MODERN VIEWS

OF

ELECTRICITY

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ELECTRICITY

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PREFACE

TO THE THIRD EDITION

IN these days it is customary and natural to attend closely to the doctrine of electrons, and to the recently discovered phenomena specially associated with that doctrine. But there is a mass of long-established electrical science before and beside all that; and, so far from lessening their importance, the discovery of electrons brings the well-known facts of electrostatics into greater prominence. It is impossible rightly to follow the newest researches without acquaintance with the fundamental truths concerning electricity and magnetism in general, and yet there is some danger that these things may be temporarily overlooked and partially neglected; consequently it seemed likely to be helpful, especially to self-taught students and general readers interested in science, if the book called "Modern Views of Electricity" were republished with a few additions and such abbreviations as are permissible.

In order to facilitate reference the numbering of sections has been retained the same as in previous editions, but no attempt has been made to indicate the little changes that have been freely introduced wherever desirable. It is noteworthy that few actual *corrections* have had to be made; showing that new discoveries are of a supplementary rather than of a revolutionary character. The chief difference is that whereas in previous editions the question of the inertia of electricity was constantly treated as an open question, within reach of being shortly answered, it may now be regarded as to a great extent settled,—at least in a proximate manner. The atomic theory of electricity, begun by Maxwell and brought into prominence by Helmholtz, now holds the field; and the experimental establishment of the separate existence of electric charges has removed all rational doubt about the electromagnetic theory of their inertia. Ultimate explanation of inertia is an etherial, and perhaps insoluble, problem, but an electric treatment of the inertia of matter is legitimate as a working hypothesis; and an estimate of the value even of ethereous inertia is not beyond us, so in the last chapter (XVII.) it is introduced.

The subject of the discharge of Electricity through gases, however, has so greatly developed that it requires a separate treatise, and is accordingly but lightly touched on. Nor has it been thought appropriate to attempt to refer to extremely recent work and theory on the nature of metallic conduction. These things are specially dealt with in the writings of Professor J. J. Thomson.

To the general reader, as well as to the student, the lectures appended at the end of the book are especially commended: the old lectures remain quite useful, and some new lectures and articles have been added: one of them dealing in a semi-philosophic way with the Interstellar Ether, and two others giving a popular account of recent discoveries as to the probable nature of matter, and some idea of the atomic theory of electricity,—a subject which is dealt with in a more thorough fashion in my book called *Electrons, or the Nature and Properties of Negative Electricity.*

For the rest we may say, much as was said in the preface to the first edition, that the doctrines expounded in this book are:—the electrical nature of light, a recent theory of matter, and an ethereous[1] view of electricity. Crudely one may say that as sound and heat are forms of energy, or modes of motion, so light and electricity and matter are all forms of ether, or modes of ethereous manifestation.

Persons who are occupied with other branches of science or philosophy, or with literature, and who have therefore not kept quite abreast of physical science, may possibly be surprised to see the intimate way in which the ether is now spoken of by physicists, and the assuredness with which it is experimented on. They may be inclined to imagine that it is still a hypothetical medium, whose existence is a matter of opinion. Such is not the case. The existence of an ether can legitimately be denied only in the same fashion as the existence of matter can be denied: the evidence for its existence can be doubted or explained away, in the one case as in the other, but the evidence for ether is as strong and almost as direct, though not so plentiful, as the evidence for air. The eye may indeed be called an etherial

[1] See footnote on p. 329.

sense-organ, in the same sense as the ear can be called an aërial one, and somewhat in the same sense as the hand and muscles may be called a sense-organ for the appreciation of ordinary matter.

A rough and crude statement, adapted for popular use, is that electricity and ether are identical. A better statement is that electricity is specifically modified ether; though that is not all that has to be said, for there are two opposite kinds of electricity, and there are not two ethers. But there may be two aspects of one ether, just as there are two sides to a sheet of paper, or two aspects of a transparent clock face, or two constituents in common salt; and similarly may positive and negative electricity be two aspects, or, as I have sometimes called them by chemical analogy, "components," of the ether. Anything which can be sheared—and ether is incipiently sheared by every electromotive force applied to it—must consist of two parts sufficiently different to travel or to be displaced in opposite directions: and, in the case of ether, these parts are only recognisable or manifested as two in the act of partial separation or shear which is called 'electric displacement.'

If this statement is vague, it is because our present knowledge of the structure of the ether is vague; not because the relationship of electricity to ether is uncertain, or will be anything but definite so soon as we know the constitution of the ether more precisely. It is impossible to treat this part of the subject in a satisfactory manner at present, but an attempt to indicate the probable lines of development is made in a concluding chapter.

Explanation always progresses by stages; no explanation is ultimate; every explanation is a step up—removal of something from a lower to a higher category. Thus comets, at one time, might have been anything; they have been shown to be a form (or swarm) of meteorites. Meteorites, again, have been shown to be lumps of common matter—usually iron or rock. There remains the question, What is iron or rock, or any form of matter? Heat was once thought to be a form of matter; it is now known to be a form of energy. There remains the question, What is energy? Electricity may have been thought to be a form of energy; it has been shown to be a form of ether. There remain the questions, What is ether? How does it oscillate to produce light? how is it modified into an electric charge or electron? and (we may now add) how do electrons build up matter?

These questions have not yet been answered.

UNIVERSITY OF BIRMINGHAM,
April, 1907.

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INTRODUCTION

THE ETHER

THE most interesting and important portion of physics at the present day is that constantly growing portion which is concerned with the properties and function of the universal connecting medium, the "ether." All the phenomena of light, of electricity, and of magnetism, as well as of what is spoken of as radiant heat, are intimately connected with, and indeed wholly dependent on, that medium; it is through these agencies that we have gradually become aware of its existence and able in some degree to investigate it. Probably gravitation, cohesion, and chemical affinity are no less closely associated with the ether; and it is becoming doubtful whether matter itself could exist without it.

The eye may be called an ethereal sense-organ, just as the ear is an aërial one. Both are adapted to appreciate ripples—the one, large ripples or waves in air; the other, minute ripples, or quivers, in ether;

and the appreciation of those electrical ripples or quiverings, insignificant though they are from many points of view, is intensely important to us. Without the power of apprehending the ripples thrown off, and reflected from, and scattered by, the several objects in our neighbourhood, we should be both blind and deaf. It is only by inference from the way they deal with, and disperse, the ethereal quiverings, that we become aware of odourless objects beyond the range of our touch: We are said to "see" them. In a room where the ether is quiescent we can see nothing; but if by any means, as by lighting a candle, we throw it into vibration, the vibration returns to our eyes from all the objects in the room; and thereby, through habit and experience, we gain such quick intuitive information concerning those objects, that we are not conscious of the means of information, and express our perception as if it were direct and immediate, by saying that we see the objects themselves. That is, in fact, what we mean by "seeing." We do not see the waves, we see the obstacles; but it is entirely by means of the ethereal waves that the existence and nature of the objects are inferred. The extraordinary precision and rapidity of this mode of inference is perfectly marvellous, and could never have been believed if it had only theoretically been explained.

Before beginning a book on electricity, where we are to come into contact with other properties and functions of this most interesting and omnipresent medium, it is as well to exercise our imagination concerning it, and try to realize the vitally important part it plays throughout the universe. Probably we are far from knowing all its functions as yet; but knowing many of them we suspect more, and the reader is recommended to turn to a couple of lectures on the subject, which he will find printed on pages 359 and 450 further on, and read those, at intervals, before and during his perusal of the rest of this book; for they will serve as a useful introduction.

The book as a whole, beginning with a survey of well-known and elementary phenomena, leads up to the generalizations shadowed forth in Chapter XVII and Lectures IV and VI, which attempt to indicate how the idea of ether and the idea of electrons can be combined so as to supplement and illuminate each other. The hypothesis ultimately suggested is that excessively minute portions of ether have, by some unknown means, been dissociated here and there into electric charges, and that these immensely numerous mobile specks of electrified ether—through the forces they exert and the disturbances they originate—constitute the substratum of what appeals to our senses as matter.

PART I

ELECTROSTATICS

CHAPTER I

FUNDAMENTAL NOTIONS ABOUT ELECTRICITY

I BEGIN by saying that the whole subject of electricity is divisible for purposes of classification into four great branches.

(1) Electricity at rest, or static electricity: wherein are studied all the phenomena belonging to stresses and strains in insulating or dielectric media, brought about by the neighbourhood of electric charges or electrified bodies at rest immersed therein; together with the modes of exciting such electric charges, and the laws of their interaction.

(2) Electricity in locomotion, or current electricity: wherein are discussed all the phenomena set up in metallic conductors, in chemical compounds, and in dielectric media, by the passage of electricity through them; together with the modes of setting electricity in continuous motion, and the laws of its flow.

(3) Electricity in rotation, or magnetism: wherein are discussed the phenomena belonging to electricity in whirling or vortex motion, the modes of exciting such whirls, the stresses and strains produced by them, and the laws of their interaction.

(4) Electricity in vibration or radiation: wherein are discussed the propagation of periodic or undulatory disturbances through various kinds of media, the laws regulating wave velocity, wave-length, reflection, interference, dispersion, polarization, and a multitude of phenomena studied for a long time under the heading "Light."

Although this last is the most abstruse and difficult portion of electrical science, a certain fraction of it has been known to us longer than any other branch, and has been studied under special advantages, because of our happening to possess a special sense-organ for its appreciation.

Now in order to be able to survey these four great and comprehensive groups in moderate compass, it will be necessary for me to assume acquaintance with the elementary facts and proceed at once to their elucidation.

The views concerning electrification which I shall try to explain are in some sense a development of those originally propounded by that remarkable man, Benjamin Franklin. The accurate and acute experimenting of Cavendish laid the foundation for the modern theory of electricity; but, as he worked for himself rather than for the race, and as moreover he was in this matter far in advance of his time, Faraday had to go over the same ground again, with extensions and additions peculiar to himself and corresponding to the greater field of information at his disposal three-quarters of a century later. Both these men, and especially Faraday, so lived among phenomena that they yielded up their hidden secrets in a way unintelligible to ordinary workers; but while these men themselves arrived at truth by processes that savour of intuition, they were unable always to express themselves intelligibly to their contemporaries, or to make the inner meaning of their facts and speculations understood. Then comes Maxwell, with his keen penetration and great grasp of thought, combined with mathematical subtlety and power of expression; he assimilates the facts, sympathizes with the philosophic but untutored modes of expression invented by Faraday, links the theorems of Green and Stokes and Thomson to the facts of Faraday, and from the union rears the young modern science of electricity, whose infancy a quarter of a century ago was so vigorous and so promising that we all looked forward to the near future in eager hope and expectation of some greater and still more magnificent generalization.

3. Everyone knows that there have been fluid or material theories of electricity for the past century: all know, moreover, that there has been a reaction against them. There was even a tendency at one time to deny the material nature of electricity and assert its position as a form of energy. This was doubtless due to an analogical and natural, though unjustifiable, feeling, that just as sound and heat and light had shown themselves to be forms of energy, so in due time would electricity also. If such were the expectation, it has not been justified by the event. Electricity may possibly be a form of matter—it is not a form of energy. It is quite true that electricity *under pressure* or *in motion* represents energy; but the

same thing is true of water or air, and we do not therefore deny them to be forms of matter. Understand the sense in which I use the word electricity. *Electrification* is a result of work done, and is most certainly a form of energy; it can be created and destroyed by an act of work. But electricity—none is ever created or destroyed; it is simply moved and strained, like matter. No one ever exhibited a trace of positive electricity without there being somewhere, connected with it by lines of force, an equal quantity of negative.

The simplest proof of this statement consists in making experiments inside a closed conducting insulated room or shell; it may be the size of a living-room, or the size of a beer-tankard, whichever is most convenient. All known electrical experiments being performed inside such a room,—bodies electrified strongly, moved about, sparks taken, &c., &c.,—a sensitive electroscope connected to the room shall not show the slightest permanent effect. In other words the room will not become in the slightest degree charged. I say no *permanent* effect, because it is just possible that small transitory effects may occur during the rapid rearrangement of internal charges. I believe that I have shown [1] that even transitory effects are not really possible; but whether they are or not, they have nothing to do with our present argument. All the electrifications that have been going on will not have resulted in the creation of the minutest quantity of electricity; the only way to charge the room is to convey a charge to it from some other body outside.

[1] *Journal Inst. Elec. Engineers*, vol. xix. pp. 371—379.

This is the first great law, expressible in a variety of ways: as, for instance, by saying that total algebraic production of electricity is always zero; that you cannot produce positive electrification without an equal quantity of negative also; that what one body gains of electricity some other body must lose.

Now, whenever we perceive that a thing is produced in precisely equal and opposite amounts, so that what one body gains another loses, it is convenient and most simple to consider the thing not as generated in the one body and destroyed in the other, but as simply *transferred. Electricity in this respect behaves just like a substance.* This is what Franklin perceived.

4. The second great law is that electricity always, under all circumstances, flows in a closed circuit, the same quantity crossing every section of that circuit, so that it is not possible to exhaust it from one region of space and condense it in another.

Another way of expressing this fact is to say that no charge resides in the interior of a hollow conductor, but that every trace of charge is on the outer surface and penetrates to no appreciable depth.

Another is to say that total induced charge is always equal and opposite to inducing charge.[1]

This second law can also be illustrated by the insulated room or conducting cavity already mentioned. Having found that internal electrification produces no effect on an outside electroscope connected to the walls, proceed to pass a charge into the cavity through

[1] To explain how it is that these statements are equivalent, and generally to emphasize this fundamental part of the subject, is the object of § 14 A at end of the next chapter.

a temporarily opened window or lid. Instantly the chamber has become charged by a definite amount, viz. by the precise amount which has then been introduced into its cavity. The charge need not be in any way communicated to the chamber; all that is necessary is that it shall be wholly inside. Moving the charge about, or letting it spark to the walls of the chamber, makes not the slightest difference to the electroscope outside. It may be watched through a microscope at the instant the spark occurs, and it will not show the slightest twinkle; although it is connected to the enclosure by a metallic wire or rod. Both these experiments of the hollow chamber were made by Faraday, and the latter is well known and often quoted as his "ice-pail" experiment, because he happened to use an ice-pail sometimes as his insulated chamber. In many modern experiments this principle is utilized, and the device is spoken of as Faraday's hollow or collecting vessel.

Another mode of illustrating the same series of facts is afforded by an insulated parrot cage, with an electroscope inside it connected by a wire to the bars of the cage. The cage may now be charged strongly: its potential may be changed from a million volts positive to a million volts negative: sparks of any length may be taken from it; but, provided the meshes are close enough for it to be regarded as a really closed vessel, the electroscope inside is wholly unaffected. In making this experiment the electroscope must be connected with the bars of the cage; for, if it be detached, it can be affected by charged air blown through the meshes. Directly a charge gets *inside* the cage it can affect the electroscope easily enough, unless there is good wall-connexion, which completely protects it.

The open-work of a cage is objectionable on this account, that it allows the permeation of electrified air, just as it might allow an electrified pith ball to be thrown in. Making the meshes close is no guarantee against this source of disturbance: I have blown electrified air, from a point, through very fine earth-connected copper gauze, and affected strongly an electroscope on the other side.

No doubt a solid metal-walled room is secure against this cause of disturbance, but then it is difficult to see the electroscope. Faraday however constructed a room for the purpose, big enough to get into himself, and thus performed the experiment quite satisfactorily.

But perhaps the most rigorous mode of examining the precise truth of the property of electricity which lies at the bottom of all these experiments is that adopted in the famous Cavendish experiment: sometimes referred to in French books by the name of Biot. This consists in charging strongly an insulated sphere provided with a couple of hemispherical caps which can afterwards be taken off mechanically, and connecting a delicate electroscope immediately afterwards to the disclosed ball. Not the faintest trace of charge is found upon it. This experiment was repeated by Clerk Maxwell and Dr. Donald McAlister in the Cavendish Laboratory, Cambridge, using a Thomson Quadrant Electrometer and all modern appliances, with absolutely negative result.[1]

[1] See Maxwell's "Electrical Researches of Cavendish," pp. 104 and 417; also Maxwell's "Scientific Papers," p. 612. An interesting

This series of experiments is most vital, and gives us fundamental information regarding electricity; let us consider how we can best express their teaching.

5. When we thus find that it is impossible to charge a body absolutely with electricity, that though you can move it from place to place it always and instantly refills the body from which you take it, so that no portion of space can be more or less filled with it than it already is,—that it is impossible by any rise of potential to squeeze a trace of electricity into the interior of a cavity, and that if a charge be introduced a precisely equal quantity at once passes through the walls to the outside;—it is natural to express the phenomenon by saying that electricity behaves like a perfectly *incompressible* substance or fluid, of which all space is completely full. That is to say, it behaves like a perfect and all-permeating *liquid*. (§ 14A.)

6. Imagine now that we live immersed in an infinite ocean of incompressible and inexpansible all-permeating perfect liquid, as fish live in the sea; how can we become cognizant of its existence? Not very easily! Not by its weight, for instance, for we can remove it from no portion of space in order to try whether it has weight.

We can weigh air, truly, but that is simply because we can compress it and rarefy it. An exhausting or condensing pump of some kind was needed before even air could be weighed, or its pressure estimated.

But if air had been incompressible and inexpansible,

little experiment with soap bubbles, made by Mr. Vernon Boys, illustrates the fact that the depth to which a charge penetrates is less than the diameter of a few molecules, for one soap bubble inside another is entirely screened from such electrostatic forces as can be applied.

if it had been a vacuum-less perfect liquid, pumps would have been useless for the purpose, and we should necessarily be completely ignorant of the weight and pressure of the atmosphere.

How then could we become cognizant of its existence? In four ways:—

(1) By being able to pump it out of one elastic bag into another: not out of one bucket into another, —if you lived at the bottom of the sea you would never think about filling or emptying buckets, the idea would be absurd;—but you could fill or empty elastic bags, and could notice the strain phenomena exhibited by the bags, and their tendency to burst when over full. Water (or air) may be pumped out of one elastic bag into another; and the analogy with an electrical machine charging two conductors oppositely, *i.e.* pumping electricity from one into the other, may be perceived.

(2) By winds or currents; by watching the effect of moving masses of the fluid as it flows along pipes or through spongy bodies, and by the effects of its inertia and momentum. A hanging vane arranged in a tube, so as to be deflected by a stream of water, may be likened roughly to a galvanometer; also the effect of suddenly stopping a stream of water, as in a water ram, is somewhat analogous to self-induction.

(3) By making vortices and whirls in the fluid, and by observing the mutual action of these vortices—their attractions and repulsions. Whirlwinds, sand-storms, waterspouts, cyclones, whirlpools, have some analogies with an electro-magnet.

(4) By setting up undulations in the medium:

i.e. by the phenomena which in ordinary media excite in us, through our ears, the sensation called "*sound.*"

In all these ways we have become acquainted with electricity, and in no others that I am aware of. They correspond to the four great divisions of the subject which I have made above (§ 1).

7. But there are differences, at first sight important differences, between the behaviour of a material liquid ocean, such as we have contemplated, and the behaviour of electricity.

The chief difference between the behaviour of electricity and that of an ordinary incompressible fluid comes out in the fourth category—that concerned with wave-motion. In an incompressible fluid the velocity and length of waves would both be infinite, and none of the phenomena connected with the gradual propagation of waves through it could exist. Such a medium therefore would be incapable of sound-vibrations in any ordinary sense. On the other hand, it is quite certain that the disturbances concerned in light-radiation take place at right angles to the direction of propagation—they are transverse disturbances,—and such disturbances as these no body with the simple properties of an ordinary fluid can possibly transmit. Such vibrations can only be transmitted by a medium having something akin to the rigidity of a solid. We are bound to admit that ether, though fluid in the sense of enabling masses to move freely through it, has a certain amount of rigidity,—at least for enormously rapid and minute oscillatory disturbances. Is there any way of conferring upon a fluid such rigidity, without solidifying it?

It can be shown that although a fluid at rest has no quasi-solid properties, a fluid in motion acquires them. Drive water rapidly through a flexible tangle of india-rubber pipe with both ends fixed, and it at once becomes semi-rigid. So, utilising that fact, imagine every particle of a mass of fluid as in a state of violent motion, not locomotion, but motion in minute closed curves—vortex motion as it is called—and it too becomes rigid or quasi-solid : it acquires the property of transmitting transverse waves.

The gross analogy of a jelly is occasionally useful. A jelly is composed almost wholly of fluid, and yet it is rigid. It is rigid because of an elastic skin to each particle of water : it is like a multitude of little elastic bags of fluid. Distend a thin india-rubber balloon with water, and put it on a plate—it looks and behaves very like a jelly, until collapsed by a needle-prick. Well, the effect of an elastic skin, which can thus in a manner rigidify stagnant water, can be imitated, much more perfectly though not so easily, by setting the water into a state of fine-grained vortex motion. All kinds of elasticity are to be explained, as Lord Kelvin has shown us, by simple motion. (See article "Elasticity," *Ency. Brit.*) Not a simple fluid, but a fluid in a violent state of minute spin—a vortex-sponge, as it has been called—is what the ether is going to turn out to be. But as this conception is difficult at present, we can vaguely say that ether contains electricity as a jelly contains water ; and that the rigidity concerned in its transverse vibrations belongs, not to the water in the jelly, but to the mode in which it is entangled in its meshes.

CHAPTER II

THE DIELECTRIC

9. RETURN now to the consideration of electrostatics. We are to regard ourselves as living immersed in an infinite all-permeating ocean of perfect incompressible fluid (or liquid), as fish live in the sea; but this is not all, for if that were our actual state we should have no more notion of the existence of the liquid than deep-sea fish have of the medium they swim in. If matter were all perfectly conducting, such would be our state: in a perfectly free ocean there is no insulation—no obstruction to flow of liquid: it is the fact of insulation that renders electrostatics possible. We could obstruct the flow, and store up definite quantities of a fluid in which we were totally submerged by the use of closed vessels, of course. But how could we pump liquid from one into another so as to charge one positively and another negatively? Only by having the walls elastic; by the use of elastic bags, and elastic partitions across pipes. And so we can represent a continuous insulating medium (like the atmosphere or space) by the analogy of a jelly, through which liquid

can flow only by reason of cracks and channels and cavities.

Modify the idea of an infinite ocean of liquid into that of an infinite jelly or elastic substance in which the liquid is entangled, and through which it cannot penetrate without violence and disruption; and you have a crude model of the general insulating atmosphere. Our ocean of fluid is not free and mobile like water, it is stiff and entangled like jelly.

Nevertheless bodies can move through it freely. Yes, *bodies* can, it is the *liquid* itself only which is entangled. It is not easy to picture freely and naturally the motion of ordinary matter through the insulating medium of space, unless we step beyond our jelly analogy to the more refined and truer theory of the vortex-sponge of perfect liquid; but it is characteristic of analogies to break down when pressed too far, though they are useful up to a certain point.

Insulators being like elastic partitions, or impervious but yielding masses, conductors are like cavities; or rather like porous or spongy bodies, perfectly pervious, though with more or less frictional resistance, to the flow of liquids through them. Thus, whereas bodies easily penetrable by matter are impervious to electricity, bodies like metals, which resist entirely the passage of matter, are quite permeable to electricity. It is this inversion of ordinary ideas of penetrability that constitutes a small difficulty at the beginning of the subject.

However, supposing it overcome, let us think of the ordinary lecture-table assemblage of insulated spheres and cylinders connected by copper wire, as so many cavities and tubes in an otherwise continuous elastic impervious medium, which surrounds them and us, and extends throughout space wherever conductors are not; all, however—cavities as well as the rest of the medium—being completely full of the universal fluid.

The fluid which is entangled in insulators is free to move in conductors; whence it follows that its pressure or potential is the same in every part of a conductor in which it is stationary. For if there were any excess of pressure at any point, a flow would immediately occur until it was equalised. In an insulator there is a tendency to equalisation, but it cannot take effect: so differences of pressure are exceedingly common in insulators, and are naturally accompanied by a strain of the medium.

It is instructive now to think over a number of ordinary electrical experiments from this point of view: to think of the fluid as flowing freely through conductors and settling down to a state of equilibrium or uniform pressure in them; but straining insulators, as high-pressure water might strain elastic walls or boundaries, straining them even to bursting if the partitions be made too thin.

10. There have been, as you know, two ancient fluid theories of electricity—the one-fluid theory of Franklin, and the two-fluid theory of Symmer and others. A great deal is to be said for both of them within a certain range. There are certainly points, many points, on which they are hopelessly wrong and misleading, *but it is their foundation upon ideas of action at a distance that condemns them, it is not the*

fluidity. They concentrate attention upon the conductors; whereas Faraday taught us to concentrate attention on the insulating medium surrounding the conductors—the "*dielectric*," as he termed it. This is the seat of all electrostatic phenomena: from the point of view of static electrification, conductors are mere breaks in it—interrupters of its continuity.

To Faraday the space round conductors was full of what he called lines of force; and it is his main achievement in electrostatics to have diverted our attention from the obvious and apparent to the intrinsic and essential phenomena. Let us try and seize his point of view before going further. It is certainly true as far as it goes, and is devoid of hypothesis.

Take the old fundamental electric experiment of rubbing two bodies together, separating them, and exhibiting the attraction and repulsion of a pith ball, say; and how should we now describe it? Something like this:—

Take two insulated disks of different material, one metal, say, and one silk; touch them together; the contact effects a transfer of electricity from the metal to the silk; rub slightly to assist the transfer, since silk is a non-conductor, then separate. As you separate the disks the medium between them is thrown into a state of strain, the direction of which is mapped out by drawing a set of lines, called lines of force, from one disk to the other, coincident with the direction of strain at every point. As Faraday remarked, the strain is as if these lines were stretched elastic threads endowed with the property of repelling each other as well as of shortening themselves ; in other words, there is a tension along the lines of force and a pressure at right angles to them. When the disks are near, and the lines short, they are nearly straight (Fig. 1), but as

FIG. 1.—Rough diagram of the state of the medium near two oppositely charged disks when close together.

the distance increases they become curved, bulging away from the common axis of the two disks and some even curling round to the back of the disk (Fig. 2), until, when the disks are infinitely distant, as many

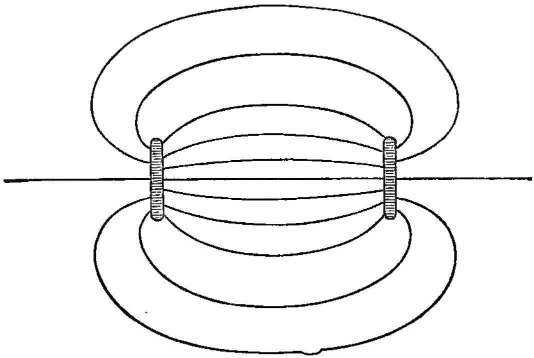


FIG. 2.—Rough diagram of the state of the medium near two oppositely charged disks when separated.

lines spring from the back of each as from its face ; and we have a charged body to all intents existing in space by itself.

The state of tension existing in the medium between the disks results in a tendency to bring them together again, just as if they were connected by so many elastic threads of no length when unstretched. The ends of the lines are the so-called "electrifications" or "charges," and the lines perpetually try to shorten and shut up, so that their ends may coincide and the strain be relieved. If one of the disks touch another conducting body, some of its lines instantly leave it and go to the body; in other words, the charge is capable of transference, and the new body is urged towards the other disk, just as the disk was from which it received the lines. If this new body *completely surrounds* the disk, it receives the whole of its lines, and the disk can be withdrawn perfectly free and inert. This is Faraday's "ice pail" experiment (§ 4).

11. Now take the two charged disks, facing one another, and let, say, a suspended gilt pith ball hang between them. Being a conductor there is no strain inside it, and so it acts partially as a bridge, and several of the lines pass through it—or, rather, they end at one side of it and begin at the other: thus it has opposite charges on its two faces—it is under induction (Fig. 3). Let it now be moved so as to touch one of the disks, the lines between it and the disk on that side have shut up, and it remains with those only which go to the other disk. Besides these, it receives, unbalanced, some of the lines which previously belonged to the touched disk. Its line of force now will pull it over to the far disk and there shut themselves up. From that disk it receives more; and it travels, with them, back to the first disk,

and so on (Fig. 4), perpetually receiving lines and shutting them up, until they are all gone and the disks are discharged. The experiment is easily performed, and illustrates "discharge by alternate contact."

This mode of stating the facts involves no hypothesis whatever—it is the simple truth. But it may at once be admitted that "lines of force" have no

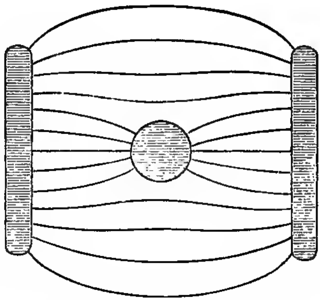


FIG. 3.—Rough diagram of the medium between two disks disturbed by the presence of an uncharged metal sphere. The two halves of the sphere are oppositely charged "by induction."

more and no less existence than have "rays of light." Both are convenient modes of expression."

12. But so long as we adhere to this mode of expression we cannot form a complete mental picture of the actually occurring operations. In optics it is usual to abandon "rays" at a certain stage and attend to "waves," which we know are of the essence of the phenomenon though we do not yet know very much about their true nature.

Similarly in electricity, at a certain point we are led to abandon lines of force and potential theories, and try to conceive the actual stuff undergoing its strains and motions. It is then that we get urged towards ideas similar to those which are useful in treating of the behaviour of an incompressible fluid.

In a much-modified sense, we have still a fluid

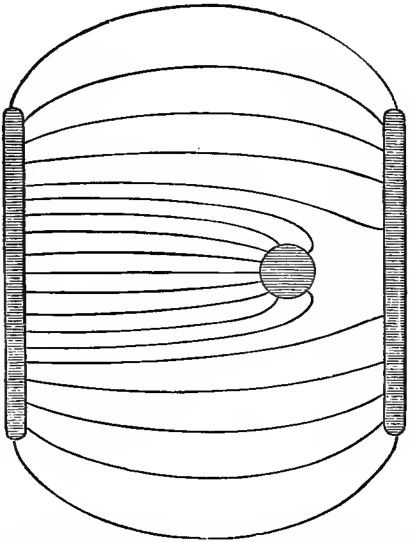


FIG. 4.—Rough diagram of the medium near two oppositely charged disks between which a metal carrier ball is oscillating, having just touched the right-hand disk. (Discharge by "alternate contact.")

theory of electricity, and a portion of the ideas of the old theories belong to the new theory also.

Thus Franklin's view that positive charge was excess, and negative charge was a deficit, in a certain standard quantity of the fluid which all bodies naturally possessed in their neutral state, remains practically true: except that we have reason to wish that he had happened to interchange the nomenclature; since it is what he called negative that turns out to be the excess. But too much confusion would result from trying to change now. His view that the fluid was never manufactured, but was taken from one body to give to another, so that one gained what the other lost—no more and no less—remains practically true. Part also—a less part—of the two-fluid theory likewise remains true, in my present opinion (§ 90); but this is not a branch of the subject on which I shall enter in the present part. It will suffice for the present to fix our attention on one fluid only.

You are to think of an electric machine as a pump which, being attached to two bodies respectively, drives some electricity from the one into the other, conferring upon one a positive and upon the other a precisely equal negative charge. One of the two bodies may be the earth, in which case the charge makes little or no difference to it.

