 it is unnecessary to refer to Cauchy's results in detail.

The hypothesis which Green made with respect to the mutual actions of portions of the elastic medium was that they possessed a work function. He investigated the form of this function and proved that when the medium is isotropic and homogeneous it involves two constants, and that, if transverse waves are propagated in the medium independently of normal waves, the velocity of propagation of normal waves must be either indefinitely great or indefinitely small. He further proved that if the elastic medium is stable the velocity of propagation of normal waves in it must be indefinitely great.

The difference between two isotropic homogeneous media is assumed to be a difference between their densities,[2] and on this assumption the relations between the amplitudes of the incident, the transmitted and the reflected waves are obtained when waves are incident on a surface separating two such media. For

[2] The assumption that the difference between two isotropic homogeneous media is a difference in the elastic constants leads to results which do not agree with the observed facts.

waves polarized in the plane of incidence the relations are the same as Fresnel's, and for waves polarized perpendicularly to the plane of incidence the relations are very approximately the same as Fresnel's, except when the index of refraction is great. The difference between Cauchy's hypothesis as to the nature of the mutual actions of the medium and Green's hypothesis has been referred to above; another important difference in their treatments is that Cauchy assumes that the direction of the disturbance in the medium is parallel to the plane of polarization, while Green, in accordance with Fresnel's view, assumes that this direction is perpendicular to the plane of polarization.

Green's investigation is of special interest, as it is the first where Lagrange's dynamical method is used for the treatment of a physical problem, and where the advantages of using a general dynamical principle as the basis of the argument rather than hypotheses which involve the assumption of particular modes of action is recognized.

In 1839 Green applied the same method of treatment to the investigation of the propagation of waves of light in a crystalline medium. In addition to the limitation used in his previous investigations, that transverse waves can be propagated in the medium independently of normal waves, he introduces the further limitation in accordance with Fresnel's theory that the media satisfy the condition that the directions of the transverse vibrations are always in the front of the wave. With these limitations he proves that, if the direction of a disturbance is parallel to the plane of polarization and the medium is free from the action of any external forces, the directions of polarization and the velocities of propagation are the same as in Fresnel's theory. In his previous investigations he had proved that in order to satisfy Fresnel's relations between the amplitudes of the incident, transmitted and reflected waves at the surface separating two isotropic homogeneous media, the direction of a disturbance is perpendicular to the plane of polarization. He then shows that in order to satisfy Fresnel's results for crystalline media when the direction of a disturbance is perpendicular to the plane of polarization it is necessary to assume the existence of extraneous forces, and that, with the appropriate restrictions on these extraneous forces, the results agree with those of Fresnel's theory.

It thus appears that an elastic solid medium which is self-contained and free from external constraints will not account for the observed facts. Cauchy arrived at the same result almost simultaneously.

Various modifications of Green's elastic solid theory of light have been proposed, but none of them is satisfactory. Perhaps the most interesting is that proposed by Lord Kelvin in his Baltimore Lectures. This theory assumes that normal waves in the elastic medium are propagated with zero velocity, and to get over the difficulty, pointed out by Green, that such a medium is not stable, the medium is supposed to be attached to a boundary. Thus, although this theory gives results for the relations between the amplitudes of the incident, the transmitted and the reflected waves at the boundary separating two isotropic media and also for the propagation of waves in crystalline media which agree with Fresnel's results, it is open to the same objection as Green's elastic solid theory which requires the intervention of extraneous forces, as the condition that the medium is attached to a boundary postulates the existence of some other medium which acts on and controls it.

Although these different investigations did not succeed in establishing a satisfactory mechanical theory of light, they were instrumental in advancing the knowledge of the subject. One important result emerged, that any theory to be satisfactory must agree with Fresnel's results, and some writers, *e.g.*, Lorenz, based many of their investigations on Fresnel's results.

In Green's treatment of the elastic solid theory the Lagrangian function used by him is of the type which is expressed as the difference of a kinetic energy function and a potential energy function. The kinetic energy function is the sum of the squares of the velocities of the medium multiplied by the density, and, if the rate of transfer of energy due to a source in such a medium emitting waves of one frequency is evaluated, it will be found that it is oscillatory, and this is also true when the potential energy function is of the most general type for an elastic medium. It should be observed that, just as in the case of waves of sound from a source or of waves in water, there is an actual displacement of the medium itself, *e.g.*, in the case of waves of sound air must be supposed to be pumped in and out at the source, and this accounts for the fact that the rate of transfer of energy is oscillatory. This suggsts that it should be possible to pump out portions of such a medium, and raises the question whether a medium which is subject to the laws of dynamics and which possesses a kinetic energy of this type can be an ultimate medium which will account for the phenomena of light.