13. But, as has been objected before, if electricity is like an incompressible and inextensible fluid, how is it possible to withdraw any of it from one body and give it to another? With rigid bodies it is not possible, but with elastic bodies it is easy.

The act of charging a sphere is therefore analogous to pumping water into an elastic bag; or rather into a cavity in the midst of an elastic medium, whose thick walls, extending in all directions and needing a great pressure to strain them, better represent the true state of the case than does the thin boundary of a mere bag.

Draw a couple of such cavities and consider fluid pumped from one into the other, and you will see that the charge (*i.e.* the excess or defect of fluid) resides on the outside. The interior was full and remains full.

If the fluid is exactly incompressible, not the least extra quantity will be squeezed by the pressure into the space originally occupied by the cavity. This is the moral of the Cavendish experiment (§ 4): it proves that electricity is precisely incompressible; a fact which is further explained in § 14 A.

You may also show that when both cavities are similarly charged, the medium is so strained that they tend to be forced apart; whereas when one is distended and the other contracted they tend to approach.

Further you may consider two cavities side by side; pump fluid into (or out of) one only, and watch the effect on the other. You will thus see the phenomena of induction, the near side of the second cavity becoming oppositely charged (*i.e.* the walls encroaching on the cavity), the far side similarly charged (the cavity encroaching on the wall), and the pressure on the fluid in the cavity being increased or diminished in correspondence with the rise or fall of pressure in the charged or inducing cavity. In other words, conductors rise in potential when brought near a positively charged body; and their charge, if any, though not altered in quantity becomes redistributed.

The actual changes in volume necessary to the strain of these cavities are a defect in the analogy. To avoid this objection, one will have to accept a dual view of electricity—a sort of two-fluid theory, which many phenomena urge one to contemplate; for the two constituents of ether may then be sheared past each other—one increasing as the other decreases in the charged cavity—setting up a shearing strain or distortion which involves no expansion or contraction in volume, and leaving the total quantity of ether everywhere unchanged (cf. § 18).

14. *Return Circuit.*—Sometimes a difficulty is felt about electricity flowing in a closed circuit—as, for instance, in signalling to America and using the earth as a return circuit: the question arises, How does the electricity find its way back?

The difficulty is no more real than if a tube were laid to America with its two ends connected to the sea and already quite full. If now a little more sea-water were pumped in at one end, an equal quantity would leave the other end, and the disturbed level of the ocean would readjust itself. Not the same identical water would return, but an equal quantity would return. That is all one says of electricity. One cannot label and identify electricity.

To imitate the inductive retardation of cables, the tube should have slightly elastic walls; to imitate the speed of signalling, the water must be supposed quite incompressible,—not elastic as it really is, or each pulse would take three-quarters of an hour to go: even through a perfectly rigid pipe.

14 A. *Incompressibility of Electricity.*—The equivalence of the different modes of expression at the beginning of § 4 is, I find, not obvious. It seems worth while to explain these fundamental matters at greater length. One of the fundamental experimental facts concerning electricity is that it is impos-

sible to charge an insulated chamber by performing electrical experiments in its interior. Electrical machines inside a conducting chamber and electroscope outside, or *vice versâ*, are perfectly independent of each other. This may be expressed by saying that the field of force outside a conductor, and the field of force inside, are quite independent; that there is entire dislocation of every line of force at the conductor; that a closed conductor acts as a perfect electrostatic screen. A second fundamental experimental fact is that if a charge be in any way communicated to, or even passed into the interior of, a hollow conductor, the same precise quantity at once appears on the outside; and a variant of this is that if the outside skin of a conductor be peeled off, all charge is removed with that outer skin: no trace remaining below it.

These two facts lead us to say that electricity behaves like an incompressible fluid of which all space is precisely full; a fluid moreover which cannot be manufactured but only moved about. For think of a closed chamber in the sea with pumps inside it. So long as there is no communication through the walls, all that the pumps could do would not result in a trace more liquid in the vessel than there was at first. The vessel cannot be thus *charged*. But now suppose some water to be pumped from the outside into the interior, through a suitable opening; how could it be done? The vessel being already by hypothesis quite full, either the water must be compressible, in which case the extra charge would exist uniformly throughout the enclosed space; or the vessel must be expansible or porous, in which case the extra charge is not found in the original space at all, but outside it. Whatever extra quantity was pumped into the original space, that same amount precisely would instantly appear outside it; and this is what happens with electricity (§ 4).

In order to examine whether *water* is incompressible or not we might perform this experiment: Inside a metal cavity provided with a pressure-gauge, introduce a strong elastic bag, and distend it by pumping water into it (Fig. 10). As the bag swells, the pressure in the outer vessel will rise, unless it is continually relieved (by connexion to "earth"). Having finished pumping into the bag, close any leak the outer vessel may have had, examine the gauge carefully, and then puncture the bag inside. The water in the bag suddenly escapes from pressure, and, if the slightest degree elastic, will increase the pressure in the outer rigid vessel and thus will cause a sudden small rise of the gauge. If it be incompressible the gauge will indicate nothing. Nothing will happen except the release of tension in the bag: the water will indicate nothing whatever, unless it had been actually compressed. This is precisely Faraday's ice-pail experiment; and the result teaches us that electricity is perfectly incompressible.

The Cavendish experiment—where the skin is removed from a charged conductor, which is then tested and found exactly uncharged—is another more stringent but more difficult mode of doing the same thing. If a real positive result could be got by either of these experiments, it would constitute a measure of the compressibility or volume-elasticity of the ether. It would show that longitudinal thrusts (such as those of gravitation may be) do not exist instantaneously throughout space, but are propagated in time at a certain velocity.

It is easy to see that the facts related above carry with them such mere technical expressions as that total "induced charge" is always equal and opposite to "inducing charge"; because "induced charge" merely represents the condition of the interior surface of a chamber into which an inducing charge has been introduced: and, an equal quantity having been thereby extruded, the inner surface of the wall must have been left negatively charged by that precise amount.

Furthermore, the incompressibility of electricity necessitates its flow always in a closed circuit. In most cases it is obvious; but take a case where it is not obvious. When a charge of electricity is moved from place to place, as for instance from outside to inside a room, it is not thereby piled up in the room and withdrawn from elsewhere; for an equal quantity instantly goes through the walls and appears outside. It has not been exhausted from one part of space and condensed in another. So even in this case, it has moved in a closed circuit, and has behaved precisely as an incompressible fluid filling all space must behave. That is what it does always.

Thus the equivalence of the statements at beginning of § 4 are clear.

CHAPTER III

CHARGE AND INDUCTION

15. *Condensers.*—Returning to the subject of charging bodies electrically, how is one to consider the fact that bringing an earth-plate near a conductor increases its capacity so greatly, enabling the same pressure to force in a much larger quantity of fluid? how is one to think of a condenser, or Leyden jar?

In the easiest possible way, by observing that the bringing near an earth-connected conductor is really *thinning down the dielectric* on all sides of the body.

The thin-walled elastic medium of course takes less force, to distend it a given amount, than a thick mass of the same stuff took; in other words a cavity enclosed by thin walls has much more capacity than if its walls were thick. Remember that capacity of elastic cavities cannot satisfactorily be measured as the capacity of buckets is measured, by the maximum quantity they will hold when full: elastic bags are never "full," till they burst; and the amount required to burst them measures rather their strength than their capacity. The only reasonable definition of capacity in such cases is the ratio which any addition to their contents bears to the extra pressure required to force it in : and this is exactly the way electrical " capacity " is defined. A Leyden jar is like a cavity with quite thin walls—in other words, it is like an elastic bag.

But if you thin it too far, or strain it too much, the elastic membrane may burst ! Exactly, and this is the disruptive discharge of a jar, and is accompanied by a spark. Sometimes it is the solid dielectric which breaks down permanently. Ordinarily it is merely the air; and, since a fluid insulator constitutes a self-mending partition, it is instantaneously as good as new again.

There are many things of interest and importance to study about a Leyden jar. There is the fact that if insulated it will not charge: the potential of both inner and outer coatings rises equally. In order to charge it, for every positive spark given to the interior an equivalent positive spark must be taken from the exterior. There is the charging and the discharging of it by alternate contacts, as by an oscillating ball; and there are the phenomena of the spark-discharge itself,

But, as a matter of fact, *all* charging is really represented by the case of a Leyden jar. The outer coat must always be somewhere—the walls of the room, or the earth, or something—you always have a layer of dielectric between two charges—the so-called induced and the inducing charge. You cannot charge one body alone (§ 5).

16. To illustrate the phenomena of charge, I will now call your attention to these diagrams—which

less completely but more simply than hydraulic illustrations, serve to make the nature of the phenomena manifest.

Fig. 5 shows an inextensible endless cord circulating over pulleys; this is to represent electricity flowing in a closed circuit. Electromotive forces are

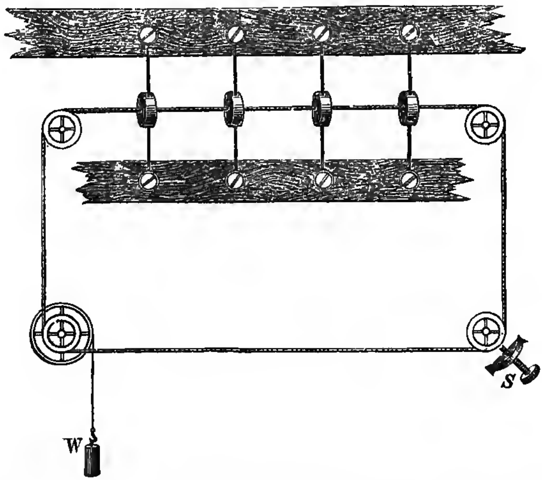


FIG. 5.—Mechanical analogy of a *metallic* circuit. The cord corresponds to electricity, the weight W to an electromotive force, and the perforated blocks to atoms of matter.

forces capable of moving the cord, and you may consider them applied either by a winch, or by a weight on the hook W. A battery cell corresponds to a small weight; an electric machine to a slow but powerful winch. Clamping the cord with the screw S corresponds to making the resistance of the circuit infinite. Instead of the cord, clamp, and driving pulley, one might consider an endless pipe full of liquid, with a stop-cock and a pump on it, but for many purposes the cord is sufficient and more simple. In Fig. 5, the only resistance to the motion is friction, and there is no tendency to spring back. The cord passes freely through fixed blocks or beads, which are to typify atoms of matter; and they may be more

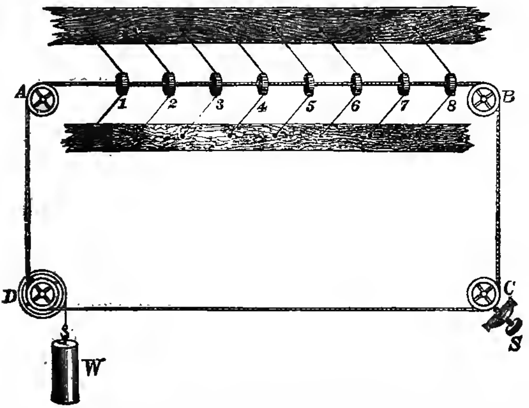


FIG. 6.—Mechanical analogy of a circuit partly *dielectric*: for instance, of a charged condenser. A is its positive coat, B its negative.

or less rough, to represent different specific resistances. If the cord be moved, heat is the only result.

Now pass to Fig. 6. Here the cord is the same as before, and still represents electricity in a closed circuit, but the beads are now firmly attached to the cord, so that if it moves they must move with it. They represent, therefore, the particles of an insulating substance. Nevertheless, their supports are not rigid—they do not prevent the cord moving at all; they allow what is called electric "*displacement*," not conduction: they can be displaced a little from their natural position, but they spring back again when the disturbing E.M.F. is removed. The beads in this figure are supposed to be supported by elastic threads. If we used the analogy of a closed pipe full of water, the beads and threads would be replaced by elastic partitions. The specific inductive capacity of the dielectric is represented by the stretchability, or inverse elastic resilience, of the elastic threads. The stiffer the threads are to pull out, the less is the inductive capacity of the medium; because evidently a greater E.M.F. is needed to cause a given displacement.

Apply a given E.M.F. to this cord, as for instance the weight W, and a definite displacement is produced. One side, A, gets more cord than usual—it is positively charged; the other side, B, gets less—it is negatively charged. If the applied E.M.F. exceeds a certain limit, the strain is too great; the elastics break, and you have disruptive discharge with a spark. But even when the strain is only moderate some of the supports may yield viscously, or be imperfectly elastic, and permit a gradual extra displacement of the cord, known to telegraphists as "soaking in"; which is explained more fully in the next section.

When, after this process, discharge is allowed, it is not at once complete; a large portion of the displacement is at once recovered, but the rest gradually "soaks out" and causes residual discharges.

If the dielectric is at all stratified in structure, so that some of the beads allow cord to slip through them—or yield more than others—then this residual charge effect will become very prominent.[1]

17. These are matters which it is easy thoroughly to understand, and Fig. 7 illustrates different stages sufficiently. In Diagram I. are represented 8 strata, each displaced from its normal position by an amount 3. The restoring force is proportional to the displacement, so the total restoring force can be called 24. The diagram represents, therefore, a Leyden jar or other dielectric strained by an applied E.M.F. of 24 units. If every stratum insulates perfectly—that is, if every bead is quite firmly attached to the cord—nothing further happens, so long as the force is kept applied. This state of things may be maintained in two ways: either by keeping on the weight W—that is, by keeping the condenser permanently connected to the battery; or by clamping the cord and thus making the resistance infinite—that is, by insulating the terminals of the condenser.

But now suppose that some of the strata are not perfectly insulating; let some of the beads slowly slide back along the cord towards their zero position. Then we shall witness different phenomena according to whether the weight has been left on or whether the cord has been clamped.

Take first the case of leaving the weight on—that is, keeping the battery connected. If every bead slides equally, all we get is a continuance of the state represented in Diagram I., combined with a slow oozing

[1] For the original details of these cord models as illustrative of Maxwell's theory of electrostatic induction, &c., see Lodge, *Phil. Mag.* November 1876.

forward of the cord—that is, a slow and steady leak through the condenser. But suppose every bead does not slide equally, suppose some do not slide at all; then the slipping of some throws extra strain on the others, and the cord moves forward, but more and more slowly, until the insulating strata ultimately have to bear all the strain, and the cord asymptotically comes to rest.

This process is observed in Atlantic cables and Leyden jars; all condensers are liable to it except air condensers, and it is called "soaking in"; it is accompanied by the development of internal charges, because plainly the original normal length of cord *between the beads* is no longer maintained; some strata have acquired an extra length—that is, are positively charged—others are negatively charged.

The strain is distributed very unequally, but its total amount, in this case, continues constant.

Remove the electromotive force now, keeping the circuit still closed: *i.e.* short-circuit the condenser. We get first a quick discharge; and then a slow leaking out or reverse motion of the cord, as it is propelled by the still displaced insulating strata through the now oppositely displaced badly conducting ones; the time of "soaking out" being comparable with that permitted to the soaking in.

It is important to see how these phenomena are entirely reconcilable with the incompressible character of electricity—that is, the unyielding character of the cord.

So much for the case when the battery is left connected; now attend to the case when the terminals are insulated. Refer to Fig. 7.

Having got the dielectric into the state represented by I., screw down the clamp and wait. If some of the beads slide, while some do not, we shall shortly

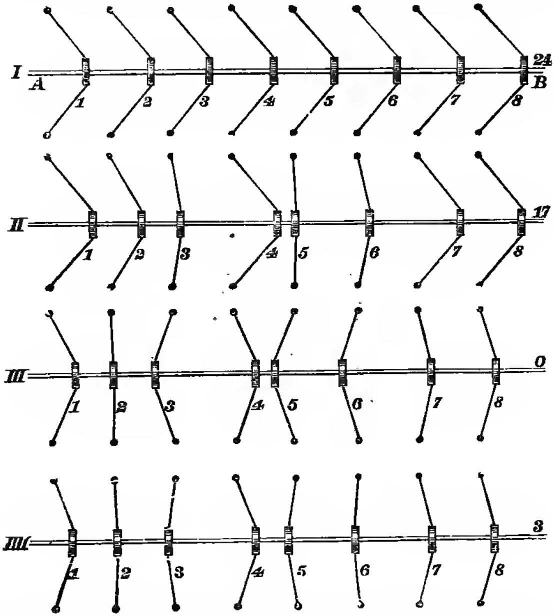


FIG. 7.—Stages in the discharge of a stratified condenser, with some of its layers of imperfect insulating power; showing one way in which the phenomena of "residual charge," "internal charge," and "soaking out" are produced. Tension in the cord, measured by the right-hand numbers, represents electric potential.

I. represents a recent charge, of E.M.F. 24.
II. represents the same after lapse of time, reduced to 17 by partial internal leakage, and shows internal charge. The circuit itself is supposed to have been perfectly insulating all the time; the charge on the plates therefore remains constant.
III. shows the first discharge.
IIII. shows the state attained after again waiting, viz. a residual charge with an E.M.F. 3 in the old direction.

arrive at the state represented by II. Beads Nos. 3, 5, and 6 have slid partially back, and the total stress on the cord has been reduced to 17. The jar will appear to have partially discharged itself by internal leakage, and yet not the slightest motion of the cord has been permitted. Internal charges have appeared: positive between Nos. 3 and 4, and between 5 and 6, negative between 2 and 3, and between 4 and 5. The charges on the coatings at A and B have remained constant; the jar has apparently increased in capacity, because the same charge is maintained by a less electromotive force. All these effects may present themselves at first sight as irreconcilable with the behaviour of an incompressible fluid, or cord of constant length; but the diagram clearly says otherwise.

Now unclamp the cord momentarily, *i.e.* discharge the condenser, and insulate again. At the instant of discharge a rush of electricity takes place, and the force falls to zero. The state of the discharged jar at the first instance after discharge is represented in III. fig. 7. The surface charges have not wholly disappeared; the internal charges have been unaffected; the displacement of none of the strata is zero. The insulating ones remain with some of their original displacement, the leaking ones have been forced into a position of inverse displacement, so as just to reduce the resultant force on the cord to zero. The most slippery, Nos. 3 and 5, have been most displaced in the inverse direction. But not long do they thus remain. They at once begin slowly to ooze back; and before long they will have got into the state represented by IIII, where the now almost unbalanced stress of the insulating strata exerts on the cord a force 3 in the original direction. This is known as the "residual charge," and on unclamping the cord, the first residual discharge can be obtained. Not even yet, however, is the jar wholly discharged. Waiting again, another but feebler residual charge makes its appearance ; and so on, almost without limit, until the sum of all the residual discharges plus the original discharge make up exactly the charge originally imparted to the jar—make it up exactly if any one of the strata has declined to leak. If *all* leaked more or less, then of course there will be some deficiency.

18. The only thing needful to guard against in following out this mechanical analogy is the idea that there need be any mechanical displacement of

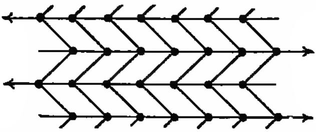


FIG. 7A. Closer representation of electric displacement or shear. Cords alternately representing positive and negative electricity. Cf. also Fig. 46.

the atoms of matter accompanying the electric displacement. Manifestly a model containing fixed beams for the attachment of the beads cannot really correspond very closely to electrical facts. To make the model more closely imitative of facts we should have to take a number of rows of beads, each row threaded on its cord and attached crosswise by elastic threads, as in Fig. 7A.

If these cords are simultaneously displaced alternately in opposite directions, and if they be considered as representing positive and negative electricity alternately, while the beads represent the electro-positive and the electro-negative elements of the material substance, then perhaps something more like the actual state of things may be imagined. There is here no displacement of the molecule as a whole, but there is a displacement of its constituent atoms; there is a shearing stress applied to each molecule, which, if strong enough, may result in electrolytic disruption. I certainly regard disruptive discharge as being of this electrolytic character (§§ 112 and 65A; see also § 13).

19. Return, however, to the simple discharge, and see how it occurs. Will it take place as a simple sliding back of the beads to their old position? Yes, if the resistance of the circuit is great; but not otherwise. If the cord is fairly free the beads will fly past their mean position, overshooting their mark, then will rebound, and so, after many quick oscillations, finally settle down in their natural position. Thus is represented the fact that the discharge of a Leyden jar is in general oscillatory. The apparently single and momentary spark, when analysed in a very rapidly rotating mirror, turns out really to consist of a series of alternating flashes rapidly succeeding one another, and all over in the hundred-thousandth of a second or thereabouts. These oscillatory currents were predicted and calculated beforehand by Lord Kelvin; they were first observed experimentally by Feddersen.[1] The oscillations continue until the energy stored up in the strained medium has all rubbed itself down into heat. The existence of these oscillations proves distinctly that electricity

[1] We now find that they were experimentally discovered with considerable clearness by Joseph Henry of Washington. (See Lect. III.)

in conjunction with matter possesses inertia. The rapidity of these oscillations is something tremendous: it may reach as high as a hundred million per second, or it may be as slow as ten thousand per second, according to the capacity and inertia of the circuit. With special arrangements, the above range of frequency for the alternations can be far exceeded both ways.[1]

The rapidity of oscillation, and its rate of dying away, as well as the circumstances which change the

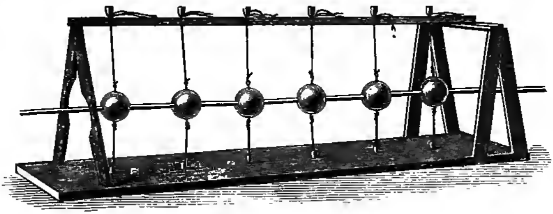


FIG. 8.—Partial model of a dielectric.

recovery from an oscillatory one into a simple one-directioned leak, are precisely analogous to those which regulate the recovery of a bent spring suddenly let go. If the spring is in a very viscous medium, or if it has but small inertia, it will not oscillate, but will merely return to its normal position. Under ordinary circumstances, however, it will make many oscillations before its energy is all rubbed into heat (§§ 123, *et seq.*).

Fig. 8 shows part of a first actual model of the kind.

20. To make the model represent *charge by induction*, all that has to be done is to immerse a conductor

[1] Lodge, *Proc. R. I.* March, 1889, and *Phil. Mag.* April and July 1889.

into the polarised dielectric; in other words, to make one or more of the beads of the fixed and slippery conducting kind, the other beads on the cords being of the elastic and adhesive or insulating kind. Then, when displacement occurs, it is plain that a deficiency of cord will exist on one side of the metallic layer and a surplus on the other, as shown in Fig. 9. This state of things corresponds exactly to the equal

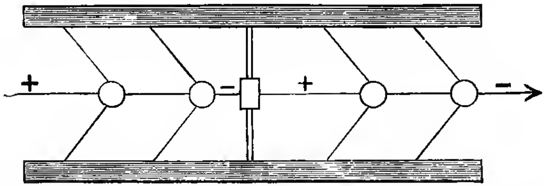


FIG. 9.—Metallic layer in the midst of a polarized dielectric, showing opposite charges "induced" on its surfaces. (Compare Fig. 3.)

opposite induced charges on a conductor under induction, as in Fig. 3.

An improved model of this kind is represented in Fig. 67.

If the strain on one side be relieved by letting the beads on that side slip back on the cord, that corresponds to touching the conductor to earth, as in Fig. 4. The other side has now to withstand the whole E.M.F., consequently the strain there and the charge there will have increased. Remove now the applied E.M.F., and the negative charge appears on both sides of the metal partition,—either equally, or more markedly on that side which has fewest beads, *i.e.* which is nearest to other conductors.

21. This being a matter which it is desirable thoroughly to understand, a series of figures illus-

trating the various stages of the process are appended in Fig. 9A.

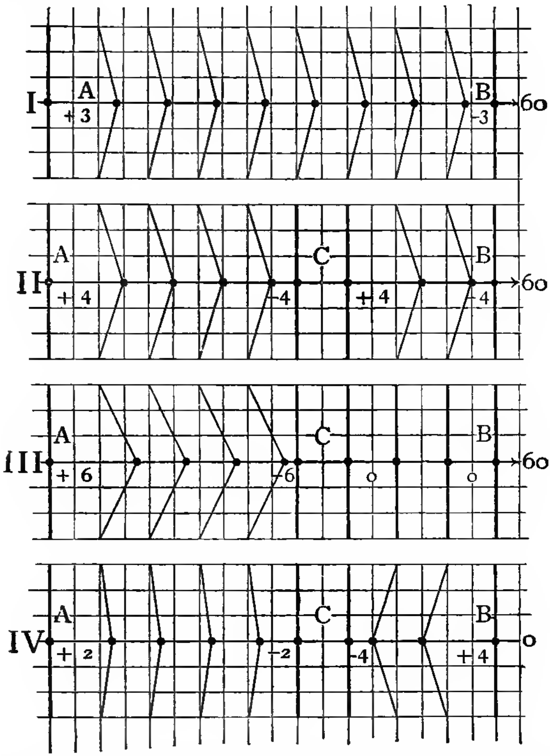


FIG. 9A.—Stages during the charge of a metal by induction and contact. C is a metallic stratum introduced into a dielectric between the opposing electrified plates, A and B, which are kept connected to a constant source, till one side has been discharged. Numbers preceded by + or − represent charges; numbers affixed to an arrow-head represent E.M.F. In this series the E.M.F. applied is supposed constant. To represent the other case, when the charge on the A plate is kept constant, the cord must not be allowed to move; but the force on it will then decrease, from 60 in I. to 45 in II. and to 30 in III.

I. represents an ordinary polarized dielectric, say air, between two oppositely charged bodies, A and B, maintained at constant difference of potential. For simplicity the field is taken of uniform strength, *i.e.* with its lines of force parallel straight lines, so that A may be considered as a large positively charged plate, and B an earth-plate facing it. The difference of potential between A and B is called 60, and is distributed among 8 strata or units of thickness, each of which therefore bears the strain $7\frac{1}{2}$, and is displaced $\frac{3}{4}$ of the width of a square from its normal position. The charges on A and B we may call ± 3 respectively.

An insulated metal plate, C, two units in thickness, is now introduced, replacing a couple of the dielectric strata. The remaining 6 have therefore more strain thrown upon them, viz. 10 on each, and accordingly each is now displaced a whole square-width from its normal position, the charge of the plates A and B has risen to ± 4, and the effect is the same as if the thickness of dielectric had been reduced in the ratio of 8 to 6. The metal partition introduced has also a charge on the surface, viz., -4 on the side facing A, and $+4$ on the side facing B. See Diagram II. in Fig. 9A.

The next stage is to connect the metal momentarily to earth. The effect of this is entirely to relieve the strain on the B side, by replacing the dielectric with metal, which allows the cord to slip through freely. The cord makes another bound forward, and all the strain is now thrown upon 4 strata, which each have to bear 15, and are displaced $1\frac{1}{2}$ from their natural position. Restoring the dielectric (*i.e.* removing the temporary earth connexion) makes no further change, but leaves everything as shown in Diagram III. The charge on one side of the metal partition is now -6, and on the other side is nothing.

Finally remove the constant E.M.F. which has been acting all this time. The cord makes a bound back, the resultant force on it becomes nothing ; the 2 strata on the right have to balance the 4 strata on the left, and accordingly their displacements are -1 and $\frac{1}{2}$ respectively. The charges on the faces of the partition are -2 and -4; both negative. The charges on A and B are $+2$ and $+4$ respectively, although they are at the same potential. The state of things is shown in IV., which exhibits the metal partition as completely charged negatively by means of induction. Of course it *may* have been charged equally on its two faces, but not necessarily; that is a mere matter of the relative proximity of adjacent objects, A and B.

If instead of maintaining A at constant potential, it possessed a constant charge, the series of operations would differ in a slight and easily appreciated manner. The resultant tension on the cord would then decrease, —both when the thick metal layer was introduced, and when it was touched to earth ; but we may now regard the series of operations as practically the electrophorus series, such as go on rapidly and continuously in all inductive machines and replenishers. It will be worth while to sketch this electrophorus series more particularly ; the process of working out what is happening in any given case will then be sufficiently illustrated.

Electrophorus.

22. Diagram I., Fig. 9B, shows the cake excited negatively, resting on its sole. The negative charge

on surface of cake is called 13 units; of these, 12 are what is sometimes called "bound" by the sole, and 1 is free. In other words, the strain due to 12

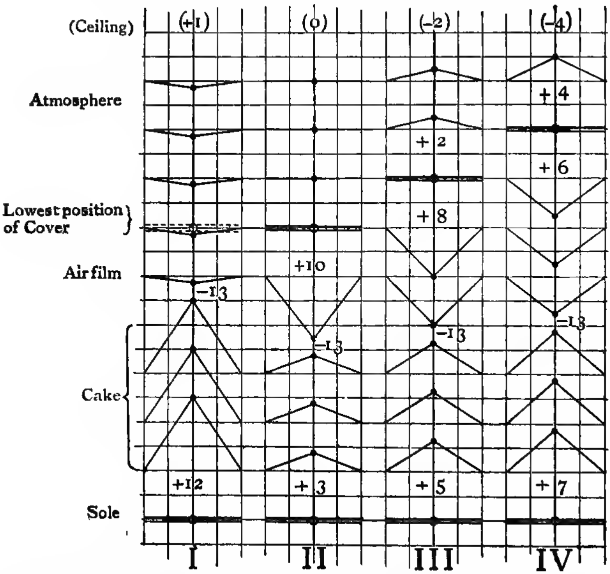


FIG. 9B.—The electrophorus series of operations. Double lines mean rigid rods supporting smooth beads, and represent metal. Gripping beads supported by elastics represent dielectric. Numbers preceded by + or − represent charges. The charge excited on the surface of the electrophorus cake remains constant all the time. The sole is supposed connected with the floor and walls of the room. Numbers in parentheses at the top represent the charge induced on ceiling and walls. The whole thickness of the atmosphere does not pretend to be represented. It must be thick enough in I. precisely to balance the stress in the cake. The resultant force on the cord is in each case zero.

I. shows the charged cake, with cover either off or in position but insulated.
II. shows effect of connecting cover and sole.
III. and IV. show effect of gradually raising cover.
I. again shows effect of having removed cover completely and discharged it.

units of charge is thrown on the layers of the cake, the remaining small strain is thrown on the atmosphere above. The strain in the atmosphere is small because it is so much thicker than the cake—there are so many layers in it that a very small displacement of each suffices to balance the stress in the cord. One unit of charge is induced on the ceiling and walls of the room by the electrified cake.

We now bring down the insulated metal cover of the electrophorus. If of any appreciable thickness it displaces a few of the strained layers, and thus there is a little extra strain on the others; but this effect is extremely small, and it is quite unessential. We may therefore take the cover as of no thickness, and bring it down into what is marked in the diagram as its lowest position; the stress passes through it, and nothing is affected except the one layer whose place it takes. Diagram I. will serve to represent the cover thus put on, so long as it is insulated. The dotted lines show it in position. It does not make intimate contact with the cake; a film, either of air or of the substance of the cake itself, intervenes between it and the negatively charged surface, and this is exhibited in the diagram.

The next thing is to connect the cover and the sole together. This immediately brings about the state of things represented by Diagram II.

A charge of 9 units has rushed round from sole to cover, making, with the charge 1 which previously existed on the walls of the room, a total of 10.[1] The strain above the cover is entirely relieved, and the whole excitement is now internal, between cover

[1] If the sole had been insulated, and connexion between it and cover also made in an insulated manner, then this unit on the walls of the room would stay there: the cover would only acquire a charge 9, and the slight strain above it shown in I. would continue to exist unaltered.

and sole. The strain in the cake is considerably relieved, but the work of balancing what remains is thrown on the very thin film between cover and top of cake. This, therefore, is highly strained.

We now raise the again insulated cover. As it ascends, fresh layers of dielectric intervene between it and the cake, and receive some of the strain. The effect of this is threefold. First they partially relieve the strain in the original very thin layer; next, they increase the strain in the cake; and thirdly, they put a little strain on the air above the raised cover. The sole therefore receives 5 units instead of 3; the cover retains its charge 10, but part of this is on its upper surface; an induced charge -2 makes its appearance on the walls of the room. This state of things is shown in Diagram III.

Diagram IV. continues the process of raising, until ultimately when the plate is removed to infinity; its charge above and below is then equal, being 5 on each, and the cake and cover have returned to their original state I., ready to begin again. The cover having now a charge 10, the walls of the room, wherever the cover is, will have a charge -10; and it may be discharged to the walls, or to anything connected with them, whenever we please, without affecting the cake at all. Having discharged it, we can put it on, as in I., and perform the cycle again.

If one chooses to put the cover on before discharging it, the cycle of operations is just reversed, from IV. to II.

It is instructive to mount an electrophorus on an insulating stand, and connect its sole to earth through a delicate galvanometer; then the rush out of it when the cover is touched, and the flow back again as the cover is raised, can be easily watched.

23. There is one more thing which is so important to see clearly that an illustration of it is desirable; and that is the effect of inserting, not a metal, but a slice of some other perfectly insulating dielectric, with a different inductive capacity, in the midst of a polarized medium. Thus, for instance, between the plates of a charged condenser insert a thick slab of glass. The effects will differ according as the condenser plates are charged each with a given quantity, or are maintained at a constant difference of potential.

Refer to Fig. 9C; the 8 similar strata are supposed to be displaced with a total E.M.F. 24; the tension in the cord (negative electric potential) accordingly rises by a step 3 at each layer. Diagram I. shows this initial state. Clamp the cord, to represent a constant charge on the plates A and B, and now introduce a slab of glass—that is, replace the 4 middle layers by elastics only half as stiff (see II.). The stress in the cord steps up now by only $1\frac{1}{2}$ at each of these layers, and the total difference of potential, instead of being 24, is now only 18. Meanwhile the charges remain the same, and there is no charge on the surface of the glass; the capacity of the whole condenser, which was $\frac{1}{8}$, has now increased to $\frac{1}{6}$.

There is no charge on the surface of the glass; but the resultant effect is very much the same as if there were. The effect on the cord will be precisely the same as if the replaced elastics were still of the

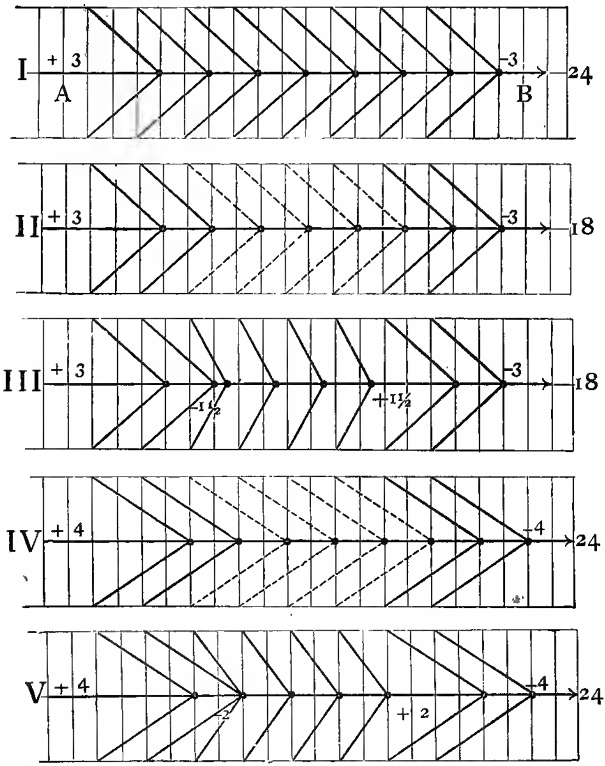


FIG. 9C.—Real and apparent effects of introducing a glass slab between the plates of an air-condenser. The numbers on the extreme right represent E.M.F.s.

I. shows the original condenser, of capacity $\frac{1}{8}$.
II. shows the effect of inserting a slab of half the whole thickness, and of specific inductive capacity 2, the charge being kept constant. The capacity has risen to $\frac{1}{6}$.
III. shows a spurious imitative mode of obtaining the same effect, without any change of inductive capacity, by help of boundary charges.
IV. shows the effect of introducing the slab into the condenser I when it is supplied with a constant E.M.F. The capacity is still $\frac{1}{6}$.
V. shows a spurious imitation of this effect by help of boundary charges.

same strength, but as if their beads had slid half-way back, into the positions shown in III., where surface charges exist as indicated by numbers. This, I repeat, is *not* the state of things caused by the glass, but it is so like it in effect as to be difficultly distinguishable from it; and we sometimes speak of the spurious or virtual charges set up on the glass surface—meaning the charges in Diagram III., which so exactly imitates the resultant effect of II.

So much for the effect of constant charge; now take the case of constant potential.

Diagram IV. shows the effect of replacing some of the elastics by weaker ones in this case. The E.M.F. is kept constant, so the strong elastics have more strain thrown on them than before; no internal charge is possible so long as the substances insulate perfectly, so all the beads are pulled forward equally. The step of potential is now 4 at all the stiffer (or air) strata, and 2 at all the weaker (or glass) strata, making up the total E.M.F., 24. The charge on the plates A and B has increased from ± 3 to ± 4 in accordance with the increase of capacity; the ratio of increase of which is still 3 : 4. Here again the real effect shown in IV. may be simulated by spurious boundary charges, without any change of inductive capacity, as is sufficiently indicated by Diagram V., wherein all the elastics are supposed of the same strength.

24. *Hydraulic Model of a Leyden Jar.*—So much for the cord model, but I will now describe and explain an hydraulic model which illustrates the same sort of facts; some of them more plainly and directly

than the cord model. Moreover, since all charging is essentially analogous to that of a Leyden jar, let us take a Leyden jar and make its hydrostatic analogue at once.

The form of jar most convenient to think of is one supported horizontally on an insulating stand with pith ball electroscopes supplied to both inner and outer coatings. Or one may use, as I commonly do, in conjunction with the hydraulic model, a vertical coated pane, with a pith ball connected to each coating; but if the electroscopes were of such a kind as

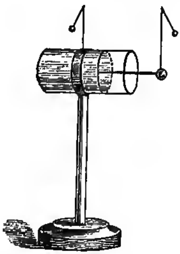


FIG. 9D.

to show a difference between positive and negative potential, they would do better.

To construct its hydraulic model, procure a thin india-rubber bag, such as are distended with gas at toy-shops; tie it over the mouth of a tube with a stop-cock, A, and insert the tube by means of a cork into a three-necked globular glass vessel or "receiver" as shown in the diagram, Fig. 10.

One of the other openings is to have another stop-cock tube, B; and the third opening is to be plugged with a cork, as soon as the whole vessel, both inside and outside the bag, is completely full of water without air-bubbles.

This is the insulated Leyden jar: the bag represents the dielectric, and its inner and outer coatings are the spaces full of water.

Open gauge-tubes, *a* and *b*, must be provided for tubes A and B, to correspond to the electroscopes

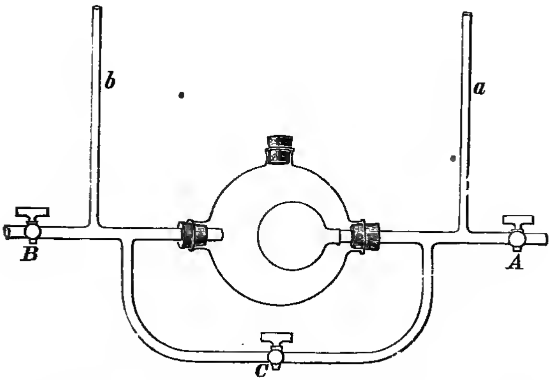


FIG. 10.—Skeleton diagram of hydraulic model of a Leyden jar. (Compare §14A.

supplied to the jar; and a third bent tube, C, connecting the inner and outer coatings, will correspond to a discharger. Ordinarily, however, of course C will be shut.

A water-pump screwed on to A will represent an electric machine connected to inner coating; and the outer coating, B, should open into a tank, to represent the earth. The pump will naturally draw its supply of water from the same tank.

The bag being undistended, and the whole filled with water free from air the level of the water in the two gauge-tubes will correspond with that in the tank; and this means that everything is at zero potential,—*i.e.* the potential of the earth.

Now, C being shut, shut also B, open A, and work the pump. Instantly the level in the two gauges rises greatly and equally: you are trying to charge an insulated jar. Turn an electric machine connected to a real insulated jar, such as Fig. 9D, and its two pith balls will similarly and equally rise.

Now open B for an instant—the pressure is relieved, and both gauges at once fall, apparently both to zero. Repeat the whole operation several times, however; and it will be found that, whereas *b* always falls to zero, *a* falls short of zero each time by a larger amount; and the bag is gradually becoming distended. This is *charge by alternate contact.* It may be repeated exactly with the real jar: a spark put into the inner coating, and an equal spark withdrawn from the outer coating each time; and unless this outer spark is so withdrawn, the jar declines to charge: water (and electricity) being incompressible (§ 14 A).

If B is left permanently open, the pump can be steadily worked, so as to distend the bag and raise the gauge *a* to its full height, *b* remaining at zero all the time, save for oscillatory disturbances.

Having got the jar charged, shut A, and remove the pump, connecting the end of A with the tank directly.

Now of course by means of the discharger C the fluid can be transferred from inner to outer coat, the strain relieved, and the gauges equalized. But if this operation be performed while the jar is insulated, *i.e.* while A and B are both shut, the common level of the gauges after discharge is not zero, but a half-way level; and the effect of this is noticeable if you charge a Leyden jar ordinarily, then insulate it, discharge it, and touch it.

Instead of using the discharger C, however, we can proceed to discharge by alternate contact; and the operation is very instructive.

Start with the gauge *b* at zero, and the gauge *a* at high pressure. Open stop-cock A; some water is squeezed out of inner coating, and the *a* gauge falls to zero, but the suck of the contracting bag on the outer coat pulls down the gauge *b* *below* zero, the descent of the two gauges being nearly equal.

Next shut A and open B; a little water flows in from the tank still further to relieve the strain of the bag, and both gauges rise; *b* to zero, *a* to something just short of its old position.

Now shut B and open A again: again the two gauges descend. Reverse the taps, and again they both rise; and so on until the bag has recovered its normal size. This is discharge by alternate contact, and exactly imitates the behaviour of an insulated charged Leyden jar whose inner and outer coats are alternately touched to earth. Its pith balls alternately rise, with positive and with negative electricity respectively, indicating potentials above and below zero.

Figs. 11 and 12 are taken from photographs of apparatus I have made to use as just described. The glass globe with the partially distended bag inside it, the pump, the tank, the gauges *a* and *b*, the stop-cocks A B C, will be easily recognized. Two small stop-cocks

A′ and B′, leading direct to tank, are extra, and are to save having to disconnect pump and connect A direct, when exhibiting the effect of "discharge by alternate contact." But the tank is not sufficiently tall in

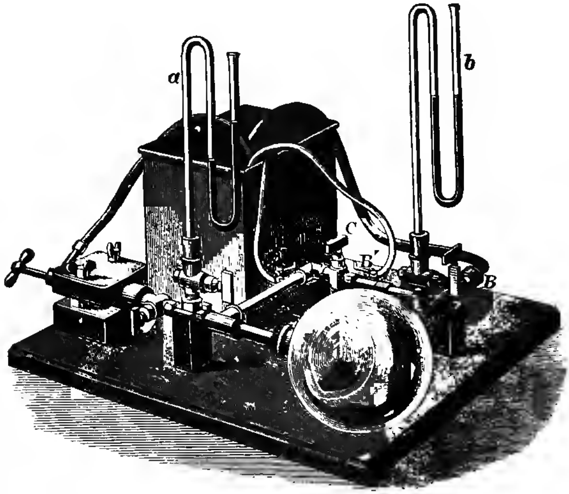


FIG. 11.—First actually constructed model Leyden jar, with mercury gauges as electrometers; the whole rigged up with things purchasable at a plumber's, except the pump. The glass globe contains an elastic bag, which swells as water is pumped into it. The tank is kept full of water, and its level represents the potential of the earth. Flexible tubes full of water effect the desired earth-connections when wished. The mercury gauges *a* and *b* represent electroscopes connected to inner and outer coats of the jar respectively.

Fig. 12; I have doubled its height since; and the gauge tubes are really longer.

In any form of apparatus it is essential to fill the whole with water—pipes, globe, everything—before commencing to draw any moral from its behaviour. It is rather difficult to get rid of a large bubble of air from the top of the globe of Fig. 11, and though it is not of very much consequence in this place, the stop-cock in Fig. 12 is added to make its removal easy. The gauges in Fig. 11 may be replaced by

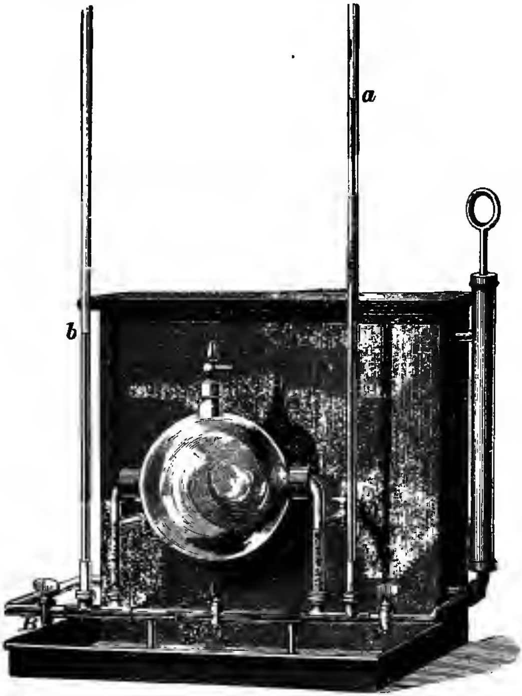


FIG. 12.—Latest form of hydraulic model of a Leyden jar with water gauges; the whole arranged vertically to be more conspicuous. The pump is a force-pump with a communication between bottom of barrel and tank; also one at the top, to get rid of stray water. The parts are labelled to correspond with the skeleton diagram, Fig. 10, as well as with Fig. 11.

others arranged as a lantern-slide, and connected by flexible tubing full of air.

25. I have explained thus fully the hydraulic illustration of Leyden jar phenomena, because these

constitute the key to a great part of electrostatics. The illustration is not indeed a complete one, but by combining with it a consideration of the endless cord models, and of what I have endeavoured to explain concerning conduction and insulation in general, a distinct step may be gained.

Think of electrical phenomena as produced by an all-permeating liquid embedded in a jelly; think of conductors as holes and pipes in this jelly, of an electrical machine as a pump, of charge as excess or defect, of attraction as due to strain, of discharge as bursting; and think also of the discharge of a Leyden jar as a springing back or recoil, oscillating till its energy has gone:—

By thus thinking you will get a more real grasp of the subject, and more insight into the actual processes in Nature—unknown though these may still strictly be—than if you employed the old ideas of action at a distance, or contented yourselves with no theory at all on which to link the facts. You will have made a step in the direction of the truth, but I must beg you to understand that it is only a step; that what modifications and additions will have to be made to it before it becomes a complete theory of electricity I am unable fully to tell you. I am convinced they will be many, but I am also convinced that it is unwise to drift along among a host of complicated phenomena without guide other than that afforded by hard and rigid mathematical equations.

The mathematical theory of potential and the like has insured safe and certain progress, and enables mathematicians to dispense for the time being with theories of electricity and with mental imagery. Few, however, are the minds strong enough thus to dispense with all but the most formal and severe of mental aids; and none, I believe, to whom some physical representation or picture of the phenomena would not be a help if it were safely available.

PART II

CONDUCTION

CHAPTER IV

METALLIC AND ELECTROLYTIC CONDUCTION

26. We have now glanced through electrostatic phenomena, and seen that they could be all comprehended and partially explained by supposing electricity to be a fluid of perfect incompressibility—in other words, a perfect liquid—extending everywhere and permeating everything; and by further supposing that in conducting matter this liquid was capable of free locomotion, while in insulators and general space it was as it were entangled in some elastic medium or jelly—to strains in which electrostatic actions are due. This medium might be burst, in a disruptive discharge, but easy flow could go on only through channels or holes in it, which therefore were taken to represent conductors; and it was obvious that all flow must take place in closed circuits.

I now want to consider the circumstances of this flow more particularly: to study, in fact, the second division of our subject (see classification in Section 1), viz., *Electricity in locomotion.*

I use the term "locomotion" in order to discriminate it from rotation and vibration: it is with *translation* only that we intend now to concern ourselves.

Consider the modes in which *water* may be made to move from place to place. There are only two: it may be pumped along pipes, or it may be carried about in jugs. In other words, it may travel *through* matter, or it may travel *with* matter. Just so it is with *heat* also; heat can travel in two ways; it can flow *through* matter, by what is called "conduction," and it can travel *with* matter, by what is called "convection." There is no other mode of conveyance of heat. You frequently find it stated that there is a third method, viz., "radiation"; but this is not truly a conveyance of *heat* at all. Heat generates radiation at one place, and radiation reproduces heat at another; but it is radiation which travels, and not heat. Heat only naturally flows from hot bodies to cold, just as water only naturally flows down hill; but radiation spreads in all directions, without the least attention to where it is going. Heat can only flow one way at any given point, but radiation can travel all ways at once. If water were dissociated on one planet into its constituent gases, and if these recombined on another planet, it would not be water which travelled from one to the other, neither would the substance obey the laws of motion of water—water would be destroyed in one place, and reproduced in another; just so is it with the relation between radiation and heat.

Heat, then, like water, has but two direct modes of conveyance from place to place. For *electricity* the same is at first sight true. Electricity can travel with matter, or it can travel through matter; by convection or by conduction. But it has recently been discovered that it can travel also without matter—isolated, detached,—in the form of electrons; though into that process we will not now enter.

Conduction in Metals.

27. Consider, first, conduction. Connect the poles of a voltaic battery to the two ends of a copper wire, and think of what we call the "current." It is a true flow of electricity among the molecules of the wire. If electricity were a fluid, then it would be a transport of that fluid; if electricity is nothing material, then a current is no material transfer; but it is certainly a transfer of electricity, whatever electricity may be. Permitting ourselves again the analogy of a liquid, we can picture it flowing through, or among, the molecules of the metal. Does it flow through or between them? Or does it get handed on from one to the next continually? The last supposition is believed most nearly to represent the probable truth. The flow may be thought of as a perpetual attempt to set up a strain like that in a dielectric, combined with an equally perpetual breaking down of every trace of that strain. If the atoms be conceived as little conductors vibrating to and fro and knocking each other, so as to be easily and completely able to pass on any electric charge they may possess, then, through a medium so constituted, electric conduction could go on much as it does go on in a metal. Each atom would receive a charge from those behind it, and hand it on to those in front of it; and thus might electricity get conveyed

F 2

along the wire. Such a theory reduces conduction to a kind of electrostatics—an interchange of electric charges among a set of conductors. If such a set of vibrating and colliding particles existed, then certainly a charge given to any point would rapidly distribute itself over the whole, and the potential would quickly become uniform; and it is now thought that the actual process of conduction is something like this. This is not the simplest mode of picturing it for ordinary purposes. The easiest and crudest idea is to liken a wire conveying electricity to a pipe full of marbles or sand conveying water; and for many purposes, though not for all, this crude idea suffices.

Leaving the actual mode of conveyance for the present, let us review how much is certainly known of the process called conduction in homogeneous metals.

This much is certainly known:—

(1) That the wire gets heated by the passage of a current.

(2) That no trace of a tendency to reverse discharge or spring back exists.

(3) That the electricity meets with a certain amount of resistance or friction-like obstruction.

(4) That this force of obstruction is accurately proportional to the speed with which the electricity travels through the metal—that is, to the intensity of the current per unit area.

28. About this last fact a word or two must be said. The amount of electricity conveyed per second across a unit area is called intensity of current;[1] and

[1] Often called "density" of current, but "intensity" is perhaps a more proper expression for the purpose.

experiment proves—what Ohm originally guessed as probable from the analogy of heat conduction—that this intensity is accurately proportional to the slope of potential which causes the flow ; or, in other words (since action and reaction are equal and opposite), that a current in a conductor meets with an obstructive electromotive force exactly proportional to itself. Or, quite briefly, a current through a given conductor is proportional to the E.M.F. which drives it. The particular ratio between slope of potential and corresponding intensity of current depends upon the particular material of which the conductor is composed and is one of the constants of the material, to be determined by direct measurement. This precise ratio is called its "specific conductivity" or its "specific resistance," according to the way it is regarded.

The law here stated is called Ohm's law, and is one of the most accurately known laws there are. Nevertheless it is an empirical relation ; in other words, it has not yet been accounted for,—it must be accepted as an experimental fact. Undoubtedly, it is one of vast and far-reaching importance : it asserts a connexion between electricity and ordinary matter of a definite and simple kind. Using the language of hydraulic analogy, it asserts that when electricity flows through matter the friction between them is accurately as the first power of the velocity, for all speeds.

29. Now, if we think of this opposing electromotive force as analogous to friction, it is very easy to think of heat being generated by the passage of a current, and to suppose that the rate of heat-production will be directly proportional to the opposing force and

to the current driven against it;—as, in fact, Joule experimentally proved it to be.

But if we are not satisfied with this vague analogy, and wish to penetrate into the ultimate nature of heat and the mode in which it can be generated, then we can return to the consideration of a multitude of oscillating and colliding particles, moving with a certain average energy which determines what we call the "temperature" of the body. If now one or more of these bodies receives a knock, the energy of the blow is speedily shared among all the others, and they all begin to move rather more energetically than before: the body which the assemblage of particles constitutes is said to have "risen in temperature." This illustrates the production of heat by a blow or other mechanical means. But now, instead of *striking* one of the balls, give it an electric charge; or, better still, put within its reach a constant reservoir of electricity from which it can receive a charge every time it strikes it, and at the same time put within the reach of some other of the assemblage of particles another reservoir of infinite capacity which shall be able to drain away all the electricity it may receive. In practice there is no need of infinite reservoirs: all that is wanted is to connect two finite reservoirs, or "electrodes" as one might now call them, with some constant means of propelling electricity from one to the other, *i.e.*, with the poles of a voltaic battery or a Holtz machine.

What will be the result of thus passing a series of electric charges through the assemblage of particles? Plainly the act of receiving a charge, and passing it on, will tend to increase the original motion of each particle; it will tend to raise the temperature of the body. In this way, therefore, it is possible to picture the mode in which an electric current generates heat.

Heat, being some mode of motion, must also be handed on after some analogous fashion, so that when heat is supplied to one point of a mass it spreads or diffuses through it. It is difficult to suppose the conduction of heat to be other than the handing on of molecular quiverings from one particle to another; and yet it takes place according to laws altogether different from those of the propagation of the gross disturbance called sound. The exact mode of conduction of heat is unknown, but, whatever it is, it can hardly be doubted that the conduction of electricity through metals is not very unlike it, for the two processes obey the same laws of propagation: they are both of the nature of a diffusion, they both obey Ohm's law, and a metal which conducts heat well conducts electricity well also.

Conduction in Liquids.

30. Leaving the subject of conduction in metals for the present, let us pass to the consideration of the way in which electricity flows through liquids. By "liquids," in the present connexion, one more particularly means definite chemical compounds, such as acids, alkalies, salt and water, and saline solutions generally. Some liquids there are, like alcohol, turpentine, bisulphide of carbon, and water, which, when quite pure, either wholly or very nearly decline to conduct electricity at all. Such liquids as these may be

classed along with air and gases as more or less perfect dielectrics. Other liquids there are, like mercury and molten metals generally, which conduct after precisely the same fashion as they do when solid. These, therefore, are properly classed among metallic conductors.

But most chemical compounds, when liquefied either by heat or by solution, conduct in a way peculiarly their own; and these are called "electrolytes."

31. The present state of knowledge enables us to make the following assertions with considerable confidence of their truth :—

(1) Electrolytic conduction is invariably accompanied by chemical decomposition, and in fact only occurs by means of it.

(2) The electricity does not flow *through*, but *with* the atoms of matter, which travel along and convey their charges something after the manner of pith balls between two oppositely charged plates.

(3) The electric charge belonging to each atom of matter is a simple multiple of a definite quantity of electricity, which quantity is an absolute constant quite independent of the nature of the particular substance to which the atoms belong.

(4) Positive electricity is conveyed through a liquid by something equivalent to a procession of the electropositive atoms of the compound, in the direction called the direction of the current; and at the same time negative electricity is conveyed in the opposite direction by a similar procession of the electronegative atoms.

(5) On any atom reaching an electrode it may be forced to get rid of its electric charge, and, combining with others of the same kind, escape in the free state; in which case visible decomposition results. Or it may find something else handy with which to combine—say on the electrode or in the solution; and in that case the decomposition, though real, is masked, and not apparent.

(6) But, on the other hand, the atom may cling to its electric charge with such tenacity as to stop the current: the opposition force exerted by these atoms upon the current being called polarization.

(7) No such opposition force, or tendency to spring back, is experienced in the interior of a mass of fluid: it occurs only at the electrodes.

32. The three first of these statements constitute a summary of Faraday's laws of electrolysis. These laws are of far-reaching importance, and appear to be accurately true. The first is called the "voltametric law," and asserts that the amount of chemical action electrolytically produced in any given substance is exactly proportional to the quantity of electricity that has passed through it. The vague phrase "chemical action" is purposely used here to include decomposition or recomposition or liberation or deposition or dissolution, or any other effect that can be brought about, in either elements or compounds, by the passage of an electric current. The weight of substance acted on measures the quantity of electricity which has passed; hence a decomposition cell can act as a voltameter, and the law is called the voltametric law. Its truth enables us to make the first of the above

statements; which many qualitative facts concerning the details of electrolysis modify into statement No. 2.

The second of Faraday's laws is called the law of electro-chemical equivalence. It asserts that, if the same current be passed through a series of voltameters for the same time, the amount of chemical action in each substance acted on is exactly proportional to its ordinary chemical equivalent; not to its atomic weight merely, but to its atomic weight divided by what is called its valency, or atomicity, or quantivalence; this being its real chemical equivalent. Thus an atom of oxygen weighs sixteen times as much as an atom of hydrogen, and is equivalent to two such atoms in combining power; hence the law asserts that 8 grammes of oxygen are liberated for every gramme of hydrogen. Again, an atom of silver is 108 times as heavy as an atom of hydrogen, and is equal to it in combining power; hence 108 grammes of silver are deposited in a silver voltameter while one gramme of hydrogen is being liberated by the same current in a gas voltameter. Once again, an atom of gold weighs as much as 197 atoms of hydrogen, and is able to replace three of them in combination: hence 65·7 grammes of gold are deposited by the same current in the same time; and so on.

Now this law plainly means that the same number of monad atoms is liberated by the same quantity of electricity, no matter what their nature may be; half that number of dyad atoms; one third that number of triad atoms. Hence, assuming statement No. 2 above, that the current flows purely by convection—each atom conveying electricity—it follows that every monad atom carries the same quantity, whether it be an atom of hydrogen or of silver, or of chlorine, or a complex radicle like NO_3; that each dyad atom carries twice as much, whether it be an atom of oxygen or of zinc or of copper, or a complex dyad radicle like SO_4; that each triad atom carries three times as much, and so on. And this is what is laid down in No. 3 of the above statements: which is virtually equivalent to Faraday's second law.

True, it is possible that every atom may have a specific charge of its own with which it never parts; but about such nothing is known; we can only make experiments on the charge it is willing to part with at an electrode, and there is no doubt that this is accurately the same for all substances, up to a simple multiple. And this quantity, the charge of one monad atom, constitutes the smallest known portion of electricity, and is a real natural unit. Obviously this is a most vital fact. This unit below which nothing is known has been styled an "atom" of electricity; and the phrase is now known to have a distinct meaning. I have ventured to suggest one or two effects which would result from the hypothesis that this unit quantity of electricity were really in fact an absolute minimum, and as indivisible as an atom of matter.[1] This natural unit of electricity is exceedingly small, being about the ten-thousandth-millionth part of the ordinary electrostatic unit; or in electromagnetic units almost exactly 10^{-20} c.g.s.

[1] See paper on "Electrolysis" at Aberdeen (*Reports of the British Association for* 1885, p. 763).

The charge of each atom being so small, its potential is not high. Something between 1 and 3 volts is a likely difference of potential for two oppositely charged atoms. But they are so near together that even this small difference of potential causes a strong electrostatic attraction or "chemical affinity" between the oppositely charged atoms of a molecule.

This electrical force between two atoms, at any distance, is ten thousand million billion billion times greater than their gravitative attraction at the same distance. The force has an intensity per unit mass, ($=10^{21}$) and therefore is able to produce an acceleration, nearly a trillion times greater than that of terrestrial gravity near the earth's surface.

These are undoubtedly the forces with which chemists have to do, and which they have long called chemical affinity.

33. But it may be asked, If the atoms in each molecule cling together by their electrostatic attractions, and if there are an enormous number of atoms between two electrodes, how comes it that a feeble E.M.F. can pull them apart and effect decomposition; moreover, how can the E.M.F. needed to effect decomposition help varying directly with the thickness of fluid between the plates? It does not depend on anything of the kind; the length of liquid between the electrodes is absolutely immaterial. This fact proves that throughout the main thickness of liquid no atoms are torn asunder at all. Probably they frequently change partners, one pair of atoms not always remaining united but occasionally getting

separated and recombined with other individuals. During these interchanges there must be moments of semi-freedom during which the atoms are amenable to the slightest directive tendency, and it is probably these moments that the applied E.M.F. makes use of.

The reality of such a state of continual interchange between molecules has been forced upon chemists by the facts of double-decomposition—such facts as the interchange of atoms between strongly combined salts when their solutions are mixed so as to form very much weaker compounds; the proof that such compounds are formed being very clear in the case when they happen to be insoluble. The fact that if a precipitate is insoluble enough it is bound to form, really proves that some small quantity of the corresponding compound is always formed in every case, whether it happens to be insoluble or not.

The state of continual interchange results in a perfect sensibility to the migratory power of extremely weak forces, so that even the faintest trace of an electromotive force is able to affect the charged atoms; on the average assisting the positive atoms down the slope of potential, and the negative atoms up the slope. The fact that the most infinitesimal force is sufficient to effect its due quota of decomposition was proved most clearly and decisively by the experiments of Helmholtz. (See his Faraday Lecture.)

Sometimes the term "dissociation" is used to signify this practical freedom of atoms to locomotion; and, as stated originally by Prof. Clausius, the idea of dissociation was certainly involved. It was thought that a certain percentage of atoms existed in the liquid in an uncombined state, wandering about seeking partners; that it was these loose atoms on which the electromotive forces acted, and that the procession of these conveyed the current. It is likely that such atoms are not really and actually free; they may be hangers on of molecular aggregates, but they are potentially free or dissociated in the sense that their bonds with their ordinary partners are broken by the solvent. But even this amount of freedom is not proven by the facts of electrolysis alone, for we now see that the addition of the idea of double-decomposition or interchange of partners to the original hypothesis of Grotthus explains all that is required by the facts, viz. a virtual or potential dissociation, a momentary state of hovering and indecision, without the need for any continuous and actual dissociation. Nevertheless something very like actual dissociation is now considered most likely; the state being brought about by the action of the solvent on a portion of the dissolved compound.