The next important stage in the development of theories of light is the discovery by Faraday in 1845 that when polarized light passed through a transparent medium its plane of polarization was rotated by the imposition of a magnetic field. In the introduction to his account of these experiments Faraday says:

> I have long held an opinion, almost amounting to conviction, in common I believe with many other lovers of natural knowledge, that the various forms under which

the forces of matter are made manifest have one common origin; or, in other words, are so directly related and mutually dependent, that they are convertible, as it were, one into another, and possess equivalents of power in their action. This strong persuasion extended to the powers of light, and led, on a former occasion, to many exertions, having for their object the discovery of the direct relation of light and electricity, and their mutual action in bodies subject jointly to their power; but the results were negative. These ineffectual exertions, and many others which were never published, could not remove my strong persuasion derived from philosophical considerations; and, therefore, I recently resumed the inquiry by experiment in a most strict and searching manner, and have at last succeeded in *magnetizing and electrifying a ray of light.*

In a footnote added subsequently Faraday says:

Neither accepting nor rejecting the hypothesis of an aether, or the corpuscular, or any other view that may be entertained of the nature of light; and, as far as I can see, nothing being really known of a ray of light more than of a line of magnetic or electric force, or even of a line of gravitating force, except as it and they are manifest in and by substances; I believe that, in the experiments I describe in the paper, light has been magnetically affected.

Almost twenty years later, in 1865, Maxwell propounded a theory of light in his memoir, "A Dynamical Theory of the Electromagnetic Field."[3] In the introduction Maxwell states:

We have therefore some reason to believe, from the phenomena of light and heat, that there is an aethereal medium filling space and permeating bodies, capable of being set in motion and of transmitting that motion from one part to another and of communicating that motion to gross matter so as to heat it and affect it in various ways.

We may therefore receive, as a datum derived from a branch of science independent of that with which we have to deal, the existence of a pervading medium, of small but real density, capable of being set in motion and of transmitting motion from one part to another with great, but not infinite velocity.

Hence the parts of this medium must be so connected that the motion of one part depends in some way on the motions of the rest; and at the same time these connections must be capable of a certain kind of elastic yielding, since the communication of motion is not instantaneous, but occupies time.

The medium is therefore capable of receiving and storing up two kinds of energy, the ''actual'' energy depending on the motions of its parts, and ''potential'' energy, consisting of the work which the medium will do in recovering from displacement in virtue of its elasticity.

[3] What might be termed an electric theory of light was propounded by Oersted; in this theory light was regarded as a succession of electric sparks.

Maxwell postulates further that the all-pervading medium possesses physical characteristics of the same kind as a homogeneous isotropic dielectric, that the effect of the action of an electric force on it is the production of what he terms "electric displacement," which is "a kind of elastic yielding to the action of the force similar to that which takes place in structures and machines owing to the want of perfect rigidity of the connections."

He shows that the application of the general equations of electrodynamics, derived from the Ampère-Faraday laws, to the case of a magnetic disturbance propagated through a non-conducting field gives the result that the only disturbances which can be so propagated are those which are transverse to the direction of propagation, and that the velocity of propagation is the velocity v, which expresses the number of electrostatic units of electricity which are contained in one electromagnetic unit.

The all-pervading medium which Maxwell postulates is a medium which possesses to some extent the physical characteristics of an elastic solid, and it is probable that his replacement of the expression for the electrokinetic energy which is obtained from Faraday's laws by an expression which gives the energy in terms of the magnetic force, was effected to make it similar to the expression for the kinetic energy function of an elastic solid. This replacement is effected by an integration by parts and neglecting the surface integral on the ground that at an indefinitely great distance the surface integral tends to zero, but this overlooks the fact that the law of variation of magnetic force with distance is not the same when the magnetic field is varying as it is when the magnetic field is steady. This does not affect Maxwell's investigation of the propagation of a magnetic disturbance, as this expression for the electrokinetic energy is not used in that investigation.