A certain average number of the atoms are virtually free, and amenable to any directive force, without necessarily remaining free for more than a brief though finite time. The more of these virtually dissociated atoms there are, the better is the liquid likely to conduct. The process of conduction is probably very much as Grotthus imagined it, a passing on of a charged ion through a chain of decomposing and recomposing molecules: but the molecular decomposition is automatic,—*i.e.* it is not caused, but only directed, by the applied electrical force. The *result* is as if a double procession of free charged atoms migrated through the liquid between the electrodes, and it is simplest so to think of the process.

34. I will now try and make the process of electrolytic conduction clearer by reverting to our mechanical analogies and models.

Looking back to Figs. 5 and 6, we see illustrations of metallic conduction and of dielectric induction. In each case an applied electromotive force causes some movement of electricity; but whereas in the first case it is a continuous almost unresisted movement or steady flow, through or among the atoms of matter, in the second case it is a momentary shift or displacement only, carrying the atoms of matter with it, and highly resisted in consequence:—resisted, not with a mere frictional rub, which retards but does not check the motion, but by an active spring-back force, which immediately checks all further current, produces what we call "insulation," and ultimately, when the propelling force is removed, causes a quick reverse motion or discharge. But the model is plainly an incomplete one; for what is it that the atoms are clinging to? What is it ought to take the place of the *beam* in the crude mechanical contrivance? Obviously another set of atoms, which are either kept still or urged in the opposite direction by a simultaneous opposite displacement of negative electricity; as in Fig. 7A, § 18. We are to picture two or any number of rows of beads, each row threaded on its appropriate cord; the cords alternately representing positive and negative electricity respectively, and being simultaneously displaced in opposite directions by any applied E.M.F. The beads threaded on any one cord have, in a *dielectric*, elastic attachments to those on some parallel and oppositely moving cord, and thus continuous motion of the cords in opposite directions is prevented: only a slight displacement is permitted, followed by a spring back and oscillation—after the fashion already described.

Very well; now picture the elastic connections between the beads all dissolved, and once more apply a force to each cord, moving half of them one way and the alternate half the other way, and you have a model illustrating an *electrolyte*, and the simplest view of electrolytic conduction. The atoms are no longer attached to each other, but they are attached to the cord. In the first respect, an electrolyte differs from a dielectric; in the second, it differs from a metal.

Moreover, electrolytic conduction is perceived to be scarcely of the nature of true conduction: the electricity does not slip through or among the molecules, it goes with them. The constituents of each molecule are free of each other; and while one set of atoms conveys positive electricity, the other set carries negative electricity in the opposite direction; and so it is by a procession of free atoms that the current is transmitted. The process is of the nature of convection: the atoms act as carriers. Free locomotion of charged atoms is essential to electrolysis.

35. In order to compare with Figs. 5 and 6, so as to bring out the points of difference, Fig. 13 is drawn. The beads representing one set of atoms of matter are tightly attached to the cord, no trace of slip between beads and cords being permitted, but otherwise they

are free, and so are represented as supported merely by rings sliding freely on glass rods. The only resistance to the motion, beside the slight friction, is offered at the electrode, which is typified by the spring-backed knife-edge, Z. This is supposed to be able to release the beads from the cord when they are

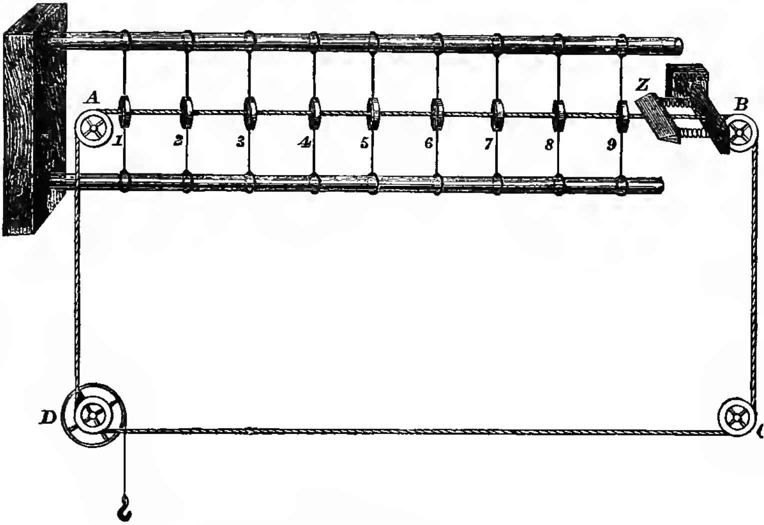


FIG 13.—Crude mechanical analogy, illustrating a few points in a circuit partly *electrolytic*. To compare with Figs. 5 and 6.

pressed against it with sufficient force. The cling between the bead and cord (*i.e.* between each atom and its charge) is great enough to cause a perceptible compression of the springs, and accordingly to bring out a recoil force in imitation of polarization.

The piece of cord accompanying each bead on its journey (*i.e.* the length between it and the next bead) represents the atomic charge, and is a perfectly constant quantity: the only variation permissible in it is that some kinds of atoms have twice as much, or are twice as far apart on their cord, and these are called by chemists dyad atoms; another kind has three times as much, another four, and so on; these being called triad, tetrad, &c.

If the cord be taken to represent positive electricity, the beads on it may represent atoms of hydrogen, or other monad *cation*, travelling down stream to the cathode. Another cord representing negative electricity may be ranged alongside it, with its beads twice as far apart, to represent the atoms of a dyad *anion*, like oxygen. If the cords are so mechanically connected that they must move with equal pace in opposite directions, we have a model illustrating several important facts. The number of oxygen atoms liberated in a given time will then obviously be half the number of hydrogen atoms set free in the same time, and will therefore in the gaseous state occupy but half the volume.

Moreover, for any element whatever, the number of atoms liberated in any time is equal to the number of atoms of hydrogen liberated in the same time, divided by the "valency" of the element as compared with hydrogen. This is one of Faraday's laws, and appears to be precisely true; and inasmuch as the relative weight of every element is known with fair accuracy, it is easy to calculate what weight of substance any given current will deposit or set free in an hour, if we once determine it experimentally for any one substance.

Summary.

We may summarise thus:—

If we apply E.M.F. to a metal we get a continuous flow, and the result is heat.

If we apply it to a dielectric we get a momentary flow or displacement, and the result is the potential energy of "charge."

If we apply it to an electrolyte we again get a continuous flow, and the result is chemical decomposition.

36. There are a large number of important points, as to the mode by which an electric current is conveyed through liquids; and I will specially select one for further emphasis, viz., that it is effected by a procession of positively charged atoms travelling one way, and a corresponding procession of negatively charged atoms the other way.

Whatever we understand by a positive charge and a negative charge, it is certain that the atoms of, say, a water molecule, are charged—the hydrogen positively, the oxygen negatively; and it is almost certain that they hang together by reason of the attraction between their opposite charges. It is also certain that when an electromotive force—*i.e.* any force capable of propelling electricity—is brought to bear on the liquid, the hydrogen atoms travel on the whole in one direction, viz., down stream, and the oxygen atoms travel in the other direction, viz., up stream; using the idea of level as our analogue for electric potential in this case. The atoms may be said to be driven along by their electric charges just as charged pith balls would be driven along; and they thus act as conveyors of electricity, which otherwise would be unable to move through the liquid.

Each of this pair of opposite processions goes on until it meets with some discontinuity—either some change of liquid, or some solid conductor. At a change of liquid another set of atoms continues the convection, and nothing very particular need be noticed at the junction; but at a solid conductor the stream of atoms must stop: you cannot have locomotion of the atoms of a solid. The obstruction so produced may stop the procession, and therefore the current, altogether; or, on the other hand, the force driving the charges forward may be so great as to wrench them free: in which case the charges are given up to the electrode, which conveys it away by common conduction, while the atoms are crowded together in such a way that they are glad to combine with each other and escape.

Speed of Travel.

37. Now notice the fact of the two opposite processions. It is impossible to get one kind of ion liberated at one electrode without having a precisely equivalent quantity of the opposite ion liberated, or deposited, or otherwise appearing, at the other electrode; and this fact may be expressed by saying that it is impossible to have a procession of positive atoms through a liquid without a corresponding procession

of negative ones. In other words, an electric current in a liquid necessarily consists of a flow of positive electricity in one direction, combined with a flow of negative electricity in the opposite direction. And if this is thus proved to occur in a liquid, why should it not occur everywhere? It is at least well to bear the possibility in mind.

Another case is known where an electric current certainly consists of two opposite streams of electricity, viz., the case of the Holtz machine. While the machine is being turned, with its terminals somehow connected, the glass plate acts as a carrier conveying a charge from one collecting comb to the other at every half revolution; but, whereas it carries positive electricity for one half of its rotation, it carries negative for the other half. The top of the Holtz disk is always, say, positively charged, and is travelling forward; while the bottom half, which is travelling backward at an equal rate, is negatively charged.

In the Holtz case the speeds are necessarily equal, but the charges are not. In the electrolytic case the charges are necessarily equal, but the speeds are not. Each atom has its own rate of motion in a given liquid, independently of what it may happen to have been combined with. This is a law discovered by Kohlrausch. Hydrogen travels faster than any other kind of atom; and on the sum of the speeds of the two opposite atoms in a compound the conductivity of the liquid depends. Acids, therefore, which contain replaceable hydrogen, in general conduct better than their salts.

The following table gives the rates at which atoms of various kinds can make their way through nearly pure water, when urged by a slope of potential of 1 volt per linear centimetre :—[1]

H . . .	1·08	centimetre per hour.
K . . .	0·205	„
Na . . .	0·126	„
Li . . .	0·094	„
Ag . . .	0·166	„
Cl . . .	0·213	„
I . . .	0·216	„
NO_3 . .	0·174	„

[1] *Brit. Assoc. Report*, 1886, p. 393.

CHAPTER V

CURRENT PHENOMENA

Electrical Inertia.

38. RETURNING now to the general case of conduction, without regard to the special manner of it, we must notice that, if a current of electricity were anything of the nature of a material flow, there would probably be a certain amount of inertia connected with it; so that to start a current with a finite force would take a little time; and the stoppage of a current would also have either to be gradual or else violent. It is well known that if water is stagnant in a pipe it cannot be quite suddenly set in motion; and again, if it be in motion, it can only be suddenly stopped by the exercise of very considerable force, which jars and sometimes bursts the pipe. The impetus of running water is utilized in the water-ram. It must naturally occur, therefore, to ask whether any analogous phenomena are experienced with electricity; and the answer is that analogous phenomena are very conspicuous. A current does not start instantaneously: it takes a certain

time—though usually a very short time—to rise to its full strength; and when started it tends to persist, so that if its circuit be suddenly broken, it refuses to stop quite suddenly, and bursts through the introduced insulating partition with violence and heat. It is this ram or impetus of the electric current which causes the spark seen on breaking a circuit; and the more sudden the breakage the more violent is the spark apt to be.

The two effects—the delay at making circuit, and the momentum at breaking circuit—used to be called "extra-current" effects, but they are now more commonly spoken of as manifestations of "self-induction."

We shall understand them better directly; meanwhile they appear to be direct consequences of the inertia of electricity; and certainly if electricity were a fluid possessing inertia it would behave to a superficial observer just in this way.

39. But if an electric current really possessed inertia, as a stream of water does, it would exhibit itself not only by these effects, but also mechanically. A conducting coil delicately suspended might experience a rotary kick every time a current was started or stopped in it; and a coil in which a steady current is maintained should behave like a top or gyrostat, and resist any force tending to deflect its plane.

Clerk Maxwell has carefully looked for this latter form of momentum effect, and found none. He took a bar electro-magnet, mounted it on gimbals so that it was free to rotate if it wished, and then spun it rapidly about an axis perpendicular to the magnetic axis. If there had been the slightest gyrostatic action, the magnet would have rotated about the third perpendicular axis. But it did nothing of the kind. One may say, in fact, that nothing like momentum has yet been observed in an electric current through solids or liquids, by any *mechanical* mode of examination. There is a now well-known exception in the case of gases; but it is safe to say that a coil or whirl of electricity does not behave in the least like a top (§ 185).

I have looked for the effect in another way suggested by Maxwell, viz., by starting and stopping a current in a freely suspended coil [also in a suspended electrolytic tube,[1] and in a small mica condenser], and watching for recoil kicks at the instants of varying current strength. Terrestrial magnetism and the reaction between fixed and movable parts of the circuit caused spurious effects; but when these were reduced to a minimum, by the thick soft-iron case of a "marine galvanometer" and other suitable precautions, no certain residual effect due to change of momentum could be perceived. The experiments were by no means final, but they were sufficient to show that to detect any possibly existent effect of the kind considerable refinement must be employed.

Suppose, however, that highly refined experiments directed to the same object still gave a negative result, would that prove that a current has no momentum of any kind? Not necessarily. It might be taken as suggesting that an electric current consists really of two equal flows in contrary directions,

[1] For discussion of a probable electrolytic momentum, by reason of the different mass of the opposite ions, see Lodge, *Phil. Mag*. Nov. 1876.

so that mechanically they neutralize one another completely, while electrically—*i.e.* in the phenomena of self-induction or extra-current—they add their effects (§ 89). Or it might mean merely that the momentum was too minute to be so observed. Or, again, the whole thing—the appearance of inertia in some experiments and the absence of it in others—may have to be explained in some altogether less simple manner, to which we will proceed to lead up.

Condition of the Medium near a Current.

40. So far we have considered the flow of electricity as a phenomenon occurring solely inside conductors, just as a flow of water through pipes is a phenomenon occurring solely inside them. But a number of remarkable facts are known which completely negative this view of the matter. Something is no doubt passing along conductors when a current flows, but the disturbance is not *confined* to the conductor; on the contrary, it spreads more or less throughout surrounding space.

The facts which prove this have necessarily no hydraulic analogue, but must be treated *suorum generum*, and they are as follows:—

(1) A compass needle anywhere near an electric current is permanently deflected so long as the current lasts.

(2) Two electric currents attract or repel one another, according as they are in the same or opposite directions.

(3) A circuit in which a current is flowing tends to

enlarge itself so as to inclose the greatest possible area.

(4) A circuit conveying a current in a magnetic field tends either to enlarge or to shrink or to turn part way round, according to the aspect it presents to the field.

(5) Conductors in the neighbourhood of an electric circuit experience momentary electric disturbances every time a current in it is started or stopped or varied in strength.

(6) The same thing happens even with a circuit conveying a steady current if the distance between it and a conductor is made to vary.

(7) The inertia-like effects of self-induction, or extra-currents, can be almost abolished in a covered wire by doubling it closely on itself, or better by laying a direct and return ribbon face to face; whereas they may be intensified by making the circuit inclose a large area, more by coiling it up tightly into a close coil, and still more by putting a piece of iron inside the coil so formed.

Nothing like any of these effects is observable with currents of water; and they prove that the phenomena connected with the current, so far from being confined to the wire, spread out into space and affect bodies at a considerable distance.

41. Nearly all this class of phenomena were discovered by Ampère and by Faraday, and were called by the latter "current-induction." According to his view, the dielectric medium round a conducting circuit is strained, and subject to stresses, just as is the same medium round an electrically charged body. The

one is called an electrostatic strain, the other an electro-magnetic or electro-kinetic strain.

But whereas electrostatic phenomena occur *solely* in the medium—conductors being mere breaks in it interrupters of its continuity, at whose surface charge-effects occur, but whose substance is completely screened from disturbance,—that is not the case with electro-kinetic phenomena. It would be just as erroneous to conceive electro-kinetic phenomena as occurring solely in the insulating medium as it would be to think of them as occurring solely in the conducting wires. The fact is, they occur in both—not only at the surface of the wires, like electrostatic effects, but all through their substance. This is proved by the fact that conductivity increases in simple proportion with sectional area ; it is also proved by every part of a conductor getting hot ; and it is further proved in the case of liquids by their decomposition.

But the equally manifest facts of current attraction and current induction prove that the effect of the current is felt throughout the surrounding medium as well, and that its intensity depends on the nature of that medium ; we are thus wholly prevented from ascribing the phenomenon of self-induction or extra-current to simple and straightforward inertia of electricity in a wire, like that of water in a pipe.

We are brought face to face with another suggestion to account for these effects, viz. this : Since the molecules of a dielectric are inseparably connected with electricity, and move with it, it is possible that electricity itself has no inertia at all, but that the inertia of the atoms of the displaced dielectric confer upon it the appearance of inertia. Certainly they do sometimes confer upon it this appearance, as we see in the oscillatory discharge of a Leyden jar. For a displaced thing to overshoot its mean position and oscillate till it has expended all its energy is a proceeding eminently characteristic of inertia; and so, perhaps, the phenomena of self-induction may be explicable (§ 98). Anyhow the oscillatory discharge of a Leyden jar depends upon self-induction.

Further consideration of this more difficult part of the subject is, however, best postponed to Part III. (§§ 48 and 88).

Energy of the Current.

42. I have now called attention to the fact that the whole region surrounding a circuit is a field of force in which many of the most important properties of the current (the magnetic, to wit) manifest themselves. But directly we begin thus to attend to the whole space, and not only to the wires and battery, a very curious question arises. Are we to regard the current in a conductor as propelled by some sort of end-thrust, like water or air driven through a pipe by a piston or a fan? Or are we to think of it as propelled by side forces, a sort of lateral drag, like water driven along a trough by a blast of air, or by the vanes of paddle-wheels dipping into it? Or, again, referring to the cord models, Figs. 5, 6, and 13, were we right in picturing the driving force of the battery as applied at one place, as shown in the diagrams, or ought we

to have schemed some method for communicating the power of the battery by means of belts or other mechanism to a great number of points of the circuit? Is a propelling force applied to electricity at one point, or is it transmitted through the dielectric to every part of the boundary of the conducting circuit?

Prof. Poynting has shown that, on the principles developed by Maxwell, the latter of these alternatives, though apparently the more complicated, is the true one; and he has calculated the actual paths by which the energy is transmitted from the battery to the various points of a circuit, for certain cases.

We must learn, then, to distinguish between the flow of *electricity* and the flow of electric *energy*: they do not occur along the same paths. Hydraulic analogies, at least hydraulic analogies of a simple kind, break down here. When hydraulic power or steam power is conveyed along pipes, the fluid and its energy travel together. Work is done at one end of the tube, in forcing in more water, and this is propagated along the tube and reappears at the distant end, as the work of the piston. But in electricity it is not so. Electric energy is not to be regarded as pumped in at one end of a conducting wire, and as exuding in equal quantities at the other. The *electricity* does indeed travel thus—whatever the travel of electricity may ultimately be found to mean,—but the energy does not. The battery emits its energy, not to the wire direct, but to the surrounding medium; the surrounding medium is disturbed and strained, and propagates the strain on from point to point till it reaches the wire and is dissipated. This, Prof.

Poynting would say, is the function of the wire: it is to dissipate the energy crowding into it from the medium, which else would take up a static state of strain and cease to transmit any more. The continuous dissipation of the medium's energy into heat renders possible the continuous propagation of electricity (§ 107).

The energy of a dynamo, for instance, does not travel to a distant motor through the wires, but through the air. The energy of an Atlantic-cable battery does not travel to America through the wire strands, but through the insulating sheath. This is a singular and apparently paradoxical view, yet it is well founded.

Think of a tram-car drawn by an underground rope. A contact piece of iron protrudes from the bottom of the car and grips the moving rope, which is thus enabled to propel the car. How does the energy of the distant stationary engine reach the car? *Viâ* the rope and the iron connector, undoubtedly. They both have to be strong, and are liable to be broken by the transmitted stress.

Next, think of an electric tram-car driven by means of a current taken up from an underground conductor, as in several electric railways. A contact piece of wire rope protrudes from the bottom of the car and drags a little truck or other sliding contact piece along the conductor, which is thus enabled to supply electricity to the electro-magnetic motor geared to the wheels. How does the energy of the distant dynamo reach the car in this case? *Not viâ* the wire connector; not even *viâ* the underground conductor.

There is no strain on either. It travels from the distant dynamo through the general insulating medium between cable and earth, some little enters the conductor and is dissipated, but the great bulk flows on and converges upon the motor in the car, which is thus propelled. All the energy sent into the conducting wire is dissipated and lost as heat: it is the energy conveyed by the insulating medium which is really transmitted and utilized.

When the attempt is made to transmit too much energy by a wire rope, the rope is liable to snap: showing what was the medium of transmission. On the other hand, when the attempt is made to transmit too much energy by an electric cable, it is not the copper wire that gives way, but the insulation which breaks down. It is the gutta-percha which is transmitting the energy, and so it is the gutta-percha which is liable to suffer from over stress. True, the wire might be melted by having to dissipate too much energy, just as the bearings of a rapidly travelling wire rope might be made red hot if insufficiently lubricated; but the energy thus converted into heat is manifestly not transmitted: it is simply being wasted on the way.

The paths by which energy travels in ordinary machinery are worth attention. In belting, energy travels against the moving matter, *viâ* the taut half of the belt; in shafts, it travels along the axis of rotation, *not* in the direction of the material motion, but at right angles to it; in mill-gearing or cog wheels, it travels neither axially nor tangentially but approximately radially, the exact paths being studied in treatises on the theory of machinery (such as that of Reuleaux).

The manner in which the transmission of electric energy goes on we will attend to further in Part III. (§ 105 *et seq.*).

Phenomena Peculiar to a Starting, or Stopping, or Varying Current.

43. There is a remarkable fact concerning electric currents of varying strength, which was brought into prominence by the experimental skill of Prof. Hughes, viz., that a current does not start or stop equally and simultaneously at all points in the section of a conductor, but starts at the outside first. This fact is naturally more noticeable with thick wires than with thin, and it is especially marked with *iron* wires, for reasons which in Part III. will become apparent; but the general cause of it in ordinary copper wires can very easily be perceived, in the light of the views of Prof. Poynting just mentioned.

For, remember that a current in a wire is not pushed along by a force applied at its end, so as to be driven over obstacles by its own momentum combined with a *vis a tergo*; but it is urged along at every point of its course by a force just sufficient to make it overcome the resistance there, and no more: the force being applied to it through the medium of the dielectric in which the wire is immersed. A lateral force it is which propels electricity; and it naturally acts first on electricity in the outer layers of the wire or rod, only acting on the interior portions through the medium of the outside (§ 102).

44. To illustrate this matter further, begin to rotate a common tumbler of liquid steadily, and watch the liquid; dusting powder over it perhaps to make it more visible. You will see first the outer layer begin to participate in the motion, and then the next, and then the next, and so on, until at length the whole is in rotation. Stop the tumbler, and the liquid also begins gradually to stop by a converse process: the outside stopping first, and then gradually the central portions.

If the liquid sticks together pretty well, like treacle, the motion spreads very rapidly: this corresponds to a poor conductor. If the liquid be very mobile, the propagation of motion inward is slow: this corresponds to a good conductor. If the liquid were perfectly non-viscous, it would correspond to a perfect conductor, and no motion would ever be communicated to it, deeper than its extreme outer skin.

Think now of an endless tube full of water, say the hollow circumference of a wheel, or the rim of a top, and spin it: the liquid is soon set in rotation, especially if the tube be narrow or the liquid viscous; but it is set in motion by a lateral not an end force, and its outer layers start first.

Just so it is with a current starting in a metal wire. If the wire be fine, or its substance badly conducting, it all starts nearly together; but if it be made pretty thick, and of well-conducting substance, its outer layers may start appreciably sooner than the interior. And if it were infinitely conducting, no more than the outer skin would ever start at all (see Chap. X. and § 103).

In actual practice the time taken for all the electricity in an ordinary wire to get into motion is excessively short—something less than the thousandth of a second—so that the only way to notice the effect is to start and reverse the current many times in succession.

45. If the hollow-rimmed wheel above spoken of were made to oscillate rapidly, it is easy to see that only the outer layers of water in it would be moved to and fro; the innermost water would remain stationary; and accordingly it would appear as if the tube contained much less water than it really does. The virtual bore of the pipe would, in fact, for many purposes be diminished. So it is also with electricity; the sectional area of a wire to a rapidly alternating current is virtually lessened so far as its conducting power is concerned; and accordingly its apparent resistance is higher for alternating than for steady currents. The effect is, however, too small to notice in practice except with thick wires and very rapid alternations: it then becomes of commercial importance.

Remember that a propelling force acts on electricity at the boundary between the dielectric and the conductor; hence the more extensive this boundary, the more readily and quickly is the electricity got into motion; and a conductor in that case need not have any inert central portion too distant from the propelling dielectric. In other words, by splitting up the conductor into a bundle of insulated wires, thus affording the dielectric access to a considerable surface of conductor, the force is applied much more thoroughly; and so the throttling effect spoken of is greatly lessened. The same thing is achieved by rolling out the conducting rod into a flat thin bar. Making the conductor hollow instead of solid offers the advantage of gain of surface per given weight; but no other gain, because no energy travels *viâ* the hollow space, it still arrives only from the outside; *unless*, indeed, the return part of the circuit is taken along the axis of the hollow, like a telegraph cable. In this last arrangement all the energy travels *viâ* the dielectric between the two conductors, and none travels outside at all. It will be perceived therefore that, as in static electricity, the term "outside" must be used with circumspection: it really means that side of a conductor which faces the opposite conductor across a certain thickness of dielectric.

46. We learn from this that, whereas in the case of steady currents the sectional area and material of a conductor are all that need be attended to, the case is different when one has to deal with rapidly alternating currents, such as occur in a telephone, or, again, such as are apt to occur in Leyden-jar discharges (see Part I., p. 46), or in wireless telegraphy, or in lightning.

In all these cases it is well to make the conductor expose considerable surface to the propelling medium—the dielectric—else will great portions of it be useless.

Hence, so far as electric facts are concerned, a lightning conductor should certainly not be a round rod, but a flat strip or a strand of wires, with the strands as well separated as convenient. Considerations of durability and chemical deterioration may modify the application of this statement to practice.

47. I might go on to say here that iron makes an enormously worse conductor than copper for rapidly alternating currents. So it does for currents which alternate with moderate rapidity—a few hundred or thousand a second—like those from a dynamo or a telephone; and so it does always as far as true conductivity is concerned,—the throttling effect is always much more marked in iron than in copper; but, singularly enough, when the rapidity of oscillation is immensely high, as it is in Leyden-jar discharges and lightning, iron acts just as well as copper does, because the current keeps to the extreme outer layer of the conductor in either case; and though the conducting layer is decidedly thinner in iron than it is in copper, yet the total obstruction due to other causes is so enormous that this extra throttling is unimportant, and practically the material matters very little as regards mere obstruction. But there is another effect that deserves special consideration, namely, the dissipation of energy by a conductor—what is called its Ohmic resistance; and for that the material makes all the difference. The magnetic quality of iron causes rapid alternations to keep to the surface, so as to avoid having to magnetise the interior, on the principle of choosing the easiest path. The extreme thinness of the superficial layer of iron which conducts rapid alternations causes it to rub out their energy with great rapidity, and accordingly iron acts as a most efficient dissipator of energy of this kind. A

Leyden jar discharge sent through thick copper is loud and violent. The same discharge taken through a good length of thin iron wire is soft and gentle; most of its energy is expended in the wire instead of in the flash.

The application of all this to the case of lightning conductors should be obvious. A lightning conductor is wanted, not only to carry the discharge current, but to enfeeble it also,—to prevent it altogether if possible, by tapping a surplus charge, but if not then to carry it off quietly. Iron for this purpose is immensely superior to any other material; and there is no need for it to be thick. A thin iron wire offers to most kinds of discharge—not to all—a path apparently as attractive as a thick copper rod does; but whereas a flash to the rod is dangerously violent, a flash to a thin enough iron wire is comparatively harmless. It is likely indeed to fuse the wire: but by that time the danger is over. It will have protected the building, at the cost of its own life. The occurrence of what are called B flashes, which discriminate between good and bad conductors—so that for them a conductor must have some reasonable thickness,—prevents this doctrine from being pressed to extremes: so also do chemical fumes in the atmosphere and other practical considerations. But undoubtedly galvanised or otherwise protected iron is the best material for lightning conductors; and its cheapness enables many to be supplied, instead of only one or two.

The Question of Electrical Momentum again.

48. We are now able to return to the important question whether an electric current has any momentum or not, as it would have if it were a flow of material liquid. Referring to Part I., § 7, a hint will be found that the laws of flow of a current in conductors—the shape of the stream-lines, in fact—are such as indicate no inertia, or else no friction. Now Ohm's law shows that at any rate *friction* is not absent from a current flowing through a metal; hence it would appear at first sight as if *inertia* must be absent.

The stream-lines bear upon the question in the following kind of way. If an obstacle is interposed

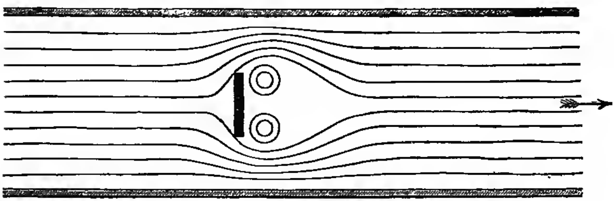


FIG. 14.—Stream-lines of water flowing through a pipe with an obstruction in it.

in the path of a current of water, the motion of the water is unsymmetrical before and behind the obstacle. The stream-lines spread out as the water reaches the obstacle, and then curl round it, leaving a space full of eddies in its wake (Fig. 14).

But if one puts an obstacle in the path of an electric current—say by cutting a slit in a conducting strip of tinfoil—the stream-lines on either side of it are quite symmetrical, thus—

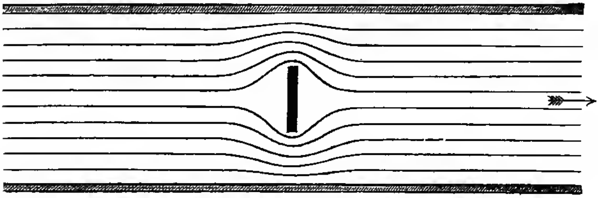


FIG. 15.—Electrical stream-lines past an obstacle.

And this is exactly what would be true for water also, if only it were devoid either of friction or of inertia, or of both; or as Sir Geo. Stokes has now found, and Prof. Hele Shaw demonstrated, if the friction just compensated the inertia so as to make the motion dead-beat.

49. Is not this fact conclusive, then? Does it not prove the absence of momentum in electricity?

Plainly the answer must depend on whether there is any other possible mode of accounting for this kind of flow. And there is.

For suppose that water, instead of being urged by something located at a distance from the obstacle—instead of being left to its own impetus to curl round or shoot past as it pleases—suppose it were propelled by a force acting at every point of its journey, a force just able to drive it at any point against the friction existing at that point and no more; then the flow of water would take place according to the electrical stream-lines shown in Fig. 15.

An illustration of such a case is ready to hand·

Take a spade-shaped piece of copper wire or sheet, heat it a little, and fix it in quiescent smoky air; looking along it through a magnifier, in a strong light, you will see the warmed air streaming up past the metal according to the stream-lines of Fig. 15;[1] and this just because the moving force has its location at the metal surface, and not in some region below it. One cannot indeed say that it is propelled at every point of its course, but it is propelled at the critical points where the special friction occurs,—and this comes to sufficiently the same thing.

We learn, therefore, that stream-lines like Fig. 15 prove one of three things, not one of two; and the three things are: (1) that the fluid has no friction; or (2) that it has no inertia; or (3) that it is propelled at every point of its course.

If any one of these is true of electricity, there is no need to assume either of the others in order to explain the actual manner of its flow. Now we have just seen in § 42 that, according to Prof. Poynting's interpretation of Maxwell's theory, the third of the above is true—electricity is propelled at every point of its course; consequently, as said in Part. I. § 7, the question of its own intrinsic inertia so far remains completely open (§§ 88, 89, and 98).

[1] See Lord Rayleigh, *Nature*, vol. xxviii. p. 139.

CHAPTER VI

CHEMICAL AND THERMAL METHODS OF PRODUCING CURRENTS. CONDUCTION IN GASES

Voltaic Battery.

50. LEAVING the last-mentioned mode of regarding the subject for the present, to return to it in Chap. X. Part III., let us proceed to ask how it comes about that a common battery or a thermopile is able to produce a current. (Read Chapter IV. again.)

If we allow ourselves to assume the existence of an unexplained chemical attraction between the atoms of different substances, an explanation of the action of an ordinary battery-cell is easy. You have first the liquid, containing, let us say, hydrogen and oxygen atoms, free or potentially free—that is, either actually dissociated, or so frequently interchanging at random from molecule to molecule that the direction of their motion may be guided by a feeble directive force (§ 33). Each of these atoms in the free state possesses a charge of electricity—the hydrogen all a certain amount of positive electricity, the oxygen twice that amount of negative. Into this liquid you then plunge a couple of metals which attract these atoms differently: for instance, zinc and copper, which both attract oxygen, but zinc more than copper; or, better, zinc and platinum, the latter of which hardly attracts it at all; or, better still, zinc and peroxide of lead, one of which attracts oxygen, the other hydrogen.

Immediately, the free oxygen atoms begin moving up to the zinc, the free hydrogen atoms to the other plate.

51. When one speaks of the plates attracting atoms, it is not necessary to think of their exerting a force on all those in the liquid, distant and near: all that it is reasonable to assume is a force acting on those which come within what is called "molecular range" of its surface—a distance extremely minute, and believed, with excellent reason, to be about the ten-millionth part of a millimetre. If the zinc plate could remove and combine with all the oxygen atoms which come within this range, they would be speedily replaced by others from the next more distant layer by diffusion, and these again by others, and so on. And thus there would be a gradual procession of oxygen atoms all through the liquid towards the zinc, the rate of the procession being regulated by the rate of diffusion possible in the particular liquid used.

The atoms which reach the zinc may be supposed to communicate to it the negative charge they carry, thus very soon making it negatively electrified enough to neutralize its attractive power on the similarly charged oxygen atoms; and then everything would stop. But if a channel for the escape of its electricity be provided, by leading a wire from it to a copper plate immersed in the same liquid—the circuit is completed, the electricity streams back by the wire, and the procession may go steadily on. The negative electricity thus imparted to the copper, or platinum, neutralizes any attraction it may have exerted on the negatively charged oxygen atoms, and enables it even to assist the opposite procession of hydrogen atoms towards it; which on their arrival deliver up their charges to it, combine with each other, and escape as gas.

Without going into all the niceties possible, this mode of thinking of the matter at least calls attention to some of the more salient features of a battery.

52. If, instead of two different plates, plates of the *same* metal be immersed, they will need to be oppositely electrified by some means, before they are able to cause the two opposite processions to so maintain a current in the liquid. This plainly corresponds to a voltameter. In a voltameter the maintained slope of potential between the plates must be supposed to act on all the ions in the liquid—not only those within molecular range of the electrodes. Every ion is directly propelled. In that respect it differs from a voltaic cell, where the chief propelling force is the chemical attraction of one of the plates for one of the constituents of the liquid through molecular range only.

53. Taking advantage of the known fact that the atoms are charged, Helmholtz avoided the necessity for postulating any chemical (non-electrical) force between zinc and oxygen, by imagining that all

substances have a specific attraction for electricity itself, and that zinc exceeds copper and the other common metals in this respect.

He would thus think of the zinc attracting, not the oxygen itself, but its electric charge; and so would liken a battery cell rather more nearly to a voltameter. The polarisation or opposition force acting at the hydrogen-evolving plate he would account for by the attraction of hydrogen for positive electricity, and the consequent repugnance of the hydrogen atoms to part with their charges.

Volta's so-called Contact Force.

54. It may be convenient to append to this account of the action of a battery a statement of the way in which the electric charges observed on plates of zinc and copper, which have been put into contact and separated, are brought about. It can be regarded in a simple fashion, though a great deal has been written about it.

Plates of zinc and copper immersed in air are under precisely the same chemical conditions as if they were immersed in water. The only difference is that, whereas water is a conductor, air is an insulator. Until the plates of zinc and copper (or other pair of metals) are made to touch, nothing happens in either case, because the chemical tendency is uniform all over both plates; and though the attraction of zinc for oxygen is pretty strong, it is impossible for charged atoms to move up to it equally on all sides, because by so doing they would be charging a conductor with one kind of electricity without any compensating opposite charge of some other conductor. (See §§ 5, 3, 4, 14A.) A piece of pure zinc surrounded on all sides uniformly by charged atoms may be considered as in the same condition as the interior of a charged conductor; and experiment shows that not a trace of charge can, in that case, make its appearance beneath the superficial layer. If the atoms were to move towards the zinc they would have to compress electricity into it, which is impossible. However much they are pulled towards it, therefore, the only effect is to increase the pressure, or slacken the tension, of the negative electricity in the zinc (speaking in language appropriate to the cord models, Figs. 5, 6, &c.); in other words, to lower the potential of the zinc below that of the air near it. The same thing, only to a less degree, occurs with the isolated piece of copper. Neither metal becomes the least charged so long as uniformity of conditions is maintained all round it.

But directly metallic contact between the two metals is effected, all the oxygen atoms at this point are swept away, and an unobstructed communication or clear passage is opened from the zinc to the copper for the flow of electricity. That is what metallic contact achieves—it disturbs the uniformity by removing the straining atoms at one spot. Unless, therefore, there is some E.M.F. at their junction—which we have good reason for asserting there is *not*, of any magnitude worth speaking of—an immediate rush of negative electricity from zinc to copper, or of positive the other way, occurs. The copper therefore becomes negatively charged, the zinc becomes positive;

the charge being effected by all the oxygen atoms moving a little nearer to the zinc, a little farther from the copper. So far everything goes on just the same whether the plates are in acidulated water or in common air.

What happens next depends upon the difference between water and air in conducting power. Acidulated water is able to conduct electricity; air is not. Accordingly, when the plates are immersed in water, the negative charge is continually conveyed back from the copper to the zinc through the liquid; whereas when they are in the air nothing further happens,—except the slight electrostatic strain into which the air is thrown by the quantity of electricity accumulated upon the metals, positive on the zinc, negative on the copper—charges which have no vent or outlet.

Unless care is taken to make the capacity of the free metallic surfaces considerable, by expanding them over a large surface or by bringing them very close together, these charges will be extremely small, the electromotive force producing them being rather under than over one volt; and accordingly the electrostatic strain in the air near a couple of zinc and copper rods in contact is extremely minute. By delicately suspending a highly-charged aluminium needle near such a junction, however, Lord Kelvin has been able to observe the state of strain; the needle when positively charged moving perceptibly towards the copper. A more usual method of displaying the phenomenon, and the one originally used by Volta, is to increase the capacity of the arrangement by bringing two carefully ground plates very close together. Although the E.M.F. is small (just the same as with a mere point contact), yet now the capacity is so great that quite a reasonable quantity of electricity can be stored in the two opposing metals, opposing each other across a microscopic air film and only touching at a few points; so that, when the plates are neatly separated, sufficient charge is found in them to affect sensibly even a common gold-leaf electroscope.

55. The mistake which has been, and still frequently is, made, with regard to this simple and not very important experiment, has been to regard the charge as evidence of a peculiar E.M.F. at the point of contact; an E.M.F. which causes a difference of potential between the two metals. And this fictitious contact E.M.F. has then been appealed to to explain the voltaic battery.

The right way of regarding the matter is to consider the battery first, explaining its action chemically so far as it is possible to explain it at present; and then to point out that similar things will occur in air (an air battery, in fact), with the slight difference that since air is a dielectric instead of an electrolyte no continuous current is possible, but merely a slight electric displacement, which is the Volta effect.

56. The effective cause of the whole phenomenon in either case is the greater affinity of oxygen for zinc rather than copper. This by itself would cause a greater strain of negative electricity towards zinc—a slackening of the negative cords in it, to speak in the language of the cord model—and a consequent rise of

negative potential. A piece of isolated zinc is therefore some 1·8 volts below the potential of the atmosphere, the difference of potential between metal and oxygen being calculable direct from their experimentally known heats of combination with oxygen.[1] The same sort of thing is true for copper, except that the intensity of strain is less; as evidenced by the less heat of formation of CuO compared with ZnO; and accordingly a piece of isolated copper is about 0·8 volt below the potential of the atmosphere.

Directly the two metals touch they necessarily become of the same potential—all parts of a conductor are at one potential unless there are disturbing internal forces,—and the equalization of potential is effected by a rush of electricity across the junction, whereby the zinc receives a positive charge and the copper a negative charge, until their potential is equalised. In air the equalization is effected in an instant. In water it is a matter of eternity. That is all the difference. The thing observed in the Volta effect is not a difference of *potential* between zinc and copper, but a difference of *charge*; the two metals being charged so as to make their potentials the same, in spite of their unequal chemical affinities for oxygen.

What is observed in the Lord Kelvin form of the experiment (§ 54) is again, not a difference of potential between zinc and copper, but a slope of potential in the air near them, from the zinc towards the copper. The metals when in contact are both

[1] See Lodge "On the Seat of E.M.F. in the Voltaic Cell," *Brit. Assoc. Report*, 1884; also *Journ. Soc. Tel. Eng.* 1885, and *Phil. Mag.* vol. xix. 1885 and 1886.

at a common potential, 1·3 volts below the atmosphere,—the mean of their original potentials; but the original difference of potential between each and the air in contact with it remains unaltered; hence there is a gradual slope of potential, of 1 volt, from the layer of air in contact with zinc to the layer in contact with copper; and this slope of potential is what

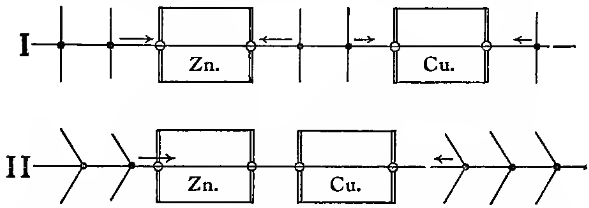


FIG. 15A.—Diagrammatic representation of the Volta effect, on the plan of the cord models (Figs. 5, 6, 7, &c.).

I. shows a piece of zinc and copper before contact, with a cord representing negative electricity passing through both, and beads representing oxygen atoms. The arrows indicate that the oxygen is being pulled by the zinc on all sides of it; and that it is also pulled by the copper, but with less force. The two metals differ in potential from each other and from the air near them, but this fact results in no sensible phenomenon so long as they are separate.

II. shows the effects of sweeping away the oxygen atoms between the two metals, by establishing metallic contact, so that the greater atom-attracting force of zinc over copper can now produce an effect, until it is balanced by the elastic stress called out by an electric displacement. The surface of the zinc has now less than its normal share of negative cord—it is positively charged—the copper is negatively charged. The two metals are now at the same potential, though oppositely charged; and a slope of potential is thrown upon the air in their neighbourhood. This is the Volta effect.

the electrometer needle feels. The diagram Fig. 15A may possibly help in making the whole thing clear.

The matter is capable of being perceived quite distinctly with the expenditure of a little time and trouble, and it is worth an effort.

True Contact Force.

57. So far we have assumed that there is actually *no* force at the contact of zinc with copper. There is indeed none of any appreciable magnitude, but the force is not absolutely zero. Between some metals, bismuth and antimony for example, the force is much larger, but it is still only a few hundredths of a volt. It is an important thing that there can be a true contact force at the junction of two metals, only it has nothing to do with the chemically produced Volta effect. If the Volta effect be called a contact force at all, it is a contact force between metal and air; any true contact force between metals acts as a slight and insignificant disturber of the simple Volta effect; and what is really observed in electroscopic experiments is the sum of the two.

58. That there is a true though weak contact force at a junction of metals is proved by the reversible heat effects which are found there when a current is passed across the junction: a current one way produces more heat than a current the other way. In a simple homogeneous piece of metal the heat produced by a current is utterly independent of direction: it is called irreversible heat; it is proportional to the square of the current strength, as Joule showed. But at a junction of different substances, or even at a junction of the same substance in two different states —two different temperatures, for example,—in addition to the irreversible heat produced by mere resistance there is a reversible heat production, one which changes sign with the direction of the current, so

that a current one way actually tends to cool the junction instead of heating it. With care this cooling tendency may be got to overpower and mask the irreversible heat; and a junction may be positively cooled and water frozen by steadily passing a moderate current in the right direction across it.

This curious fact was discovered by Peltier. It may be considered as the fundamental fact of thermo-electricity. Its meaning is that something in the metals, at the junction, is helping to propel the current along; doing work, in fact, and consuming its own heat in the process. The vibratory motion of the molecules is getting used up in propelling electricity. The contact force is acting in the direction of the current, and the junction is thereby cooled.

If the current be reversed, it will be driven *against* the force exerted by the molecules, and an extra amount of heat will then be added to the irreversible or frictional generation of heat.

59. This thermal evidence of contact force, though the most direct, was not the earliest discovered. The earliest known fact in thermo-electricity was that in a complete circuit of different metals a current could be excited by having the parts at different temperatures; manifestly because these contact forces, of which we have been speaking, change with temperature—some increasing, others decreasing, as the temperature is raised. They are accurately balanced in a circuit of uniform temperature, but they have a resultant whenever the temperature is not uniform; and this resultant E.M.F. is able to propel a current, as discovered by Seebeck.

Thermo-electric Pile.

60. A thermopile may be thought of in the following way, but in trying to understand the nature of these actions, at present, one must admit that some speculation and vagueness exist.

We have seen that when electricity is propelled through or among the molecules of a metal it experiences a certain resistance or opposition-force which is exactly proportional to the speed of its motion (§ 28). In other words, there is a connection between matter and electricity in many respects analogous to fluid friction, but varying accurately as the first power of the relative velocity. Hence, if an atom of matter be vibrating about a fixed point, it will tend to drive electricity to and fro with it; but if it be only one of a multitude, all quivering in different phases, they will none of them achieve any propulsion. This may be considered the state of an ordinary warm solid. But if from any cause a set of atoms could be made to move faster in one direction than in the reverse direction—to move forwards quickly and backwards slowly—then such an unsymmetrically-moving set *will* exert a propulsive tendency, and tend to drive a current of electricity forwards, simply because the force exerted is proportional to the velocity, and so is greater on the forward journey than on the return. Referring back to the cord model, Fig. 5, Ohm's law requires that the friction between cord and beads should be directly as the velocity; hence if a bead begins to oscillate unsymmetrically, travelling forward quickly and back slowly, it will propel the cord along in the direction in which it moves most quickly, somewhat as a child can propel its chair by jogging it upon a rough floor.

It might be thought that the weaker force of the slow return journey would be exactly compensated by the extra time it lasts. And so it would if there were only one propeller, or if they were all in the same phase; but the quick moving ones would grip the cord and prevent its return, if there is a balance of motion being transmitted in one direction; so that the result would be an effect analogous to the effect of barbs or valves: such an effect as is typified by the hammering in of a nail against a much weaker, though much more durable, extracting force. (For an incomplete account see Lodge, *Philosophical Magazine*, December 1876.)

Wherever conduction of heat is going on along a substance the atoms are moving unsymmetrically. They are driven forward infinitesimally quicker by the more rapidly moving atoms at the hot end than they are driven back by the less rapidly moving atoms in front. And, whatever may be the precise way in which such dissymmetry acts, such a slope of temperature exerts a propulsive tendency: there is an electromotive force in a substance unequally heated.

This fact was discovered theoretically and verified experimentally by Lord Kelvin.

61. But not only is there such a force at a junction of a hot and cold substance; there is also a force at the junction of two substances of different kinds, even though the temperature be uniform. It is not quite so easy to explain how it comes about that the atoms

at this kind of junction are moving faster one way than the other; nevertheless, such a thing is not unlikely, considering the state of constraint and accommodation which must necessarily exist at the boundary surface of two different media. However it be caused, there is certainly a weak E.M.F. at such a junction; which is in general greater when the resistance, or grip between electricity and metal, is greater.

Thus, then, in a simple circuit of two metals with their junctions at different temperatures, there are altogether four electromotive forces—one in each metal, from hot to cold or *vice versâ*, and one at each junction; and the current which flows round such a circuit is propelled by the resultant of these four.[1]

These four forces, two Kelvin forces in the metals, and two Peltier forces at their junctions, may some of them help and some hinder the current. Wherever they help, the locality is to that extent cooled; wherever they hinder, it is to that extent warmed.

Frictional Electricity.

62. But the contact force at a junction is by no means confined to metals. It occurs between insulators also, and it is to this fact that the striking effects produced by all frictional electric machines are due. The essential thing in the production of "frictional electricity" is the contact of dissimilar substances. It is by their contact force that electricity gets transferred from one to the other, so that one becomes positive and the other negative. A rapid succession

[1] See Lodge, *Phil. Mag.* Dec. 1876; also June 1885.

of contacts, easily obtained by sliding one of the surfaces over the other, is usually necessary to aid the transfer, the substances being so badly conducting.

By thus noticing that the connection between matter and electricity, known as resistance and defined by Ohm's law (§ 28), is competent to produce contact electromotive forces, we may perceive how it comes to pass that in good conductors such forces are so weak, while in insulators they are so strong. Electricity slips through the fingers of a metal, as it were, and the driving force it can exert is very feeble; while an insulator gets a good grip and thrusts it along with violence. A consequence of the above view is that in *perfect* conductors thermo-electric and all other contact forces would necessarily be zero.

Specific Relation between Matter and Electricity; sometimes called "Specific Heat of Electricity."

63. The metals differ in their gripping power; and, roughly speaking, the best conductor makes the worst thermo-electric substance. A bad conductor, like antimony, or, still better, galena, or selenium, or tellurium, makes a far more effective thermo-electric element than a well-conducting metal. Not that specific resistance is all that has to be considered in the matter; there is also a specific relation between each metal and the two kinds of electricity. Thus, iron is a metal whose atoms have a better grip of positive than of negative electricity, and so a positive current gets propelled in iron from hot to cold. Copper, on the other hand, acts similarly on

negative electricity, and it is a negative current which is driven from hot to cold in copper. And all the metals can be classed with one or other of these two; except perhaps lead, which appears to grip both equally, and so to exert no differential effect upon either.

How this relation can be likened to a "specific heat" may be thought out by attending to the last paragraph of § 61, and by regarding electricity as a material fluid (see also § 182).

Pyro-electricity.

Certain crystals, called by mineralogists hemihedral, having different forms at the two ends of their axis which may be called the A end and the B end respectively, exhibit some properties not quite the same in the direction A B as in the direction B A. They are said to be more easily scratched, for instance, in one sense than in the other. Such crystals, of which the class of tourmalines may be taken as the type, have other very singular properties. Such of them as are fairly clear are opaque to light in a singular fashion—not opaque to light polarized in all planes, but selectively opaque. Vibrations occurring perpendicular to the axis are rapidly quenched, so that one cannot see at all through a slice cut perpendicular to the axis; while vibrations occurring along the axis are transmitted with but moderate absorption. This opacity seems quite different from the conductive opacity of metals, about which we shall speak later, for, in the first place, the light stopped is not reflected, but absorbed; and, in the second place, a crystal of tourmaline is not a conductor, but a very fair insulator.

And yet there are some peculiarities about such conducting power as it has, which are very noteworthy, and which *may* be intimately connected with the selective opacity which fits a slice of crystal cut parallel to the axis for use as a "polarizer" in optics. One of these peculiarities was found by Dr. S. P. Thompson in conjunction with the present writer: viz. that while, like all other uniaxial crystals, the conductivities for heat along and across the axis are not the same (being, in the case of tourmaline, less good along the axis than across), yet, in addition to this, a warming crystal conducts heat better in the sense B A than in the sense A B, while a cooling crystal does the opposite. While the temperature is rising heat gets conveyed more easily towards A than towards B.[1]

Whether on account of inequalities of temperature thus set up, or for some more direct reason, electricity gets automatically transferred in one direction rather than in the other. And accordingly, while a crystal is rising in temperature, positive electricity accumulates at the A end, and negative electricity at the B end. So long as the temperature remains constant nothing further happens; except ordinary leakage, principally no doubt over the surface, which may in time completely mask the effect produced. On now cooling the crystal, an inverse electrification will be set up; or, if no leakage has been permitted, the

[1] *Phil. Mag.* July 1879.

effect of cooling is simply to replace the electricity displaced by the warming.

While the temperature of the crystal is steady, no difference in electric conductivity has been detected by the writer, between the sense A B and the sense B A. Neither is there any difference in the thermal conductivity when the temperature is steady. Both effects depend on a varying temperature. But the electrical phenomenon is more than a unilateral conductivity, it is a true axial electromotive force.

Passage of Electricity through a Gas.

64. There remains to be said something about the way in which electricity can be conveyed by *gases*: a subject which has grown immensely of late years. But here we will be brief, and deal with the matter in another book.

The first thing to notice is that gases and vapours can be divided into two classes: those which conduct electricity, and those which do not. Those which conduct, do so electrolytically—that is to say, they conduct like liquids by the locomotion of charged or carrier atoms, or *ions*; and there is good evidence that such gases are in a state of dissociation so long as they possess any conducting power. A high temperature, or a recent electrical discharge, either of which is well known to be a dissociating agency, is found to confer upon some gases and vapours a conducting power which they do not possess in their ordinary state. A gas whose molecules are dissociated into charged ions becomes an electrolyte, and is said to be *ionised*.

Undissociated or non-conducting gases and vapours appear not to conduct in the slightest degree; in other words, a substance in this condition behaves as a perfect insulator—perhaps the only perfect insulator there is. Not water vapour, not even mercury vapour, is found to conduct in the least; except when ionised. An electrified liquid does not lose its charge by evaporation: steam carries off no electricity, though spray does. This shows that mere bombardment of molecules, such as is known to go on in gases, is not sufficient either to remove or to impart any electric charge. Schuster and J. J. Thomson have found, however, that some gases do conduct electrolytically; and Schuster has described several curious facts concerning their conductivity during and shortly after an electric discharge.

The commonest way in which electricity makes its way through a non-conducting gas, setting aside the mere mechanical conveyance by solid carrier, is that of disruptive discharge.

When one says that a gas does not ordinarily act as a common electrolyte, the experimental grounds of the statement are that a finite electrostatic stress is certainly possible in its interior—a stress of very considerable amount; and when this stress does overstep the mark and cause the material to yield, the yielding is evidently not a quiet and steady glide or procession, but a violent breaking down and collapse, due to insufficient tenacity of something. One may therefore picture the molecules of a gas, between two opposite electrodes or discharge terminals maintained at some great difference of potential, as arranged in a set of parallel chains from one to the other, and strained nearly up to the verge of being torn asunder. In making this picture one need not suppose any fixture of individual molecules: there may be a wind blowing between the plates; but all molecules as they come into the field must experience the stress, and be relieved as they pass out.

65. If the applied slope of potential overstep a certain limit, fixed by observation at something like 33,000 volts per linear centimetre for common air, the molecules give way, the atoms with their charges rush across to the plates, and discharge has occurred. The number of atoms thus torn free and made able to convey a charge by locomotion is so great that there is ordinarily no difficulty in conveying any amount of electricity by their means. In other words, *during* discharge the gas becomes a conductor; and, being a conductor by reason of locomotion of atoms it may be called an electrolyte.

Schuster discovered that this conductivity of gases, or power of equalizing even very feeble potentials lasts for a little time and extends to some little distance from the region of a disruptive discharge; as if a number of ions or charged carrier atoms had been liberated and diffused, for a time, until they recombined and neutralized each other once more.

But whether the charge then possessed by each carrier atom intrinsically belonged to it all the time, or whether it was conferred upon the components of the molecules during the strain and the disruption, is a point not yet decided.

What is called "the dielectric strength" of a gas—that is, the strain it can bear without suffering disruption and becoming for the instant a conductor—depends partly on the nature of the gas, and very largely on its pressure. Roughly, one may say that a gas at high pressure is very strong, a gas at low pressure very weak. An ordinary electrolyte might be called a dielectric of zero strength.

One reason why pressure affects the dielectric tenacity of a gas may be suggested: it is certainly not the only one, but it can hardly help being at least partially a *vera causa;* and that is the fact that in a rare gas there are fewer molecules between the plates to share the strain between them.

A Current regarded as a Moving Charge.

66. To review the ground we have covered so far. We first tried to get some conception of the nature of electrostatic charge, and the function of a dielectric medium in static electricity. We next proceeded to see how far the phenomena of current electricity could be explained by reference to electrostatics. For a current, being merely electricity in locomotion, need consist of nothing but a charged body borne rapidly along.

Charge a sphere with either positive or negative electricity, and throw it in some direction; this constitutes a positive or a negative current in that direction. There is nothing necessarily more occult about a current than that. And a continuous current between two bodies may be kept up by having a lot of pith balls, or dust particles, oscillating from one to the other, and so carrying positive electricity one way and negative the other way. But such carriers, as they pass each other with their opposite charges, would be very apt to cling together and combine. They might be torn asunder again electrically, or they might be knocked asunder by collision with others. Unless one or other of these things happened, the current would shortly have to cease, and nothing but a polarized medium would result.

Instead of pith balls, picture charged atoms as so acting, and we have a rough image of what is going on, in an electrolyte on the one hand and in a dielectric on the other. The behaviour of metals and solid conductors is more obscure. Locomotive carriage by progressing atoms, is not to be thought of in them ; but, inasmuch as no new phenomenon appears in their case, it is natural to try and picture the process as one not wholly dissimilar : to picture something as being passed on from hand to hand, by a set of merely vibrating atoms,—that something being electricity. And this is what in §27 we tried to do.

67. I have said that an electric current need be nothing more occult than is a charged sphere moving rapidly ; and a good deal has been made out concerning currents by minutely discussing all that happens in such a case. But, even so, the problem is far from being a simple one. One has to consider not only the obviously moving charge, but also the opposite induced charge tied to it by lines of force (or tubes of induc-

tion, as they are sometimes called), and we have this whole complicated system in motion. And the effect of this motion is to set up an altogether new phenomenon in the medium—a spinning kind of motion that would not naturally have been expected: whereby two similarly charged spheres in motion repel one another less than when stationary, and may even begin to attract, if moving fast enough; whereby also a relation arises between electricity and magnetism, and the moving charged body begins slightly to deflect a compass needle (§§ 113 and 184). Of which more in the next Part.

PART III

MAGNETISM

CHAPTER VII

RELATION OF MAGNETISM TO ELECTRICITY

68. We next proceed to consider electricity in a state of *rotation*. What happens if we make a whirlpool of electricity? Coil up a wire conveying a current, and try. The result is it behaves like a magnet: compass-needles near it are deflected, steel put near it gets magnetized, and iron nails or filings are attracted by it,—sucked up into it if the current be strong enough. In short, it *is* a magnet. Not of course a permanent one, but a temporary one, lasting as long as the current flows. It is thus suggested that magnetism may perhaps be simply electricity in rotation. Let us work out this idea more fully.

First of all, one may notice that everything that can be done with a permanent magnet can be imitated by a coiled wire conveying a current. (It would not do altogether to make the converse statement.) Float a coil attached to a battery vertically on water, and you have a compass-needle; it sets itself with its axis north and south (Fig. 16). Suspend two coils, and they will attract or repel or turn each other round just like two magnets.

69. As long as one only considers the action of a coil at some distance from itself, there is no need to trouble about the shape of the particular magnet which it most closely simulates ; but as soon as one begins to consider the action of a coil on things close to it, it is necessary to specify the shape of the corresponding magnet.

If the coil be a long cylindrical helix like a close-spired corkscrew, as in Fig. 16, it behaves like a

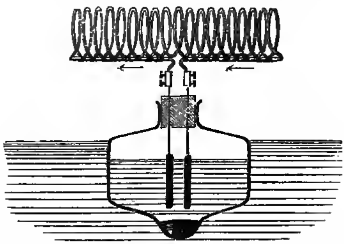


FIG. 16.—Floating battery and helix acting as a compass-needle,

cylindrical magnet filling the same space. If the coil be a short wide hank, like a curtain-ring, it behaves again like a cylindrical magnet, but one so short that it is more easily thought of as a disk. A disk or plate of steel magnetized with one face all north and the other face all south can be cut to imitate any thin hank of wire conveying a current. It will be round if the coil be round, square if it be square, and irregular in outline if the coil be irregular. It is called a magnetic shell.

There is no need for the coil to have a great number of turns of wire, except to increase its power: one is sufficient, and it may be of any shape or size. So when we come to remember that every current of electricity must necessarily flow in a closed circuit, one perceives that *every current of electricity is virtually a coil of more or less fantastic shape*, and accordingly imitates some magnet or other which can be specified. Thus we learn that every current of electricity must exhibit magnetic phenomena: the two are inseparable—a very important truth. See Appendix (*a*).

There is one detail in which the magnetized disk and the coil are not equivalent, and the advantage lies on the side of the coil: it has a property beyond that possessed by any ordinary magnet. It has a penetrable interior, which the magnet has not. For space outside both, they simulate each other exactly; for space inside either, they behave differently. The coil can be made to do all that the magnet can do; but the magnet cannot in every respect imitate and replace the coil: else would perpetual motion be an every-day occurrence.

70. Now I want to illustrate and bring home forcibly the fact that there is something rotatory about magnetism—something in its nature which makes rotation an easy and natural effect to obtain, if one goes about it properly. One will not observe this by taking two magnets: one will see it better by taking a current and a magnet, and studying their mutual action.

A magnet involves, as you know, two poles—a north and a south pole—of precisely opposite properties: it may be considered as composed of these two poles, for many purposes; and the action of a current on a magnet may be discussed as compounded of its action on each pole separately. Now how does a current act on a magnetic pole? Two currents attract or repel each other; two poles attract or repel each other; but a current and a pole exert a mutual force which is neither attraction nor repulsion: it is a rotatory force. They tend neither to approach nor to recede; they tend to revolve round each other. A singular action this, and at first sight unique. All ordinary actions and reactions between two bodies take place in the line joining them: the force between a current and a pole acts exactly at right angles to the line joining them.

Helmholtz long ago (in 1847) showed that the conservation of energy could only be true if forces between bodies varied in some way with distance and acted in the line joining them. Now here is a case where the force is not in the line joining the bodies, and accordingly the conservation of energy is defied: the two things will revolve round each other for ever. This affords, and has afforded, a fine field for the perpetual motionist; and if only the current would maintain itself without a sustaining power, perpetual motion would in fact be attained. But this after all is scarcely remarkable, for the same may be said of a sewing-machine or any other piece of mechanism: if only it would continue to go without sustaining power it would be a perpetual motion. Attend to pole and current only, and energy is *not* conserved, it is perpetually being wasted; but include the battery as an essential part of the complete system, and the mystery disappears: everything is perfectly regular.