As has been seen, Faraday's view, as set forth in his 1845 paper, is different, and he explains his views in greater detail in a letter which was published in the *Philosophical Magazine* in 1846. In this letter he states:

The view which I am so bold as to put forth considers, therefore, radiation as a high species of vibration in the lines of force which are known to connect particles and also masses of matter together. It endeavors to dismiss the aether, but not the vibration. The kind of vibration which, I believe, can alone account for the wonderful, varied, and beautiful phenomena of polarization, is not the same as that which occurs on the surface of disturbed water, or the waves of sound in gases or liquids, for the vibrations in these cases are direct, or to and from the centre of action, whereas the former are lateral. It seems to me, that the resultant of two or more lines of force is an apt condition for that action which may be considered as equivalent to a *lateral* vibration; whereas a unifom medium like the aether does not appear apt, or more apt than air or water.

The occurrence of a change at one end of a line of force easily suggests a consequent change at the other. The propagation of light, and therefore probably of all radiant action, occupies *time;* and that a vibration of the line of force should account for the phenomena of radiation, it is necessary that such vibration should occupy time also.

And again:

The aether is assumed as pervading all bodies as well as space: in the view now set forth, it is the forces of the atomic centres which pervade (and make) all bodies, and also penetrate all space. As regards space, the difference is, that the aether presents successive parts or centres of action, and the present supposition only lines of action; as regards matter, the difference is, that the aether lies between the particles and so carries on the vibrations, whilst as respects the supposition, it is by the lines of force between the centres of the particles that the vibration is continued.

Faraday, like Fresnel, appears to be thinking in terms of geometrical relations, while Maxwell is seeking to construct a mechanical model whose motions will resemble those which constitute light.

Starting from Faraday's ideas, the problem of the propagation of a magnetic disturbance in free space can be approached in a direct manner. There are three vectors involved—the electric current at a point in the space, the magnetic force at the point, and the electric force at the point. The relation between the electric current and the magnetic force is given by Ampère's law,[4] and the relation between the magnetic force and the electric force is given by Faraday's law. Assuming, with Faraday, that the phenomena of light and of electricity have a common origin, Fresnel's law of transversality, that the vectors which specify the disturbance are perpendicular to the direction of propagation, will hold for the propagation of an electric or a magnetic disturbance as well as for light. These three laws are sufficient to determine the circumstances of the propagation of a magnetic disturbance in free space. It follows that for plane waves the direction of the vector j, whose time rate of increase is the electric current, at a point coincides with the direction of the electric force E at the point, and the relation between E and j is $E=4\pi V^2 j$, where V is the velocity of propagation of a magnetic disturbance in free space. Further, if the changes which constitute the disturbance satisfy the laws of dynamics, the potential energy per unit of volume is $\frac{1}{2}\,Ej$—that is, $E^2/8\pi V^2$ in electromagnetic units—and, if E_1 is the same electric force in electrostatic units, the potential energy is $E_1{}^2/8\pi$; therefore $E=VE_1$, that is, the velocity of propagation is the velocity by which an electric force expressed in electrostatic units must be multiplied to convert it into electromagnetic units, or since the product of an electric charge and the electric force on it, being a mechanical force, is the same in both systems of units, the velocity of propagation is the velocity by which an electric charge expressed in electromagnetic units must be multiplied to convert it into electrostatic units.

[4] It should be noted that Ampère's law was established initially for steady electric currents; its extension to the case where the electric currents are varying is a result of Faraday's work.

The Lagrangian function of the changes which belong to the propagation of an electric or magnetic disturbance in free space is the difference of a kinetic energy function and a potential energy function. The potential energy function is the function given above—the kinetic energy function depends on the electromagnetic momentum and the electric current at a point; the contribution from an element in the neighborhood of a point can not be expressed in terms of one vector: it depends on the electric currents throughout space. On this theory the rate of transfer of energy from a source emitting waves of one frequency is steady and not oscillatory as on an elastic solid theory.

Consistently with the foregoing, the effect of material media, so far as electric and magnetic phenomena are concerned, can be represented by a distribution of electric currents and of magnetic currents throughout the space occupied by the material media. These electric current and magnetic current distributions can be supposed to be due to electric charges and to magnetic particles which are in motion, and it follows from the electrodynamical equations, when these current distributions are taken account of, that the current distributions can be represented by a distribution of electric and magnetic oscillators throughout the space occupied by the material media.

Further, the magnetic field due to a distribution of electric and magnetic currents inside a closed surface at any point outside this closed surface can be expressed in terms of the components of the electric and magnetic forces tangential to the surface—that is, any distribution of electric and magnetic currents inside a closed surface produces the same magnetic field at points outside the surface as a distribution of electric and magnetic currents on the surface which is determined by the components of the magnetic and electric forces tangential to the surface at points on it, but a knowledge of the magnetic field external to a closed surface does not determine the distribution of electric and magnetic currents inside the surface which is producing the magnetic field.

When the states of motion belonging to the electric and magnetic current distributions in the material medium are steady states of motion the material medium is in a state of relative equilibrium, but, when an electric or magnetic disturbance is being propagated in the material medium, these steady states of motion will be disturbed and, under certain conditions, the effect of the disturbance will be to set up small oscillations about the steady states of motion; a material can be regarded as being perfectly transparent for a disturbance whose only effect is to set up small oscillations about the steady states of motion. A condition for this is that none of the frequencies involved in the disturbance are equal to or nearly equal to any of the natural frequencies belonging to the steady states of motion.

Fresnel's relations between the amplitudes of the incident, the transmitted and the reflected waves when a train of waves is incident on the surface separating two transparent media follow on this hypothesis, and also Fresnel's results for the propagation of waves in crystalline media. It should be noticed that on this hypothesis the electric and magnetic forces at a point in a material medium which appear in the equations are not the total electric and magnetic forces at the point, but the parts of them which are due to the disturbance.

Faraday's results for the rotation of the plane of polarization by an imposed magnetic field when light is being propagated in a non-magnetic transparent medium follow immediately from the above hypothesis without making any additional assumptions.

Further, on the same hypothesis there will be ranges of frequencies for which a material medium is transparent, the extent of such a range will depend on the intensity of the disturbances, and between any two consecutive ranges there will be a range of frequencies for which the medium is not transparent, and the mathematical treatment of the effect of disturbances involving these frequencies will require additional hypotheses.

The theory advanced above is not a mechanical theory of light in the sense that it is possible to construct a machine whose motions will resemble the motions involved in the propagation of light. The form of the electrokinetic energy function raises the question whether all the time rates of change involved in the propagation of a magnetic disturbance can be represented by moving points, and whether every time rate of change associated with physical phenomena involves change of position in space. It may be necessary to contemplate time rates of change which do not involve change of position in space, although they satisfy the laws of dynamics. In this connection it is of interest to observe that a result of Faraday's laws is that, when there are electric currents in a system of circuits which are in motion, the kinetic energy function does not contain terms which involve the product of an electric current and a velocity, a result which Maxwell verified experimentally.

A possible hypothesis is that physical phenomena are due to the interaction of time rates of change which satisfy the laws of dynamics, and the Lagrangian function in that case would be a homogeneous quadratic function of all the time rates of change. In actual cases only some of the changes are being observed, and the Lagrangian function which is obtained from the experimental evidence is a modified Lagrangian function where the unobserved changes are supposed to be eliminated. In certain cases this function will be expressed as the difference of a kinetic energy and a potential energy function; an important case is the case where the unobserved changes appear in the original Lagrangian function as velocities only and there are no product terms which involve a velocity belonging to the observed and a velocity belonging to the unobserved changes. There are also cases where the modified function is of this form approximately.

OBITUARY

WILLARD JAMES FISHER

DR. WILLARD JAMES FISHER, for the past twelve years research associate and lecturer in astronomy at the Harvard Observatory, died from heart failure on September 2. Dr. Fisher was born in Waterford, N. Y., in 1867. He was instructor in physics at Cornell University and professor at New Hampshire College and had been in charge of the departments of physics at the University of the Philippines and at the University of Hawaii. A correspondent writes: "Dr. Fisher's activity in recent years has been in the fields of lunar eclipse phenomena and meteoric astronomy. He has made many important contributions to knowledge of meteors, especially dealing with the phenomena of fireballs, meteoric dust, photographs of meteors, and the distribution of iron and stony meteorites. A paper by him now in press calls attention to the significant fact that iron meteorites are found in America abundantly only south of the region formerly covered by the Pleistocene ice sheet; apparently the known iron meteorites are the gleanings of many geological periods, and most of those that fell in our northern states prior to the glacial ages have been buried below the agriculturally explored surface. Some years ago Dr. Fisher very successfully guided the organization of special lunar eclipse observers throughout the American Arctic, obtaining the assistance of the Canadian Mounted Police, the fur