71. The easiest way perhaps of showing the rotation of a conductor conveying a current round a magnetic pole, is to take an 8-feet long piece of gold thread, such as is used for military uniforms, and, hanging it vertically, supply it with as strong a current as it will stand. Then bring near it a vertical bar-magnet, and in-

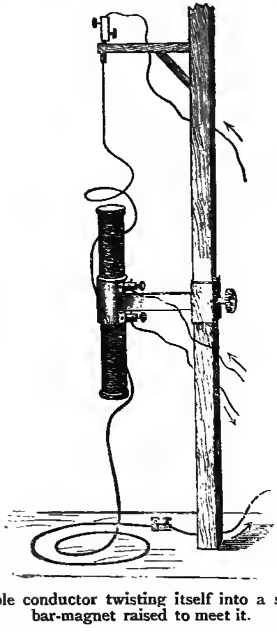


Fig. 17.—A long flexible conductor twisting itself into a spiral rouod a powerful bar-magnet raised to meet it.

stantly you will see the thread coil itself into a spiral: half of it twisting round the north end of the bar, and half twisting, as part of the same spiral, round the south end (Fig. 17).

If the magnet were flexible and the conductor rigid, instead of *vice versâ*, the magnet would in like manner coil itself in a spiral round the current; the force is strictly mutual. A rigid magnet, put near a stiff conductor, shows only the last remnants of this action: it sets itself at right angles to the wire, and approaches its middle to touch it, but that is all it can do.

The experiment with the flexible gold thread is simple, satisfactory, and striking, but the rotatory

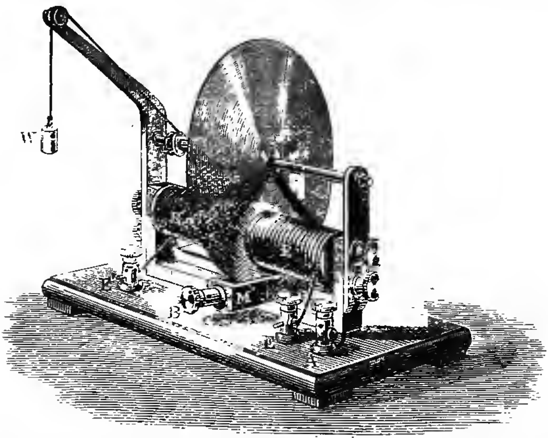


Fig. 18.—Pivoted disk with radial current, revolving in a magnetic field and winding up a weight. The current is supplied to the axil by screw A, and leaves the rim by mercury trough M. The same apparatus obviously serves to demonstrate currents induced by motion; both directly and by the damping effect.

properties connected with a magnet may be illustrated in numbers of other ways. Thus, pivot a disk at its centre, and arrange some light contact to touch its edge, either at one point or all round, it matters not; then supply a current to disk from centre to circumference, and bring a bar-magnet near it along its axis, or, better, two bar-magnets, with opposite poles one on each side, near the contact place of the rim; the disk at once begins to rotate (Figs. 18 and 19).

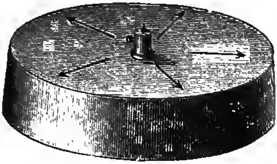


Fig. 19.—Another pivoted disk with flange to dip into liquid so as to make contact all round its rim. It rotates when a magnet is brought above or below; or even in the field of the earth.

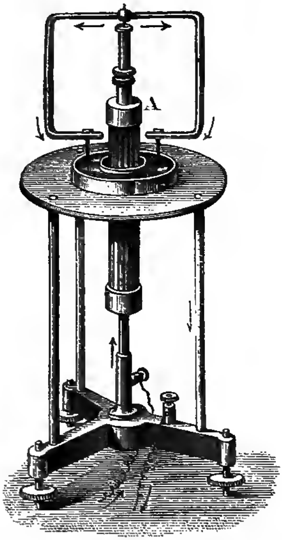


Fig. 20.—A couple of radii of the above disk, provided with points to dip into mercury and rotating constantly under the influence of the steel magnet A; or under the influence of a current conveyed by a coil of wire round the circular trough.

Instead of a disk one may use a single radius of it, viz. a pivoted arm (Fig. 20) dipping into a circular trough of mercury; or we may use a light sphere rolling on two concentric circular lines of railway (Gore's arrangement, Fig. 21).[1] In every case rotation begins as soon as a magnet is brought near.

72. Nor is the revolving action confined to metallic conductors and to true conduction. Liquids and gases, although they convey electricity by something

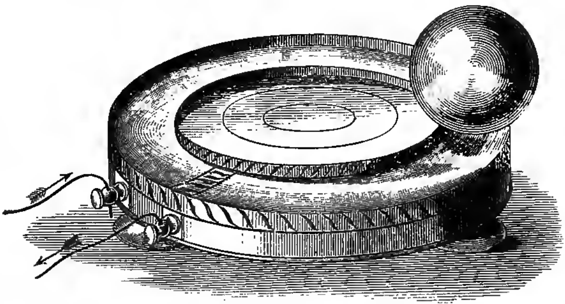


Fig. 21.—Gore's circular railway. The light spherical metal ball revolves round the two concentric metal hoops or rails whenever it is made to convey a current between them in a vertical magnetic field.

of the nature of convection, are susceptible to rotation in a precisely similar manner.

[1] This is not what Gore's railway is commonly used to illustrate, nor is it the cause of the motion as observed by the inventor, or as described in Tyndall's *Heat*. Ordinarily the ball moves by reason of an irregular disturbance due to heat at its point of contact with the rails, and it is mere accident which way it goes. But, in so far as the earth's vertical magnetic field is strong enough, it should exhibit a preference for one direction over the other ; and if the field is strengthened by bringing the south pole of a bar-magnet below the apparatus, true magnetic rotation is bound to occur. It may, however, be convenient to state that the current's own lines of force are powerless to cause continuous motion in this case. An external field is essential in cases like this of fixed and finite area for the circuit. All that the current's own magnetism could do would be very slightly to urge the ball to the end of a diameter opposite to where the current enters.

To show the rotation of liquid conductors under the influence of a magnet, take a circular shallow trough of liquid, supply it with stout sheet copper electrodes at centre and circumference, and put the pole of a magnet below it. The liquid at once begins to rotate, and by using a magnet and current of fair strength it can easily be made to whirl so fast as to fly over the edge of the trough (Fig. 22).[1] The experiment is plainly the same as Fig. 19, except that a

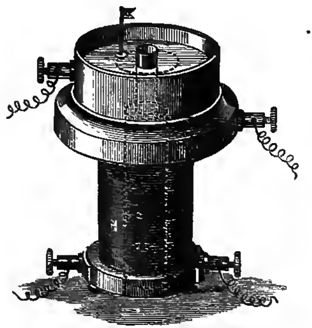


Fig. 22.—Rotation of a liquid disk conveying a radial current in a vertical magnetic field.

liquid disk is used in place of a solid one. Or, again, it may be considered the same as Fig. 21. Reverse the magnet, and the rotation is rapidly reversed.

Another method is to send a current along a jet

[1] In practice it is most convenient to split a battery current between magnet and liquid : *i.e.* to connect them in parallel instead of in series. It is also well to make the smaller surface of copper the cathode; because with intense currents (say 3 amperes per square centimetre) a crust of oxide forms on the anode which almost entirely stops the current by its resistance. This alone is a curious experiment, worth trying with small copper electrodes.

of mercury near a magnet and note the behaviour of the jet. It twists itself into a flat spiral as shown in Fig. 23.

The rotation of a gas discharge is most commonly illustrated by an arrangement like Fig. 24, where the

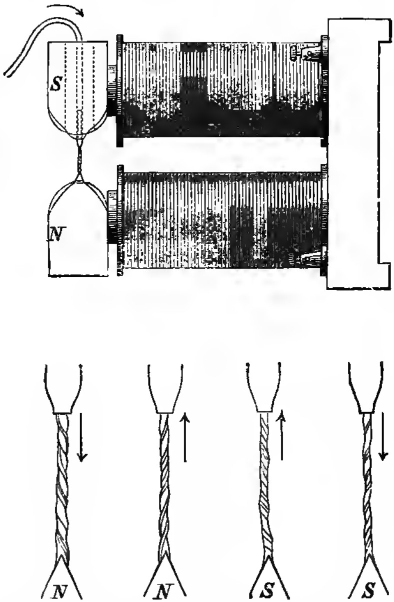


Fig. 23.—A falling stream of liquid conveying a current between two magnetic poles. and being thereby twisted into a spiral. (Copied from a paper in *Phil. Mag.* by Dr. Silvanus Thompson.)

terminals of the induction coil are connected to the rarefied gas respectively above one pole and round the middle of a magnetized bar. If the discharge can be got to concentrate itself principally down one side, which it is not easy always to do (it seems to depend on the presence in the vacuum of some traces of foreign vapour, *e.g.* CS_2 vapour), the line of light so formed is seen to revolve.

Fig. 24.—Induction coil discharge from *a* to *b* through rarefied gas, rotating round a glass protected magnetized iron rod.

Action between a Magnet and an Electric Charge in Relative Motion.

73. Remembering all this, and the fact that a moving charge constitutes a current, it is not to be doubted that a charged pith ball moving in the neighbourhood of a magnet is subject to the same rotatory action. There is no known action between a magnet and a *stationary* charged body, but directly

either begins to move there is an action between them, tending to cause one to rotate round the other. It is true that for ordinary speeds of motion this force is extremely small; but still it is not to be doubted that if a shower of charged pith balls or Lycopodium granules are dropped on to a magnet pole, they will fall, not perfectly straight, but slightly corkscrew fashion. In this way electrified particles, shot out by the sun, are guided spirally along the earth's magnetic line of force; and are thus led from the tropics to the poles, where they illuminate the rarefied atmosphere electrically.

If a set of charged particles were projected horizontally and radially from the top of a magnet, their paths would revolve like the beams of a lighthouse. And if by any means their paths were kept straight, or deflected the other way, they would exert on the magnet an infinitesimal "couple" tending to make it spin on its own axis. Conversely, if a magnet were spun on its axis rapidly by mechanical means, there is very little doubt but that it would act on charged bodies in its neighbourhood, tending to make them move radially either to or from it. This, however, is an experiment that ought to be tried; and the easiest way of trying it would be to suspend a sort of electrometer needle, electrified positive at one end and negative at the other, near the spinning magnet, and to look for a trace of deflection—to be reversed when the spin is reversed, A magnet of varying strength might be easier to try than a spinning one.[1] (See §§ 114—116.)

[1] For experiments directed to discover this effect and exhibiting a very minute trace of it, see Lodge, *Phil. Mag.* June 1889, p. 469.

Rotation of a Magnet by a Current.

74. The easiest way to show the actual rotation of a magnet is to send a current half-way along it and back outside. Thus take a small, round, polished steel bar-magnet with pointed ends, pivot it vertically, and touch it steadily with two flakes or light pads of tin-foil, one near either end and one near the middle; supply a current by these contact pieces, and the

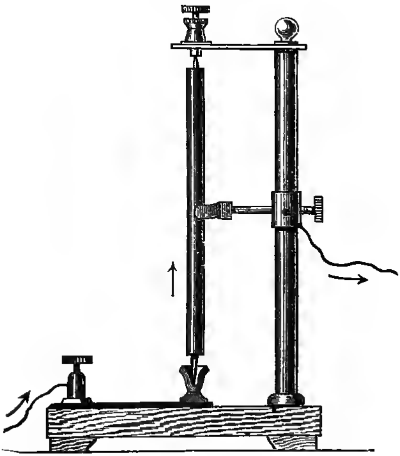


Fig. 25.—Round bright steel bar-magnet pivoted at its ends, spinning rapidly on its axis under the influence of a current supplied to either the bottom or top pivot, or both, and removed near the middle by a scrap of tin-foil lightly touching it.

magnet spins with great rapidity. Reverse the current, and it rotates the other way. Conversely, by producing the rotation mechanically a current will be excited in a wire joining the two pieces of tin-foil (Figs. 25, 26, and 27).

The two contacts may be made anywhere on the magnet except symmetrically: if the two are equidistant from the middle, no effect will be produced. The nearer one is to the middle and the other to

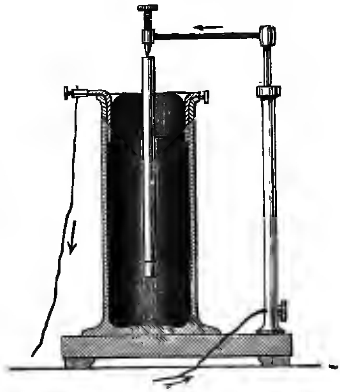


Fig. 26.—Another mode of exhibiting the same thing as Fig. 25. The magnet is loaded sn as to float upright in mercury.

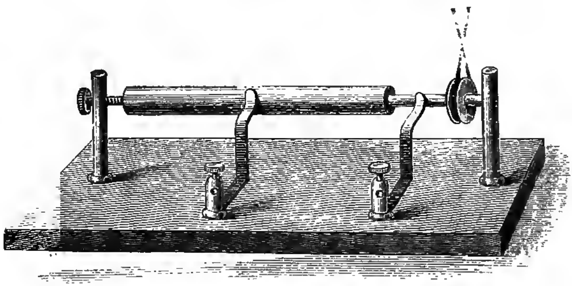


Fig. 27.—The converse of Fig. 25. Spinning the magnet mechanically gives a current between two springs, one touching it near or beyond either end, the other toucbing it near the middle.

the end the stronger the effect; stronger still if one of the contacts is either at or beyond the end, as in Fig. 25, where the lower cup contains mercury.

75. The customary or Faraday plan of exhibiting the effect depicted in Fig. 25, with a mercury ring trough round the magnet, into which a projecting wire carried by the magnet dips, is not quite so simple and obvious a method as Fig. 25 ; neither is it so effective unless the ring trough fits the magnet pretty closely. The arrangement in Fig. 25, where the contact is made actually on the surface of the magnet, gives the theoretically greatest force.

Many more variations of the experiment could be shown, but these are typical ones, and will suffice. They all call attention to the fact that a magnet, considered electrically, is a rotary phenomenon.

CHAPTER VIII

NATURE OF MAGNETISM

Ampère's Theory.

76. THE idea that magnetism is nothing more nor less than a whirl of electricity is no new one—it is as old as Ampère. Perceiving that a magnet could be imitated by an electric whirl, he made the hypothesis that an electric whirl existed in every magnet and was the cause of its properties. Not of course that a steel magnet has an electric current circulating round and round it, as an electro-magnet has; nothing is more certain than the fact that a magnet is not magnetized as a whole, but that each particle of it is magnetized, and that the actual magnet is merely an assemblage of polarized particles. The old and familiar experiment of breaking a magnet into pieces proves this. Each particle or molecule of the bar must have its circulating electric current, and then the properties of the whole are explained.

There is only one little difficulty which suggests itself in Ampère's theory—How are these molecular currents maintained? Long ago a similar difficulty was felt in astronomy—What maintains the motions of the planets? Spirits, vortices, and other contrivances were invented to keep them going.

But in the light of Galileo's mechanics the difficulty vanished. Things continue in motion of themselves until they are stopped. Postulate no resistance, and motion is essentially perpetual.

What stops an ordinary current? Resistance. Start a current in a curtain-ring, by any means, and leave it alone. It will run its energy down into heat, in the space of half a second or so. But if the metal conducted infinitely well there would be no such dissipation of energy, and the current would be permanent.

In a metal rod, electricity has to pass from atom to atom, and it meets with resistance in so doing; but who is to say that the atoms themselves do not conduct perfectly? They are known to have various infinite properties already; they are infinitely elastic, for instance. Pack up a box of gas in an adiabatic enclosure for a century, and see whether it has got any cooler. The experiment, if practicable should be tried; but our present experience warrants us in assuming no loss of motion among colliding atoms, until the contrary has been definitely proved by experiment. To all intents and purposes *certainly* atoms are infinitely elastic; why should they not also be infinitely conducting? Why should dissipation of energy occur in respect of an electric current circulating wholly inside an atom? Excepting for loss by radiation, there is no known reason why it should: there are many analogies against it. Magnetic properties are probably due to such currents.

How did these currents originate? We may as well ask, How did any atomic qualities originate? How did their motion originate? These questions are unanswerable. Suffice it for us, there they are. The atoms of a particular substance—iron, for instance, or zinc—have an electric whirl of certain strength circulating in them as one of their specific physical properties.

This much is certain, that the Ampèrian currents are not producible by magnetic experiments. When a piece of steel or iron is magnetized, the act of magnetization is *not* an excitation of Ampèrian current in each molecule—is not in any sense a magnetization of each molecule. The molecules were all fully magnetized to begin with; the act of magnetization consists merely in facing them round so as to look mainly one way—in polarizing them, in fact. This was proved by Beetz long ago: I will not stop to explain it further, but will refer students to Maxwell (vol. ii. chap. vi.).

Ampère's Theory extended by Weber to explain Diamagnetism also.

77. Let us see how far we have got. We have made the following assertions:—

(1) That a magnet consists of an assemblage of polarized molecules.

(2) That these molecules are each of them permanent magnets, whether the substance be in its ordinary or in its magnetized condition, and that the act of

magnetization consists in turning them round so as to face more or less one way.

(3) That when all the molecules are faced in the same direction the substance is magnetically completely saturated.

(4) That if each molecule of a definite substance contains an electric current of definite strength, circulating in a channel of infinite conductivity, the magnetic behaviour of the substance is completely explained.

But now, supposing all this granted, how comes it that the molecular currents are not capable of being generated by magnetic induction? And if we cannot excite them, are we able to vary their strength?

78. The answer to these questions is included in the following propositions, which I will now for convenience state, and then proceed to explain and justify.

(5) If a substance possessing these molecular currents be immersed in a magnetic field, all those molecules which are able to turn and look along the lines of force in the right direction will have their currents weakened; but on withdrawal from the field they will regain their normal strength.

(6) If the currents naturally flowing in conducting channels be feeble or *nil*, the act of immersion of the substance in a magnetic field will reverse them or excite *opposite* currents, which will last so long as the body remains in the field, but will be destroyed by its removal.

(7) The molecular currents so magnetically in-

duced are sufficient to explain the phenomena of *diamagnetism.*

79. Let us first just recall to mind the well-known elementary facts of current induction. A conducting circuit, such as a ring or a coil of wire, suddenly brought near a current-conveying coil or a magnet, has a momentary current induced in it in the opposite direction to the inducing current: in other words, such as to cause momentary repulsion between the two. So long as it remains steady, nothing further happens; but on withdrawing it, another momentary current is induced in it, in the contrary direction to the first excited. The shortest way of expressing the facts quite generally is to say, that, while from any cause the magnetic field through a conductor is increasing in strength, a momentary current is excited in it tending to drive it out of the field; and that, whenever the magnetic field decreases again to its old value, a reverse flow of precisely the same quantity of electricity occurs. Fig. 28 shows a mode of illustrating these facts. A copper disk is supported at the end of a torsion arm and brought close to the face of an unexcited bar electro-magnet On exciting the magnet the disk is driven violently away: to be sucked back again, however, whenever the magnetism ceases.

80. Now, why are all these effects so temporary? What makes the induced current cease so soon after excitation? Nothing but dissipation of energy: only the friction of imperfect conductivity. There is nothing to maintain the current, it meets with resistance in its flow through the metal, and so it soon stops.

But in a perfect conductor, like a molecule, no such dissipation would occur. Electricity in such a body will obey the first law of motion, and continue to flow till stopped by applied force. Destroying the magnetic field will stop an induced molecular current, but nothing else will stop it. Hence it follows that

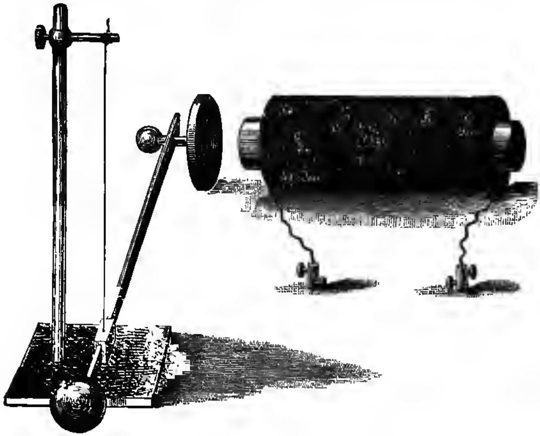


FIG. 28.—Stout disk of copper supported on a horizontal arm near one pole of a bar electro-magnet. The disk is repelled while the magnet is being excited, and is attracted while the magnetism is being destroyed. An alternating current round the magnet maintains continual repulsion, because of a lag of phase in the alternating current induced in the disk (*cf.* § 202).

the repulsion experienced by a molecule is no transitory effect like that in Fig. 28, but is as permanent as the magnetic field which excites and exhibits it.

Thus, then, a body whose molecules are perfectly conducting, but without specific current circulating in them, will behave diamagnetically, *i.e.* will move away from strong parts of the field towards weak ones; or, if only free to point, will set its length equatorially, just as bismuth is known to do.

Whether this be the true explanation of diamagnetism or not, it is at least a possible one. It seems to me extremely probable. It is known as Weber's theory.

It does not necessarily follow that the specific molecular currents of a diamagnetic substance are really *nil;* all that is needful is that they shall be weaker than those induced by an ordinary magnetic field. By using an extremely weak field, however, the specific currents need not be quite neutralized, and in such a field the body ought to behave as a very feebly magnetic substance. Such an effect has been looked for.[1]

81. It is however just possible for a substance to possess specific molecular currents and yet not to be sensibly magnetic: every molecule might be so jammed as to be unable to turn round, and such a substance could hardly exhibit any noticeable magnetic properties. The molecules would have got themselves into a state of minimum potential energy, and if jammed therein nothing could be got out of them. The induced currents of diamagnetism would be superposed upon them just as if no initial molecular currents existed. By varying the temperature of such a substance, however, one might expect to alter its molecular arrangement, and so develop magnetic properties in it, just as electrical properties are developed in crystals like tourmaline by heat or by cold.

We are now able clearly to appreciate this much—that the molecular currents needful to explain magnetism are not conceivably excited by the act of

[1] See Lodge on Permanent Magnetic Polarity in many Substances, *Nature*, vol. xxxiii.

magnetization, for they are in the wrong direction. *Induced* molecular currents will be such as to cause repulsion: those which cause attraction must have existed there before, and be merely rotated into fresh positions by the magnetizing force. An intense magnetic field will weaken them, and thus tend to render a magnetic substance less magnetic.

Function of the Iron in a Magnet. Two Modes of expressing it.

82. We can now explain the function of iron, or other magnetic substance, in strengthening a magnetic field. Bend a long coil of wire, Fig. 29, and send a current round it: there is a certain field—a certain number of lines of force—between its ends. Fill the coil with iron, so as to make it a common electro-magnet, and the strength of the field is greatly increased. Why? The common mode of statement likens the magnetic circuit to a voltaic circuit; there is a certain magneto-motive force, and a certain resistance, or, as Mr. Heaviside preferably calls it, "reluctance": the quotient gives the resulting magnetic induction, or total number of lines of force. Iron is more permeable than air—say, 3000 times more permeable—and accordingly the resistance of the iron part of the circuit is almost negligible in comparison with that of the air-gap between the poles. Thus a good approximation to the total intensity of field is obtained by dividing the magneto-motive force by the width of the air-gap; or more completely and generally by treating the varying material and section of a

magnetic circuit just as the varying material and section of a voltaic circuit is treated, and so obtaining its total resistance. Iron is thus to be regarded as a magnetic conductor between 100 and 10,000 times better than air. Its specific magnetic conductivity or inductivity, or, as it is more usually called (after Kelvin), permeability, is measured by the ratio of

FIG. 29.—A nearly closed magnetic circuit.

the magnetization produced to the magnetizing force applied, and is generally denoted by the symbol μ.[1]

83. This mode of regarding the case is undoubtedly simple and convenient, its thorough recognition has greatly improved the construction of electro-magnets and dynamo-machines, and it is difficult to overestimate its practical convenience; nevertheless it is well to remember that it is not the fundamental mode. If we look at the matter less with a view to practical simplicity than with the aim of seeing what is really going on, we shall express it thus:—

Before the iron was inserted in the coil, there were a certain number of circular lines of force inside it

[1] See Appendix (*b*).

due to the current alone. A piece of common iron, although full of polarized molecules, has no external or serviceable lines of force: they are all shut up, as it were, into little closed circuits inside the iron. But directly the iron finds itself in a magnetic field some of these open out, a chain of polarized molecules is formed, and the lines due to its molecular currents add themselves to those belonging to the current of the magnetizing helix.

Thus our ring electro-magnet has now not only its own old lines of force, but a great many of those belonging to the iron also, which have sympathetically laid themselves alongside the first.

Parenthetically we may make the following remark. So long as the iron adds some 3000 lines of its own (more or less according to the quality of the iron) for every one otherwise excited in the field, so long it has its maximum permeability: it is infinitely far from saturation. But after a certain call upon it, it begins to show signs of poverty, and ultimately may refuse to add any lines of its own at all; it is then said to be completely saturated: its permeability is then just as if it were air. The permeability of iron is an extremely indefinite quantity. Not only does it vary with the same piece as it nears saturation, but it is exceedingly different for different specimens. Thus some manganese-steel exists with a permeability one and a half times that of air, or only about as much as zinc, while Ewing finds some iron with a permeability as high as 20,000, under shaking.

The end result of either mode of regarding the matter is of course the same—the lines of force between the poles are increased in number by the presence of iron ; but—whereas, in the first-mentioned mode of treatment, the fact of permeability had to be accepted unexplained,—in the second nothing is unexplained except the fundamental facts of the subject, such as the reason why currents tend to set themselves with their axes parallel, and other matters of that sort.

Permanent Magnetism.

84. There is one curious effect of introducing iron or other solid magnetic medium into a magnetic field which must not be overlooked. This effect depends on the solidity of the substance, *i.e.* the fixedness or stiffness of its molecules. In a fluid the molecules are free to take up any fresh arrangement with ease : there is no set arrangement in the internal structure of a fluid, any more than there is a definiteness in its external shape. But with a solid it is different : its molecules once set into any position tend to remain more or less in that position ; the substance may be elastic to a certain extent, but after large disturbances there will always be a certain amount of "permanent set." Hence it is that solid bodies have a definite shape, which it requires force to change ; hence it is also that their molecules are able to crystallize into geometrical patterns.

Now, since the act of magnetization consists in making a number of already polarized molecules face round more or less in one direction, it follows that solid magnetic substances will behave differently from fluid ones. In fluid media the magnetized arrangement can only be maintained by a continuous exertion of magnetizing force; and directly this is withdrawn the molecules will quickly take up their old higgledy-piggledy arrangement of minimum energy, and all trace of magnetization will cease. They will be perfectly easy to magnetize, and they will automatically demagnetize themselves. But with solids it is otherwise. If the molecules have been set in their magnetized position by only a feeble force, they will spring back almost completely when the magnetizing force is removed; but if they have been arranged by a force of some violence, the spring back will be only partial, and a permanent set will remain. The spring back portion of the whole arrangement is called temporary magnetism; the set portion is called permanent magnetism. The difference can be illustrated by bending a bit of tin plate or paper, nearly double, and then letting it go.

Substances differ greatly in their power of thus retaining magnetization: and, as is well known, steel has the property well developed; but all substances exhibit it more or less.[1] Moreover, many substances can retain a little of the set if they are left carefully undisturbed, but they lose it if shaken or heated: sometimes even if gently touched. A long thin bar of soft iron is most instructive in this respect. It can be easily magnetized by the earth's magnetism if held vertically and struck with a finger. If then inverted slowly and cautiously, it will retain nearly the whole of the induced magnetism; but if struck again, or

[1] See Lodge in *Nature*, vol. xxxiii. p. 484.

even if the fingers are shuffled on it (so sensitive some bars are), the whole is immediately reversed. Soft iron can, in fact, retain enormously more magnetism than steel can, but it retains it in a very feeble and loose manner. Its magnetism can only be styled sub-permanent.

85. A short thick bar can retain much less magnetism than a long thin one; in fact, if a stout bar is made of the softest iron, it can retain hardly any. A piece of iron shaped like Fig. 29 would have a much better chance of retaining its magnetism, and if the gap were closed by another piece of iron, called a "keeper," it would retain it very well; while if the last trace of air-gap, the air-films between keeper and magnet, be abolished by making the whole one welded ring, then its magnetism is retained almost perfectly. There is some demagnetizing force even in this case, for a fluid magnetized as a ring would not remain magnetized, and I find that tapping or beating such a ring does appreciably weaken its magnetization, but the demagnetizing force is very small compared with what it is when there is an air-gap.

Hence we learn that the specially demagnetizing portion of a magnetic circuit is the fluid portion—the air portion; and the greater the proportion of the fluid portion to the whole, the more easily is demagnetization accomplished—fluids having no power of their own to retain magnetism. If lines of force are forcibly maintained in air or other fluid in the neighbourhood of a solid magnet, all the strain of upholding not only its own magnetism, but all the rest of the magnetism in the field—the strain of keeping the molecules faced round in opposition to their mutual restoring forces—has to be thrown upon the rigidity and retentivity of the solid.

86. All the known facts of magnetism have had new life and interest put into them by the researches of Ewing. The long-known fact that solid substances store up in their structure any previous arrangement of their molecules, so that traces of the effect are recognizable long after the cause of the effect has been withdrawn, is not indeed by any means confined to magnetism; it is a general property of solids, and constitutes a considerable difficulty in dealing with them theoretically. The properties of all fluids, whether liquids or gases, depend upon their state at the moment, and upon nothing else; not at all upon how they reached that state, or upon what has happened to them in past times. "Hydrogen at 0° C. and 76 centimetres pressure" is a perfectly definite substance. "Water at 50° C. and one atmosphere pressure" is again a quite complete specification. And the same is very nearly true of some crystalline solids. Quartz or ice at given temperature and pressure is generally considered quite a definite statement, though perhaps it is not so exactly definite as we imagine. But glass, or steel, or copper, at a specified temperature, is by no means a definite substance. If it has been cooled down to that temperature it will not be the same as if it had been warmed up to it. We must be told whether it has been hardened, or tempered, or annealed, and so on. The properties of a solid body depend on its past history as well as on its present state.

All this is pre-eminently true of magnetization. To understand completely the behaviour of a magnet we must not only know its present state, but we must know how it got to that state. A piece of steel once magnetized and then demagnetized is not in the same condition as if it had never been in a magnetic field: unless, indeed, it has been re-melted and made afresh.

This much, however, must be granted, that if *everything* were known about the instantaneous state of a body there would be no need to go back upon its past history: it might even be possible to deduce some of its past history from its present state. But it is precisely because a knowledge of the position and relation of every individual molecule is impossible, and because we have to put up with a few salient features of information, that an inquiry into past history is necessary. A few salient features are sufficient in the case of fluids: they are, in general, not sufficient in the case of solids.

I have laid stress upon this matter because it is an important general distinction between states which are 'self-contained,' so to speak, and states which are 'led up to.' The first condition represents what is expressed in mathematical language by saying that a function "is a complete differential," or "has a potential."

87. A further detail of the distinction is that, in solids, a direct and a return series of changes are not usually the same; a precisely inverse cause does not precisely invert the effect. Take a body from one *self-contained* state to another. Then, whenever you reverse the series of operations which brought it there,

it will return through the same series of states to its previous condition ; everything will be as it had been and no work need have been done on the whole. Not so with the *led-up-to* states. Magnetize a piece of steel by one series of operations, and then perform the same operations in reverse order: it will not return by the same series at all, nor will it return to its original condition. Continue the process of magnetization and reverse magnetization several times, and you may at length succeed in getting the body to go through a cycle of changes,—at least approximately. But it will go by one 'path,' so to speak, and return by another.

Now when a body of any kind is taken from a state A to a state B by one path, and back from B to A by some other path, as steam is, for instance, between boiler and condenser in a steam-engine, the result is always that some work is either done by the substance, or has to be done upon it, in performing the cycle. The return by a different path is optional in the case of steam, and accordingly work may or may not be done on it; but in the case of a magnetized solid it is not optional. The ascending curve of increasing magnetism, and the descending curve of decreasing magnetism, do not coincide, and cannot be made to coincide. Consequently, whenever a piece of iron is taken round a cycle of magnetic changes, some work is necessarily done.

This work, in general, results in a production of heat, and accordingly a piece of iron magnetized and demagnetized several times, in rapid succession, gets slightly warm. This direct heating effect is, however, very small, though it is becoming perceptible in the "transformers" of modern electrical engineering.[1]

All this behaviour of iron and other substances with regard to magnetism is called by Ewing hysterēsis (from ὑστερέω, to lag behind).

87A. A remarkable discovery has been recently made with regard to the mechanism of the act of magnetization and the nature of the forces in a solid to which magnetic retentivity is due. It used to be thought that a kind of friction, or other mechanical constraint, was necessary to hold the molecules in place—permitting their elastic yield up to a certain limit as magnetic forces rotated them, while beyond that limit a sort of viscosity set in and fixed them more or less permanently in their new positions. But Ewing has experimentally shown that all the fixity required in a solid composed of polarized molecules is the fixity of their pivots or axes of rotation. If the atoms are capable of locomotion, as in a fluid, then no doubt permanent magnetization will be impossible; but if locomotion be prevented, so that the atoms can only rotate on fixed centres, then every detail of the magnetic behaviour of a solid can be explained by the magnetic forces among the polarized but otherwise perfectly free atoms. No mechanical constraint is necessary to explain magnetic retentivity and hysterēsis. It all follows at once from the behaviour of a number of magnetic particles rotating within the range of each other's influence; and it can be very

[1] The large indirect heating by induced currents—the so-called Foucault current—is too familiarly known to need any other statement than that it is quite distinct from what we are here discussing.

sufficiently imitated by a flock of pivoted compass-needles. This is a considerable step towards removing complexity and indistinctness from the constitution of solids. The properties of liquids and gases are known to merge into one another, and to be explicable by a number of similar particles approaching more or less within each other's range of force. The properties of solids will probably follow too, by adding to the above conception that of fixity of centre, or absence of locomotion.

Electrical Momentum once more.

88. There is just one point to which I must stop here to call attention. The theories of magnetism and diamagnetism, which I have given according to Ampère, Weber, and Maxwell, require as their foundation that in a perfect conductor electricity shall obey the first law of motion—shall continue to flow until stopped by force. But the property of matter which enables it to do this is called *inertia;* the law is called the law of inertia; and anything which behaves in this way must be granted to possess inertia.

It would not do to deduce so important a fact from a yet unverified theory; but at least one must notice that momentum is essentially involved in Ampère's theory of magnetism. It is the only theory of magnetism yet formulated, and it breaks down unless electricity possesses inertia.

Nevertheless it is a fact that an electro-magnet does not behave in the least like a fly-wheel or spinning-top: there is no momentum mechanically discoverable (§ 39). Supposing this should turn out to be strictly and finally true, we must admit that a molecular electric current consists of two equal opposite streams of the two kinds of electricity: one must begin to regard negative electricity not as merely the negation or defect of positive, but as a separate entity. Its relation to positive may turn out to be something more like that of sodium to chlorine than that of cold to heat.

89. I said that no effect due to electric inertia was *mechanically* discoverable; and on the hypothesis that an electric current consists of a pair of equal opposite currents of positive and negative electricity respectively this is very natural. Think of a couple of india-rubber pipes tied together so as to form a double tube, and through each propel a current of water, one in an opposite direction to the other. The double current has no gyrostatic properties, and the only way the water can exhibit momentum is by its resistance to change of velocity—like the " extra-current " effects in electricity (§ 38).

So long as one considered the flow of electricity in ordinary conductors, we could partially avoid the question of inertia by considering it urged forward at every point with a force sufficient to overcome the resistance there and no more; but though this explained the shape of the stream-lines (§ 49), yet it did not suffice to render clear the phenomena of self-induction—the lag of the interior electricity in a wire behind the outside until definitely pushed (§§ 43–48);

still less does it explain its temporary persistence in motion after the pushing force has ceased.

But, now that we are dealing with perfect conductors, with no pushing force at all, the persistence of molecular currents without inertia, or an equivalent property so like it as to be rightly called by the same name at present, becomes inexplicable. Inertia must be recognized as an essential property of electricity.

CHAPTER IX

STRUCTURE OF A MAGNETIC FIELD

Representation of a Magnetic Field.

91. The disturbance called magnetism, which we have shown in Chap. VII. to be something of the nature of a spin—a rotation about an axis—is conspicuously not limited to the steel or iron of the magnet: it spreads out through all adjacent space, and constitutes what is called the magnetic field. A map of the field is afforded by the use of iron filings, which cling end to end and point out the direction of the force at every point (Fig. 33).

These lines of force so mapped are to be regarded as the axes of molecular whirls (Fig. 30). They are continuous with similar lines in the substance of the steel, and every line really forms a closed curve, of which a portion is in the steel and a portion in the air. In a wire helix, such as Figs. 16 or 29, the lines are wholly in the air, but in one part of their course they thread the helix, and in another part they spread out more or less between its faces.

But according to Ampère's theory of molecular currents there is no *essential* difference between such a helix and a steel magnet; directly the currents in the molecules of the magnet are considered, everything resolves itself into chains of molecular currents, threading themselves along a common closed curve or axis. Each atom, whether in the steel or in the air, is the seat of a whirl of electricity, more or less faced round so as on the average to have its plane at right angles

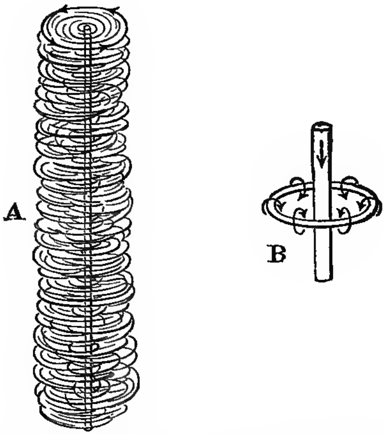


FIG. 30.—A, an element of a magnetic line of force with the electric whirl round it; B, a bit of an electric circuit with one of its magnetic lines of force shown round it, and the electric whirl round this: each magnetic line of force round a current being an electric vortex ring. Compare Fig. 39.

to the lines of force. The simplest plan of avoiding having to consider those only partially faced round, is to imagine the whole number divided into a set which face accurately in the right direction, and a set which look any way at perfect random; and to neglect this latter set.

92. Well, now try and picture a chain of whirls like beads spinning on a wire threading them all, and

think of the effect of a material fluid thus rotating. Obviously it would tend to whirl itself fatter, and to shorten its length, as in Fig. 31 or 32. An assemblage of parallel straight whirls would thus squeeze each other laterally, or cause a lateral pressure, and would tend to drag their free ends together, causing a longitudinal tension.

Such whirls cannot in truth have free ends except at the boundary of a medium—as at the free surface of a liquid. Magnetic whirls are in reality all closed curves; but inasmuch as part of them may be in a mobile fluid like air, and part of them in a solid like iron or steel, it is convenient to distingush between their two portions; and one may think of the air whirls alone, as reaching from one piece of iron to another, and by their shortening tendency or centrifugal force pulling the two pieces together.

The arrangement shown in Fig. 31 illustrates the kind of force exerted by a spinning elastic framework, along and perpendicular to its axis of rotation.

One can easily see this effect of a whirl in a tea-cup or inverted bell-jar full of liquid. Stir it vigorously and leave it. It presses against the walls harder than before, so that if they were flexible they would bulge out with the lateral pressure, and it raises the level of the peripheral liquid; moreover, it sucks down the top or free end of its axis of rotation, producing quite a depression or hollow against the force of gravity.

A cyclone model can be made by a horizontal disk with vanes spinning fast on a vertical axis. Paper and other light objects can be sucked up by the axis of the whirl of air below it. Or, as another illustration, make the apparatus sketched in Fig. 32.

Two circular boards joined by a short wide elastic tube or drum : a weight hung to the lower board, the top board hung from a horizontal whirling table, the

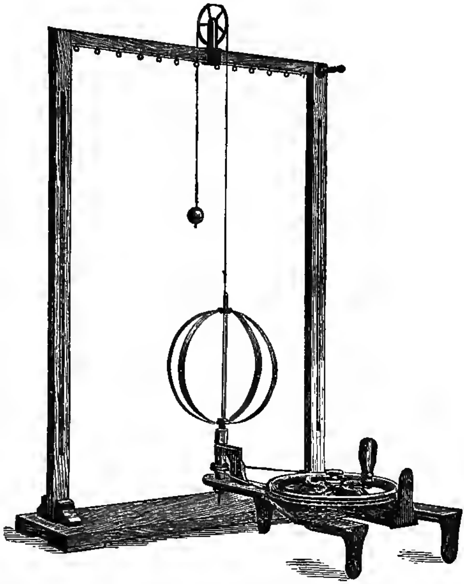


FIG. 31.—A "shape of the earth" model which, when whirled, exerts a tension along its axis, pulling up the weight attached to it, and a pressure at right angles, by reason of its bulging out. Its semicircular springs hold up a ring sliding on a vertical guide-rod.

drum filled with water, and the whole spun round. The weight is raised by the longitudinal tension ; the sides bulge out with the lateral pressure.

There is no need for the whole vessel to rotate. If the liquid inside rotates, the same effect is produced.

93. Imagine now a medium composed of a multitude of such cells with rotating liquid inside; let the cells be either very long, or else be joined end to end so as to make a chain—a series of chains side by side—and you have a picture of a magnetic medium traversed by a field of force. End-boundaries of the field will be dragged together, thus representing magnetic attraction; while sideways, the lines of force

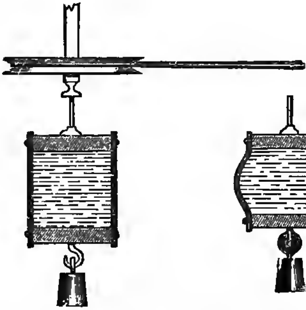
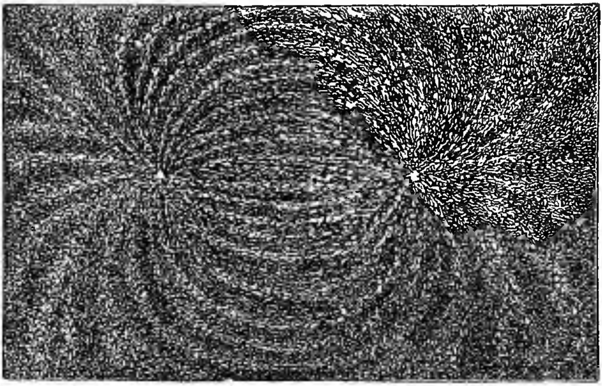


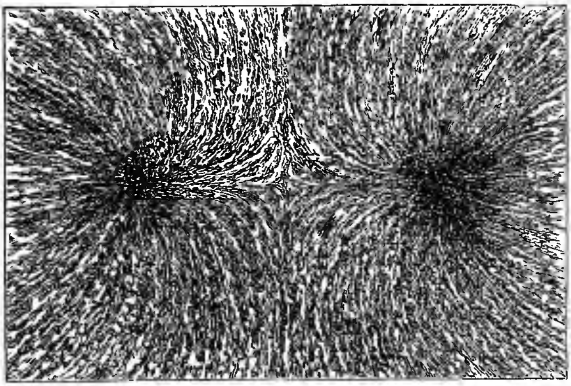
FIG. 32.—An elastic-walled cylindrical vessel full of liquid hanging from a whirling table, and, by reason of centrifugal force, raising a weight and bulging out literally when spun, thereby illustrating a tension along the axis of rotation and a pressure in every perpendicular direction. The vessel is sketched twice—first stationary and then spinnnig.

(axis of whirl) squeeze each other apart, thus illustrating repulsion. This is Clerk-Maxwell's view of an electro-magnetic medium, and of the mode in which magnetic stress, and magnetic attractions and repulsions between bodies, arise.

Wherever lines of force reach across from one body to another, those bodies are dragged together as if pulled by so many elastics (Fig. 33); but wherever lines of force from one body present their *sides* to lines of force proceeding from another body, then those bodies are driven apart.



Attraction.



Repulsion.

FIG. 33.—Attraction and Repulsion. The tension along the lines of force or axis of rotation drags the one pair of poles together; and the pressure in direction perpendicular to the axis of rotation, due to the centrifugal force of the whirls, drives the other pair apart.

CHAPTER X

MECHANICAL MODELS OF A MAGNETIC FIELD

First Representation of the Field due to a Current.

94. RETURN now to the consideration of a simple circuit, or, say, a linear conductor, and start a current through it ; how are we to picture the rise of the lines of force in the medium? how shall we represent the spread of magnetic induction? First think of the current as exciting the field (instead of the field as exciting the current, which may be the truer plan ultimately).

If we can think of electricity in the several molecules of the insulating medium as something connected like so many cog-wheels gearing into one another, and also gearing into those of the metal conductor, it is easy to picture a sideways-spread of rotation brought about by the current, just as a moving rack will rotate a set of pinions gearing into it and into each other (Fig. 34). But then half the wheels will be rotating one way, and half the other way, which is not exactly right.

How is it possible for a set of parallel whirls to be all rotating in the same direction, as in Fig. 35?

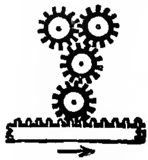


FIG. 34.

If there is any sort of connexion between them they will stop each other, because they are moving in

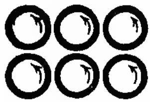


FIG. 35.

opposite directions at their nearest points: and yet, if there is no connexion, how can the whirl spread through the field?

Well, return to the old models by which we endeavoured to explain electrostatics, and think whether they will help us if we proceed to superpose upon them a magnetic whirl in addition to the properties they already possess. Looking at Figs. 5, 6, and 7A, we remember we were led to picture atoms and electricity like beads threaded on a cord. And these cords had to represent, alternately, positive and negative electricity, which always got displaced in different directions (see § 90).

We are forced to a similar sort of notion in respect of the wheels at present under discussion; in order that they may co-operate properly, they must represent positive and negative electricity alternately. If they *then* rotate alternately in opposite directions, all is well, and the electrical circulation or rotation in the field is all in one direction. Each wheel gears into and turns the next, and so the spin gets propagated right away through the medium, at a speed depending on the elasticity and density concerned in such disturbances.

In Fig. 36 the dotted lines may be taken to represent cords on which the axles of the wheels are supported,

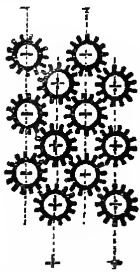


FIG. 36.—Rows of cells alternately positive and negative, geared together and free to turn about fixed axles. It is an extension of Fig. 7A.

with their axis of rotation at right angles to the cord; not after the fashion of simple and ordinary beads. The figure may then be looked at sideways and compared with Fig. 7A § 18, and also with Figs. 6, 8, and 13.

Any longitudinal shift of the cords—positive and negative always moving in opposite directions—constitutes an electric shear of the medium and must be accompanied by some rotation of the wheels;—very small if the shift is small and elastically resisted, as in a dieletric ; large up to any amount if the movement of the cords is continuous, constituting a steady current, as in a conductor. Thus a current of every kind, even a mere displacement, has some magnetic concomitant.

The case of an electric charge moving through the medium may be typified by the rack of Fig. 39. An uncharged body would be like a perfectly smooth bar, without a rack. The only grip or attachment known between matter and ether is afforded by an electric

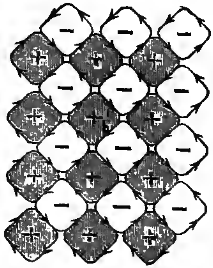


FIG. 37.—Section of a magnetic field perpendicular to the lines of force. Alternate cells rotating oppositely. Another mode of drawing Fig. 36.

charge; and even then its only result is to set up a magnetic rotation or an electric shear, not to induce locomotion after the fashion of a viscous drag. (Cf. Lecture V. below.)

It is not convenient at the present stage to ask the question whether the wheels represent atoms of matter or merely electricity. It may be that each atom is electrostatically charged and itself rotates, in which case it would carry its charge round with it, and thereby constitute the desired molecular current.

The apparent inertia of electricity would thus be explained simply enough, as really the inertia of the spinning atoms themselves; and the absence of any moment of momentum in an electro-magnet, as tested mechanically, would be equally explained by the simultaneous opposite rotation of adjacent atoms. A question may arise as to why the opposite molecules should have exactly equal opposite momenta; as they have, else a fluid magnetized medium would bodily rotate; and there may be other difficulties connected with a bodily rotation of electrostatically charged molecules; but we need not lay any stress on the idea that the matter itself need move. For our present purpose a spin of the electricity inside each atom, or even independently of any atoms, is quite sufficient. Besides, since magnetic induction can spread through a vacuum quite easily, the wheel-work has to be largely independent of material atoms.

If any difficulty is felt concerning the void spaces in Fig. 36, it is only necessary to draw it like Fig. 37, which does every bit as well, and reduces the difficulty to any desired minimum. The original model of Clerk Maxwell, referred to in § 155, is the basis of all these modes of representing the equations of an electro-magnetic field.

Representation of an Electric Current.

95. Now notice that in a medium so constituted and magnetized—that is, with all the wheel-work stationary and revolving uniformly—there need be

nothing of the nature of an electric current proceeding in any direction whatever. For, at every point of contact of two wheels, the positive and negative electricities are going at the same rate in the same direction; and this is no current at all. Only when positive is going one way and negative going the *opposite* way, or standing still, or at least going at a different rate, can there be any advance of electricity, or anything of the nature of a current.

A current is nevertheless able to be represented by mechanism such as that of Fig. 36 or 37: if the wheels are permitted to gear imperfectly and to work with slip. At any such slipping-place the positive is going faster than the negative, or *vice versâ*, and so there is a current there. This slip must be supposed passed on from one pair of wheels to the next in the direction of the slip, as oil or dust might be transferred. A line of slip among the wheels corresponds to a linear current.

Now a little attention here makes it quite plain that such a line of slip must always have a closed contour, in other words that electricity must flow in a closed circuit (§ 4). For, if only one wheel slip, then the circuit is limited to its circumference; if a row slip, then the direct and return circuit are on opposite sides of the row; while if a large area of any shape, with no slip inside it, is enclosed by a line of slip, then this gives us a circuit of any shape, but always closed. Understand: one is not here thinking of a current as analogous to a *locomotion* of the wheels —their axes may be quite stationary on this mode of thought—the slip contemplated is that of one *rim* on another; and any locomotion or progression there may be only relates to whatever it is which the rims push forward and hand on from one to another: actual electrons, as we are now beginning to think. This progress forward is typified by the rack of Fig. 39; it would be propelled by the spinning wheels.

Imagine all the wheels inside the empty contour of Fig. 38 to be rotating, the positive clockwise, the

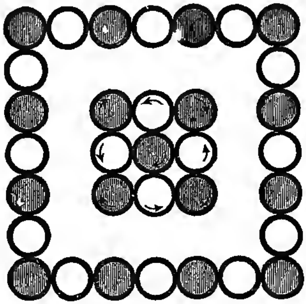


FIG. 38.—Diagram of a peripheral current partitioned off from surrounding medium by a perfect conductor, which transmits no motion, and therefore acts as a perfect magnetic screen. See also § 101, and Fig. 41. Shaded wheels stand for positive. The current is flowing clockwise round the outside of the inner nine wheels.

negative counter clockwise, and let all those outside the contour be either stationary or rotating at a different rate or in an opposite direction; then the boundary of the inside region is a line of slip, along which the positive rims are all travelling clockwise with the negative rims going the other way, and hence it represents a clockwise positive current round the inside of the empty contour.

But it may be said that the spin inside the contour, if maintained, must sooner or later rotate the wheels outside as fast as themselves, and that then all slip will cease. Yes, that is so, unless there is a complete breach of connexion at the contour, as in Fig. 38 there is. If the outer region has any sort of connexion with the inner one, the slip at its boundary can only be temporary—lasting during the era of acceleration.

Distinction between a Dielectric and a Metal, as affected by a spreading Magnetic Field.

96. In a dielectric the connexion between the atoms is definite and perfect. If one rotates, the next must rotate too; there may be instantaneous delay due to elasticity, but there is no slip between the geared surfaces. A dielectric is a case of cogged wheels like Fig. 36, a conduction-current in it is impossible.

But in a metallic conductor—say a metallic mass immersed in a growing magnetic field—the gearing is imperfect; it is a case of friction-gearing, with more or less lubrication and slip, so that turning one wheel only starts the next gradually—it may be very quickly but not instantaneously,—and there is a motion of a positive rim incompletely compensated by an equal similar motion of a negative rim while getting up speed; in other words, there is a momentary electric current, lasting till the wheels have fairly started.

In a *perfect* conductor all gearing is absent; the lubrication is so perfect that the atoms are quite free of one another, and accordingly a spin ceases to be transmitted into such a medium at all. The only possible current in a perfect conductor is a skin-deep phenomenon.[1] This is the case depicted in Fig. 38. (See also Chap. V. and § 104.)

A magnetized medium, of whatever sort, is thus to be regarded as full of spinning wheels, the positive rotating one way and the negative the other way. If the medium is not magnetized, but only magnetic—*i.e.* capable of being magnetized—it may be thought of either as having its wheels stationary, or as having them facing all ways at random ; the latter being probably the truer—the former the easier—representation, at least to begin with.

Whether the medium be conducting or insulating makes no difference to the general fact of spinning wheels inside it wherever lines of force penetrate it. But the wheels of a conductor are imperfectly cogged together ; and accordingly, in the variable stages of a magnetic field, while its spin is either increasing or decreasing, there is a very important distinction to be drawn between insulating and conducting matter. During the accelerating era conducting matter is full of slip, and a certain time elapses before a steady state is reached. A certain time may be necessary for the propagation of spin in a dielectric, but it is excessively short, and the process is unaccompanied by slip, only by slight distortion and recovery. (See §§ 103 and 159.)

97. As for strongly magnetic substances, like iron,

[1] It has been suggested to me that although no current can be excited inside a perfect conductor by the lateral action of the surrounding dielectric, yet that thermo-electric currents excited by contact force might be possible in its interior. I have ventured to surmise however (§ 62) that no thermo-electric forces can exist in a perfect conductor, because it cannot get a grip of the electricity.

nickel, and cobalt, one must regard them as constituted in the same sort of way, but with wheels greatly more massive, or very much more numerous, or both. The quantity which we have called permeability in §§ 82, 83, and denoted by the symbol μ, may now be thought of as physically equivalent to a density of the magnetic medium; so that substances with a large μ, like iron, have their magnetic mechanism or wheel-work exceedingly massive, but not spinning at any different rate.

Phenomena connected with a varying Current. Nature of Self-induction.

98. Proceed now to think what happens in the region round a conductor in which a current is rising: as partially described in Chapter V. Without attemptting a complete and satisfactory representation of what is going on, we can think of mechanical arrangements which have some close analogy with electrical processes.

Take first a system of wheel-work connected together and moved at some point by a rack (Fig. 39). Attend especially to alternate wheels, as representing positive electricity. The intermediate negative wheels are necessary for the transmission of the motion, and they also serve to neutralize all systematic advance of positive electricity in any one direction, except where slip occurs, but they need not otherwise be specially attended to.

Remember that every wheel is endowed with inertia like a fly-wheel (§ 88).

Directly the rack begins to move, the wheels begin to rotate, and in a short time they will all be going full speed. Until they are so moving, the motion of the rack is opposed, not by friction or ordinary resistance, but by the inertia of the wheel-work.

This inertia represents what is called self-induction, and the result of it is what has been called the "extra-current at make," or, more satisfactorily, the opposing E.M.F. of electro-magnetic inertia or self-induction.

Having once started the rack, so long as it moves steadily forward, the wheel-work has no further effect upon it; but, directly we try to stop it, we find it cannot be stopped suddenly without great violence: its motion is prolonged for a short time by the inertia of the wheel-work, and we have what is known as the "extra-current at break."

99. If the rack is for a moment taken to represent the advancing electricity in a copper wire, then the diagram may be regarded as a section of the complete field: the complete field being obtained from it by rotating the diagram (Fig. 39) round the axis of the rack. Imagining this done: we see that the axis of each wheel becomes prolonged into a circular core, and each wheel into a circular vortex ring surrounding the rack, and rolling down it as it moves forward, as when a stick is pushed through a tight-fitting umbrella-ring held stationary (see Fig. 30, B, p. 167).

As one goes further and further from the rack the lengths of the vortex cores increase, but there is only a given amount of rotation to be shared among more and more stuff, hence it is not difficult to imagine the rate of spin diminishing as the distance increases, so that at a reasonable distance from the conductor the medium is scarcely disturbed. A slightly magnetized medium has to be considered—on this mode of representation—as if it consisted of a few spinning and many quiescent wheels: an unsatisfactory feature of the model.

100. To perceive how much rotation of the medium is associated with a given circuit, one must consider

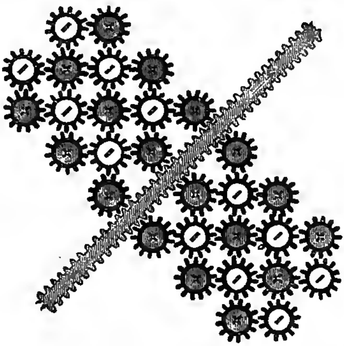


FIG. 39.—A provisonal representation of a current surrounded by dielectric medium, either propelling or being propelled. Section through the wire. Compare Fig. 30, B.

the shape of its contour—the position of the return current.

Take first a long narrow loop and send a current up one side and down the other. The rotations belonging to each are superposed, and though they agree in direction for the space enclosed by the loop, they oppose each other outside, and so there is barely any disturbance of the medium outside such a looped conductor; very little dielectric is disturbed at all, and accordingly the inertia or self-induction is very small (see Fig. 40).

If the loop opens out as as to enclose an area, as the centrifugal force of the wheels will tend to make it do, then there is a greater amount of rotation, a greater moment of momentum inside it, and accordingly its self-induction is increased. The axis of every wheel is, however, continuous, and must return outside the

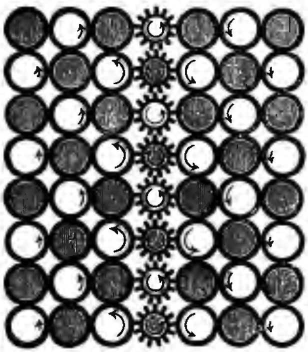


FIG. 40.—Diagram of a direct and return current close together, showing distribution of rotation and of slip in the thickness of the conductor, and in the dielectric between. The dielectric outside is very little disturbed. The smooth wheels represent a metallic conductor, the cog wheels represent a thin layer of dielectric between the direct and return part of the metallic circuit.

For two currents going in the same direction, see Fig. 44.

loop: so the outside region is somewhat affected by rotation, but of a kind opposite to that inside.

101. Figs. 38 and 41 show the state of things for a closed circuit conveying a current. The free space in Fig. 38 represented a perfect conductor, or perfect breach of connection. Along the inner boundary of this space positive electricity was seen streaming in the direction of the arrows, and it may be streaming

quite independently on the outer boundary also, but nothing happens in the interior of the perfect conductor—which was therefore only represented by empty space.

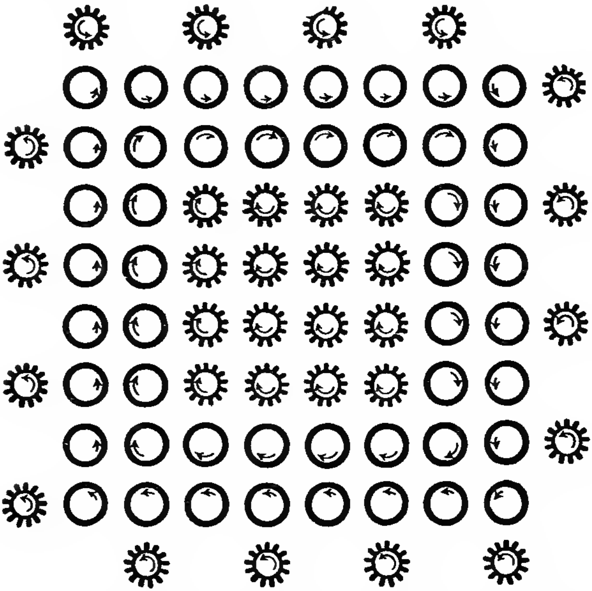


FIG. 41.—Diagram of simple conducting circuit like a galvanometer ring, with the alternate connecting wheels omitted. The same number of dielectric wheels are drawn outside as inside, to indicate the fact that the total spin is equal inside and out, though the outside is so spread out as to be much less intense. The diagram shows a clockwise current flowing steadily round the ring; with the accompanying distribution of magnetism. Section in the plane of the ring. The length of the arrows must be attended to as well as their direction.

The corresponding portion in Fig. 41 is intended for an ordinary conductor, full of wheels capable of slip. And slip in this case is a continuous necessity, for the rotation on one side of the conductor is in an opposite direction to that on the other side; so the atoms of the conductor have to accommodate themselves as best they can to the conditions, some of them rotating one way, some the other, and some along a certain neutral line of the conductor being stationary. If we imagine a number of square-contoured closed circuits of thread, of regularly increasing size, surrounding the groups of wheels in Fig. 41 symmetrically—something like the lettered contours of Fig. 43—we shall see that the inner one, being totally surrounded by cogged wheels, will not move; since it is urged equally in opposite directions by the wheels inside it and the wheels outside it. But the next larger contour will travel forward clockwise, since the inner wheels which drive it forward are rotating faster than the outer ones which push it back: and, as always, we assume the force of propulsion to be proportional to the speed, in accordance with our interpretation of Ohm's law. The still larger thread contour will likewise be pushed forward in the same direction, and so will the thread enclosing all the nearly smooth or conductor-representing wheels. But outside, in the outer dielectric, there will be no progressive movement, any more than there was in the interior, and for the same reason.

Specifying the rim speed inside all the metal contours as u_0, that outside all as u'_0, and the rim speed of successive metal contours as u_1, u_2, etc., we should have in general $u_0 - u_1$, slightly greater than $u_1 + u_2$; this slightly greater than $u_2 + u_3$, etc.; and slightly the least current, namely, $u'_0 - u_n$ on the outside of the ring, where the journey is furthest.

But if we consider the simple case of a *thin* wire contour with uniform distribution of current throughout, we shall have

$$u_0 - u_1 = u_1 + u_2 = u_2 + u_3 = \dots\dots = u_0 - u_n$$

wherefore all the conductor *u*'s are then equal, being equal to $\frac{1}{3}$ of u_0; and the neutral line of no spin is in the middle of the wire.

In any case the annular space, filled by what represents the conductor in the diagram, is characterised by a progressive tendency round and round the ring, throughout its thickness; and this is the easiest mode of thinking of the electric current, represented by the slipping of the wheels and corresponding to the given distribution of magnetism.

If a conductor is straight and infinitely long, the neutral line of no rotation is in the middle. If it be a loop, the neutral line is nearer the outside than the inside, because the rotation of the medium inside is the strongest. If the loop be shut up to nothing, the neutral line is its outer boundary, or nearly so (Fig. 40). If, again, the circuit is wound round and round the core of a ring, as string might be lapped upon a common curtain-ring so as to cover it, then the axes of whirl are wholly enclosed by the wire, and there is no rotation outside at all. (See Fig. 47.)

Fig. 42 shows a section of this last-mentioned condition, and here the wheels of the dielectric outside are not rotating at all. The inside is revolving, it may be furiously, and so between the inner and outer layers of the conductor we have a great amount of slip and dissipation of energy—in other words, a strong current, but the outside is not revolving at all: the magnetism is wholly interior and annular.

102. The process of slip which we have depicted goes on in all conductors conveying a current, whether steady or variable, and in fact *is* the current. The slip is necessarily accompanied by dissipation of energy and production of heat: only in a perfect conductor can it occur without friction. In a steady current the slip is uniformly distributed throughout the

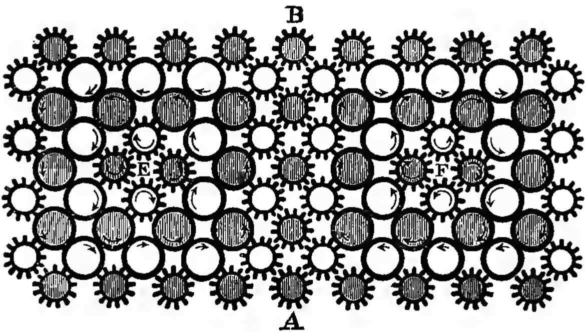


FIG. 42.—Section of a closed magnetic circuit, or electric vortex-ring, or hollow bent soleooid like Fig. 29. enclosiog an anchor-ring air space; the axis of the ring being A B. the section of its core being E and F. The lengths of the arrows indicate the intensity of the spin, *i.e.* of the magnetic field, which is a maximum at the middle of each section and nothing at all outside. If the core contains iron instead of air, its wheels have to be from 100 to 10,000 times as massive: slipping wheels, if of solid iron; cogged wheels, if a bundle of fine varnished iron wires. Cf. Fig. 47.

section of the conductor; in the variable stages it is unequally distributed, being then more concentrated near the periphery of the wire; as the diagrams endeavour to show, and as has been described in § 43.

When a current is started in a wire, the outer layers start first, and it gradually though very quickly penetrates to the axis. Hence the lag is greater as the wire is thicker, and also as it is made of better conducting substance. If it is of iron, the massiveness of the wheels is so great that the lag is much increased, and the spin momentum of its outer layers is great enough to produce the experimental effects discovered by Prof. Hughes[1]; but we are not to suppose that the velocity is greater inside a magnetic material, otherwise the model would suggest current phenomena which have no existence.

One must never confuse the *slip* with the *spin*. Slip is current, spin is magnetism. There is no spin at the axis of a straight infinite wire conveying a current, and the spin occurs in opposite directions as you recede from the axis either way; arranging itself in circular vortex cores round the axis (Fig. 30, B). But the slip is uniformly distributed all through the wire, as soon as the current has reached a steady state. The slip is wholly in the direction of the wire, and is of a locomotive character. The axes of spin are all at right angles to that direction, and are stationary.

[1] Address to Society of Telegraph Engineers, January 1886.

CHAPTER XI

MECHANICAL MODELS OF CURRENT INDUCTION

Rise of Induced Current in a Secondary Circuit.

103. TO study the way in which a magnetic field, excited in any manner, spreads itself into and through a conducting medium, look at Fig. 43, and suppose the region inside the contour A B C D to be an ordinary conducting region—that is, full of wheels imperfectly geared together, and capable of slip.

Directly the rack begins to move, all the wheels outside A B C D begin to rotate, and quickly get up full speed. The outer layer of wheels inside the contour likewise begins to rotate, but not at once; there is a slight delay in getting them into full motion. For the next inner layer the delay is rather greater, and so on. But ultimately the motion penetrates everywhere equally, and everything is in a steady state.

But while the process of starting the wheels was going on, a slip took place round the contour A B C D, and round every concentric contour inside it; the periphery of the positive wheels moving in a direction opposite to that of the wheels in contact with the rack, and so suggesting the opposite induced current excited at "make" in the substance of a conductor near a growing current, or, generally, in an increasing magnetic field.

The penetration of the motion deeper and deeper, and the gradual dying away of all slip, illustrate also the mode in which this induced current arises and gradually dies away; becoming *nil* as soon as the

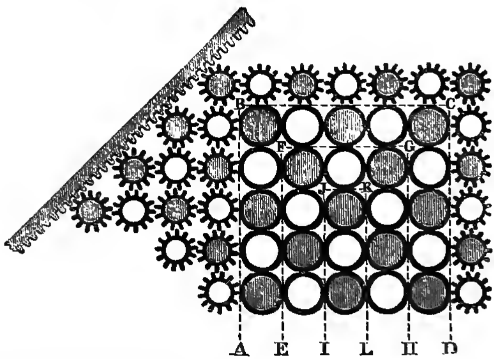


FIG. 43.—Diagram illustrating the way in which an induced current arises io a mass of metal immersed in an increasing magnetic field : also how it decays. A B C D is the boundary of the mass of metal. The dotted lines A B C D, E F G H, I J K L are successive lines of slip.

magnetic field (*i.e.* the rotation) has penetrated to the interior of all conductors and become permanently established there as elsewhere.

Suppose the motion of the rack now stopped: all the *cogged* wheels stop too, though it may be with a jerk and some violence and oscillation due to their momentum; but those inside the contour A B C D will continue moving for a little longer. The outside layer of this region will slip in such direction as to illustrate the direct induced current at "break," and will begin to stop first; the slip and the stop will then gradually penetrate inwards, just as happened during the inverse process, until all trace of rotation ceases. This inverse slipping process is the direct induced current at "break."

Let us imagine threads round the successive lettered contours of Fig. 43, rubbed in a definite manner by alternate wheels,—all those of one sign,—as we did in connexion with Fig. 41, and then suppose the rack of Fig. 43 to start moving in a downward slanting direction;—the threads would all experience a clockwise impulse forward, the outer one A B C D first, then the next E F G H, and so on. But as soon as the interior is fully reached, all motion of the threads will cease, notwithstanding the continued motion of the rack, because now all the wheels are rotating at the same pace.

This condition of electrically generated magnetism, with cessation of induced current at make, will last until the rack stops or slackens in speed. Whenever this happens, the threads will be moved counter-clockwise a certain amount; until, in the simplest case, they regain their initial position soon after the rack has stopped. This simplest case obtains when the conductor contains nothing disobedient to Ohm's law—nothing like an air-gap or other valve-like device.

In that last more complex case, the ultimate displacement of each thread may depend on whether the force of propulsion is adequate to overcome equally-well both-ways whatever obstacle it encounters in its course. If the force is not equally effective both ways there will be a permanent shift or displacement of electricity in the circuit, due to the valve-like action; and a Leyden jar might thereby become charged. In what I have called a pertinacious current, this action is employed to maintain currents of immense electromotive force—which can be applied to keep air electrified for agriculture, for deposition of fume, and for other practical purposes. (*Proc. Roy. Inst.*, March 1905.)

104. Through a perfect conductor the disturbance could never pass, for the slip of the dielectric wheels on its outer skin would be perfect, and would never penetrate any deeper. A superficial current lasting for ever, or rather as long as the magnetic field (the rotation of the dielectric wheels) lasts, is all that would be excited, and it would be a perfect magnetic screen to any dielectric beyond and enclosed by it. Such a perfect conductor is represented by the empty space in Fig. 38. A magnetic field or spin excited outside that space would never reach the set of wheels enclosed and protected by it; and *vice versâ* (§ 153).

105. It will now be perceived that a fly-wheel in rotation is the mechanical analogue of magnetism, or more definitely of a section of a line (or tube) of magnetic force; and that a brake, either an accelerating or retarding brake, applied to such a fly-wheel,—with consequent slip, dissipation of energy, and production of heat,—is a mechanical analogue of an electric current.

A magnetic field is to be regarded as full of geared elastic vortices or whirls, some of which are cogged together, so to speak, while others are merely pressed together by smooth rims. It is among these latter that slip is possible, and it is in the regions occupied by these that currents exist; the energy dissipated here being transmitted through the non-slippery or dielectric regions from the source of power, just as energy is transmitted from a steam-engine through mill-work or shafting to the various places where it is dissipated by friction. (Refer back to §§ 42—44.)

Transfer of Energy to a Distance.

106. Let us now try to understand the use of a telegraph wire from this point of view. Given the means of exciting a magnetic field at one place, how can we transmit it to another place so as to move magnetic needles or make other signals there? The first idea of a method might be that inasmuch as no perfect conductor, or absolute magnetic screen, intervenes, the field of any magnet is infinite in extent, and consequently already reaches the distant place. Have *here* a long iron bar capable of being magnetized and demagnetized at pleasure, and have *there* a very sensitive magnetometer,—and the thing is done. I see no reason why, under certain circumstances, this mode of signalling without wire over short distances should not be attempted. But an obvious objection to it is that the effect produced by a given magnet varies inversely with the cube of its distance; so that, a few miles away, the force of a magnet, even several yards long, is terribly weak. And even a coil of wire several acres in area has not very much distant power:

though something can be done by this means, when the effect is collected by another similar coil.[1]

The next idea might be to carry some of the magnetic lines of force to the distant place by means of an iron rod or wire. A soft iron wire transmits them so much better than air, that an arrangement of a very elongated loop of iron, with a magnetizing coil upon it at one end, and a receiving coil upon it at the other, might serve to establish some connexion between the two places, and enable primary currents at this end to produce secondary induced currents at that. This would be a magnetic telegraph in which a magnetic whirl only is propagated along the wire, and a current is excited by it at the distant place.

The current loop and the magnetic loop are, however, reciprocal; and the next idea might be that instead of a long magnetic loop with little current loops threading it at either end, it might be better to have a long current loop with little magnetic loops threading it at either end;—and that is exactly what we have in the electric telegraph.

It is a better plan for this reason. Iron conducts magnetism, say, a thousand times better than air, but by no means infinitely better; hence from a long loop of iron a great many lines of force would leak, and would take a shorter circuit back through air. But copper wire conducts electricity almost infinitely better than gutta-percha or porcelain. That is why an electric telegraph is better than a magnetic. Lead

[1] Lodge, on "Magnetic Space-Telegraphy," *Proc. Inst. E. E.* Dec. 1898.

or German silver conducts a million times better than dilute sulphuric acid, and yet it would be very unsatisfactory to have to signal through an ocean of dilute acid with an uncovered lead or German silver wire immersed in it. The percentage of loss in the case of a corresponding magnetic circuit of iron would be far greater still.

107. But now what is it precisely that the wire of an electric telegraph does? By its means a magnetic field at this end is made to excite a magnetic field at the other end, with very little loss; it is nearly all concentrated upon the other end by means of the wire. Somehow the wire enables us to transmit the magnetic effect exactly in the direction we wish, and to reproduce it where we please.

It is not very easy to draw a diagram of the arrangement, because it entails such a number of wheels, and because the diminution of spin with distance is not well represented by them. But the diagram may be imagined thus:—

Let the rack in Fig. 39 be regarded as an infinitesimal portion of a long circuit extending to New York and back. At some distant point, by means of a battery, or a dynamo, or any other electromotive arrangement, excite in a few of the wheels the motion which in Fig. 39 would occur if the rack were pushed. Out and away through the dielectric the motion transmitted by the cog-wheels spreads, at a pace which for the present we may consider infinite, but which we shall learn later is the velocity of light. At length it reaches the rack, which is immediately propelled forward. In the wire, and in the wire only, exists the current, surrounded by a strong magnetic field. Right along the wire flashes the vortex-like motion; all the way along it is surrounded with rings of whirl, as in Fig. 30, B; and by concentrating some quantity of this whirl into small compass at the distant station, a visible motion or signal is produced.

That is the function of the wire, it guides the effect transmitted through the dielectric. The wire transmits the electricity only, not any energy—the insulating sheath it is which transmits all the energy: the wire directs it on its way, by holding asunder the mutually opposing gearing of the dielectric through which the disturbance arrives.

Later on we shall learn that the gearing in a dielectric is not rigid, but elastic, and that this is why a certain time is required for transmission—why a definite velocity of transmission exists. We may be said to have learnt it already, indeed; and we have also learned that some dielectrics are less rigid than others—gutta-percha less than air, for instance (see §§ 16 and 23),—and accordingly transmit the disturbances more slowly; but always, as we shall find, with the velocity of light appropriate to that particular medium, so far as the dielectric alone is concerned (§§ 133 *et seq.*).

Mechanical Force acting on a Conductor conveying a Current.

108. In Fig. 41 the conducting portion of a circuit is shown with its appropriate opposite rotations on either side of it. Now superpose a uniform rotation

all in one direction upon this, so as to increase the spin on one side of the conductor and diminish it on the other; in other words, immerse the circuit in a magnetic field. Immediately the extra centrifugal force on one side will urge any movable part of the conductor from the stronger to the weaker portion of the field. And whether there be any movable portion or not, the whole circuit will *tend* to expand if the superposed magnetic whirl agree in direction with the whirl already inside; while it will tend to contract if the superposed whirl agree with that outside.

The field for a direct and return circuit may be similarly drawn by superposition of their separate whirls (see Fig. 40). In this case there is strong centrifugal force of the whirl between the wires, while outside there is next to no whirl at all. Hence the wires tend to get driven apart; and so it becomes evident why a circuit tends to expand so as to enclose the largest possible area, even if no other magnetic field than its own be acting on it. The circuit shown in Fig. 41, for instance, tends to expand even without any superposed magnetic field, simply because the whirl inside is more concentrated, and therefore more intense, than the whirl outside.

In Fig. 44, on the other hand, the conductors are carrying currents in the same direction, and the whirl is greater in the region outside them (above and below in the diagram) than it is between them; hence they tend to be pressed together,—a fact which is expressed briefly by saying that 'similar currents attract.'

109. As for the effect of iron introduced into a

circuit, it brings into the region of space it occupies some hundred or thousand times as many lines of whirl as were there before, and these naturally contribute mightily to the effects, both those exhibiting mechanical force and those exhibiting inertia.

When one says, as roughly one may do, that iron brings 1000 fresh lines into the field, one means that, for every whirl otherwise excited, 1000 more are faced

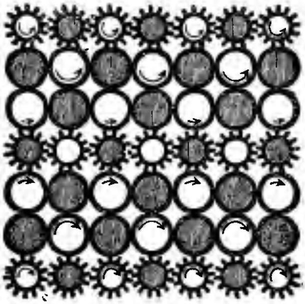


FIG. 44.—Two parallel conductors conveying equal currents in one direction and getting pushed together by the centrifugal force of the outside whirls, no whirl existing between them. The length of the arrows again suggests the distribution of magnetism in the conductors. Fig. 40 showed the correlative repulsion of opposite currents.

round in the iron. And this process goes on while the field is increasing in strength until the total number of whirls in the iron begins to be called upon; when this point is reached the rate of addition is not maintained, and the iron is said to show signs of saturation. Ultimately, if ever all its whirls were faced round, the iron would be quite saturated; but long before this point is reached another cause is likely to make itself felt, viz. the falling off in the strength of the whirls already faced round, by the action of the strong magnetic induction, which is all the time acting so as to weaken the iron currents so far as it is able. And thus at a certain point, hitherto unreached by experiment, the iron may not only fail to increase the strength of the field any more, but may actually begin to diminish it. That is to say, its permeability may conceivably and exceptionally become less than 1, as if it were a diamagnetic substance (cf. § 81).

The easiest way to picture the effect of iron is to think of its wheels as some hundred or thousand times as massive as those of air, so that their energy and momentum are very great although their speed is the same (cf. § 97).

That which is commonly called magnetic permeability, and denoted by μ (§ 82), may in fact be thought of as a kind of inertia, an inertia per unit volume; in other words, a *density*—an ethereal density; though how it comes to pass that the ether inside iron is endowed with so great inertia one cannot say. Perhaps it is that the iron atoms themselves revolve with the electricity (§ 94), perhaps it is something quite different. Whatever the peculiar behaviour of iron, nickel, &c., be due to, it must be something profoundly interesting and important as soon as our knowledge of their molecular structure enables us to perceive its nature.

Representation of an Electrostatic Field again, and superposition of it on a perpendicular Magnetic Field

111. An electrostatic strain is, we know, caused by a displacement of positive electricity one way along

the lines of force, and by an equal displacement of negative the other way. The process was indicated crudely in Fig. 7A; we may now represent it rather more fully with the help of our elastic cells by Fig. 46.

Here the positive cells have been pulled one way, the negative the other way; and when the distorting force is removed, the medium tends to spring back to its normal condition, exerting an obvious tension on

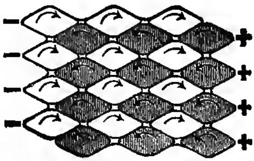


FIG. 46.—A portion of an electrostatic field between two oppositely charged bodies with its lines of force going from right to left, and showing a tension along and a pressure at right angles to them, due to the elasticity of the cells (which elasticity may be due to their containing fluid in a state of whirl, see § 156). Magnetic lines of force perpendicular to the paper are also shown in section. While this magnetic field was being excited and propagated from below upwards, a slight strain would be produced in the elastic cells, like but immensely less than that shown; as contrasted with its normal condition (Fig. 37). Conversely, while this electrostatic strain was being produced, the postitive whirls would be infinitesimally quickened and the negative ones retarded during the displacement, thus producing a minute magnetic effect. If the medium is not magnetized, the whirls are not necessarily absent, only faced all ways.

bodies attached to it in the direction of its lines of force, its elongated direction, and an obvious pressure in all perpendicular directions, its compressed directions.

Now, if all the cells are full of parallel whirls, as in the preceding magnetic diagrams, it is not improbable that this electrostatic distortion or "shear" of the medium may affect its magnetic properties slightly, and that, if the direction of electrostatic strain were rapidly reversed, a small magnetic oscillation would also ensue; but the exact details of these mutual actions are difficult to specify at present.

There is a point here that deserves attention. If the cells in Fig. 46 represented a set of stretched elastic threads pulling the opposite boundaries (which may be thought of as metal plates) together, motion of the plates to or fro would either relax or increase the tension in the threads; but in the case really intended—that of the strained electric medium—it is not to be supposed that motion of the plates would either relax or intensify the strain in each cell.

If the plates move farther apart, more cells are thrown into the field; but so long as the field intensity is uniform—which will be true except near the edges of the plates when they are big compared with their distance apart—the strain of each cell is unaltered. So also when the plates move nearer together, they wipe out the strain from one cell after another, but leave the rest unchanged. Whenever lines of force are spoken of as elastic threads, this peculiarity, in which the analogy breaks down, must be remembered; otherwise the energy under different conditions will be wrongly estimated.

Disruptive Discharge.

112. Disruptive discharge may be thought of as a pulling of the shaded cells violently along past the others; the process being accompanied by a true disruption—a sort of electrolysis—of the medium, and a passage of the two electricities in opposite directions along the line of discharge.

Consider the locomotion of any one horizontal row of shaded cells in Fig. 46 during the occurrence of such a disruption of the medium. The row of cells slides towards the right, and, as it slides, the spin of the negative cells above it is retarded while that of those below it is accelerated; consequently a true magnetic effect is produced, just like that accompanying a current, in rings round the line of locomotion; and so a disruptive discharge has all the magnetic properties of a current.

Effects of a Moving Charge.

113. This locomotion of a set of positive cells, or of negative cells the other way, as just considered, is very near akin to the motion of a charge through a dielectric medium.

When a charged body moves along with extreme rapidity, it can be thought of as exciting a rotation in the cells most closely in contact with it, greater than that which it excites in the opposite kind of cells; and it thus produces the whirl proper to a magnetic field. It behaves like the rack in Fig. 39. Thus does a moving charge behave just like a current of a certain strength.

It may be, indeed, that this is the customary way of exciting a voltaic current; for the chemical forces in a cell cause a locomotion of charged atoms, and thus set up a field, which, spreading out in the way Prof. Poynting has sketched (§ 42), reaches every part of the metallic circuit and excites the current there.

Electrostatic Effects of a Moving or Varying Magnetic Field.

114. Just as we have seen that a moving or varying electrostatic field may produce slight magnetic effects, it can be perceived that a moving or varying magnetic field brings about something of the nature of an electrostatic strain.

For a spreading out field is continually propagating the rotation on from one layer of wheels to the next. If there is any slip, we thus get induced currents (Fig. 43), and the rate of propagation is comparatively slow, being a kind of diffusion; but even if there is not any slip, yet unless the wheel-work is absolutely rigid, the rate of propagation will not be infinite. The actual rate of propagation is very great, which shows that the rigidity or elasticity of the wheels is very high in proportion to their inertia; but it is not infinite, and accordingly the propagation of rotation is accompanied by a temporary strain. One part of the field is in full spin, another more distant part is as yet unreached by the spin; between the two we have the region of strain, the wheel-work being distorted a little while taking up the motion. Thus does a spreading out magnetic field cause a slight and temporary electrostatic strain, at right angles both to the direction of the lines of force and to the direction of their advance.

Generation of a Magnetic Field. Induction in Closed Circuits.

115. Picture to yourself an unmagnetized piece of iron: its whirls are all existent, but they are shut up

into little closed circuits, and so produce no external effect; magnetize it slightly, and some of the closed circuits open out and expand, with one portion of them in the air. Magnetize it strongly, and we have a whole set of them opened out into vortex cores, still with the whirl round them, constituting the common magnetic lines of force. There is no need to think of iron and steel in this connexion. In air or any substance the whirls are still present, though much fewer or feebler, and their axes ordinarily form little closed circuits—it may be inside the atoms themselves.

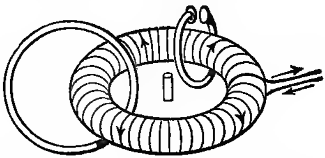


FIG. 47.—Closed magnetic circuit like Fig. 42, with a single-ring secondary circuit, aod another open secondary loop; also with a short conducting-rod standing up in it.

But wrap a current-conveying wire round them, and at once they open out into the lines of force proper to a circular current.

Again, think of an iron ring, or a hank of iron wire as bought at an ironmonger's: wrap a copper wire several times round it, as each segment of a Gramme ring is wound (Fig. 47), and pass a current. The closed vortices in the iron at once expand: a portion of each flashes out and across the air-space inclosed by the ring (not by any means confining itself to a plane, of course), and enters the ring on the opposite side, having expanded and travelled laterally across the intervening space; so that, directly the current is steady, the lines all lie inside the iron again, but now inclosing an area—the area of the ring—instead of being shut up into infinitesimal links. It may be said that the iron is still apparently unmagnetized; for its lines of force still form closed contours within it, and none protrude any part of themselves into the air, except for irregularities. But in reality it is highly and permanently magnetized, round and round in itself: the magnetism being not easy to get out of it again, except by judiciously graduated alternating currents.

It is now like one great electric vortex ring, instead of like a confused jumble of microscopic ones. Its section was shown in Fig. 42. (See also Appendix (*d*) and (*n*).)

During the variable period, while the current is increasing in strength, or while it is being reversed, the whole region near the ring is full of myriads of expanding lines of force, flashing across, broadside on, from one side of the iron to the other, and there stopping. It is the presence of these moving lines, changing rapidly from a "simply-connected" into a "multiply-connected" space, or *vice versâ*, which causes the powerful induced currents of "secondary generators."

In every case of varying magnetic field, in fact, we have lines moving broadside on, propagating their whirl, and more or less disturbing the medium through which they move. They never can move end-on nor thread a needle like a thread, for they never have free ends: they are always closed curves; they can only move laterally.

Next consider a moving or spinning magnet. Its lines travel with it, and, being closed curves, they also must move broadside through the field ; so that in this case we may expect just the same effect as can be obtained from a varying magnetic field.

If a broadside-moving line of force cut across a conductor, its motion is delayed, for its wheels slip and only gradually get up a whirl inside the ill-geared substance ; thus, as we know, causing an induced current (see § 103).

If a conducting circuit is looped with the iron ring previously mentioned, as a snap hook is looped with an eye, so as to make what may be called a secondary, like the circle in Fig. 47, then every expanding vortex, while the ring is being magnetized, has necessarily to cut through the conductor or secondary circuit once and no more, no matter what its shape or size. The total or integrated E.M.F. induced in the secondary is therefore perfectly definite in this case, being proportional to the total number of magnetic lines transferred across the open space near the iron ring. At every exact reversal this would be just twice the number of lines of magnetic induction circulating inside the core of the ring. If the secondary consists of a wire of several turns, with joined ends, then this same E.M.F. is induced in each turn of wire ; so the previous result has now to be multiplied by the number of turns made by the secondary looped round the core of the ring.

Instead of supposing a closed conducting secondary circuit, imagine an open one, likewise shown in Fig. 47 : there is still an E.M.F. in it, though it is slightly less than before, because a few of the expanding lines flash through the gap and produce no effect; but there can be now no continuous current, only an accumulation of opposite charges at the gap terminals during the impulse; so while the ring is being magnetized and demagnetized, electricity must surge to and fro in the conductor as water surges to and fro in a suddenly tilted trough, and a small condenser attached to the free ends will be alternately charged and discharged.

In another case, the gap might become so large that nothing is left but a short rod (Fig. 47): in this also similar electric oscillations would occur.

But now suppose no secondary conductor at all; nothing but dielectric inclosed by the ring. In the dielectric itself an electric displacement must be excited every time the magnetism of the ring is reversed. The displacement will be in one direction during rise of magnetism, and in an opposite direction during reversal of magnetism. A charged body delicately suspended within the ring may feel the effect of the minute electrostatic strain so magnetically produced,[1] and a needle with oppositely charged ends, if light enough, must be infinitesimally deflected.

116. To see the *mode* in which an electrostatic displacement arises in the space embraced by the ring we have only to turn to Fig. 42, and look at the set of wheels along the line A B separating one half the section from the other. They cannot steadily rotate either way, for they are urged in opposite directions by

[1] For the experimental detection of these effects, see Lodge, *Phil. Mag.* June 1889.

the two halves; in other words, there is no magnetic field anywhere outside such a ring, as is well known; but the wheels of one sign are being urged in one direction by the spin inside the ring; consequently there is a slight electric displacement along the axis of the ring, which lasts as long as thc ring is magnetized, and recovers or reverses directly the magnetism ceases or is reversed. This is the only effect which changes in the ring's magnetism produce in the surrounding dielectric—a slight and almost imperceptible electric field.

PART IV

RADIATION

CHAPTER XII

RELATION OF ETHER TO ELECTRICITY

117. So far as we have been able to understand and explain electrical phenomena, it has been by assuming the existence of a medium endowed with certain mechanical or *quasi*-mechanical properties, such as mobility (§ 12), incompressibility or infinite elasticity of volume (§ 5), combined with a certain amount either of plasticity or of finite elasticity of shape (§ 9). We also imagined the medium to be composed of two opposite constituents, which we called positive and negative electricity respectively (§ 90), and which were connected in such a way that whatever one did the other tended to do the precise opposite. Further, we were led to endow each of these constituents with a certain amount of inertia (§§ 38 and 88), and we recognized something of the nature of friction between each constituent and ordinary matter (§§ 28 and 63).

Broadly speaking, we may say—

(1) That *friction* makes itself conspicuous in the discussion of current-electricity or the properties of conductors; and that the laws of it are summarized in

the statement known by the name of Ohm, viz. that the current through a given conductor is proportional to the force that drives it, or that the opposition force exerted by a conductor upon a current is simply proportional to the strength of that current.

(2) That *elasticity* is recognized as necessary when studying the facts of electrostatics or the properties of insulators—electric displacement and recoil, or charge and discharge: the laws having been studied by Faraday, and the relative pliability (or shearability, if there were such a word for the reciprocal of rigidity or elasticity of figure) of the medium in different substances being measured and stated in terms of that of empty space as their specific inductive capacity, κ; or, rather, for numerical specification, as the ratio κ/κ_0.

(3) That *inertia* is brought into prominence by the facts of magnetism, studied chiefly perhaps by Lord Kelvin; who has called the relative density of the medium in different substances their magnetic 'permeability' or magnetic inductive capacity, μ; the ratio of its value for any substance to its value for space being strictly denoted by μ/μ_0.

(4) That the *doubleness of constitution* of the medium—its being composed of two precisely opposite entities—is suggested by the facts of electrolysis, by the absence of mechanical momentum in currents and magnets, and by the difficulty of otherwise conceiving a medium endowed with rigidity which yet is perfectly fluid to masses of matter moving through it.

118. With the hypothesis of doubleness of constitution this last-mentioned difficulty disappears.

The ether as a whole may be perfectly fluid, and allow bodies to pass through it without resistance, while its two components may be elastically attached together and may resist any forces tending to separate them, as if it possessed the characteristic rigidity of a solid. It is like the difference between passing one's hand through water, and chemically decomposing it; it is like the difference between waving a piece of canvas about, and tearing it into its constituent threads.

To put the matter boldly and baldly: we are familiar with the conceptions of matter and of ether, and it is known that the two things react on each other in some way, so that although a free portion of the ether appears to move freely through matter, yet another portion appears to move with matter as if bound to it. This mode of regarding the facts is as old as Fresnel (§ 184). We now proceed a step farther, and analyze the ether into two constituents—two equal opposite constituents—each endowed with inertia, and each connected to the other by elastic ties: ties which the presence of gross matter in general weakens and in some cases dissolves. The two constituents are called positive and negative electricity respectively; and of these two electricities we imagine the ether to be composed. The tie between them is dissolved in metals: it is relaxed or made less rigid in ordinary insulators. The specific inductive capacity of a substance means the reciprocal of the rigidity of its doubly constituted ether. The measure of this rigidity is probably $4\pi/\kappa$.

The neighbourhood of gross matter seems also to renders ether more *dense*. It is difficult to suppose that it can really condense an incompressible fluid; but it may load it, or otherwise modify it, so as to produce the *effect* of increased density. In iron this internal ethereous density reaches its highest known value, and in all substances the density or inertia per unit volume of their ether may be denoted by $4 \pi \mu$ and is proportional to their magnetic permeability. The hypothetical ethereous density here spoken of is not to be confused with the familiar density of ordinary material. It cannot be estimated by weighing.

119. Let it be understood what we are doing. In Part I. we discussed effects very analogous to those which would be produced by an elastic incompressible medium (roughly like india-rubber or jelly); that is, we were led to postulate a medium possessing elasticity, or something very analogous to elasticity. In Parts II. and III. we discussed effects suggesting, and more or less necessitating, the idea of a property of the medium very analogous to inertia; and we were also led to postulate a doubleness of constitution for the medium, so that shearing stresses may occur in it and yet it be perfectly fluid as a whole. We are now pushing these analogies and ideas into greater definiteness and baldness of statement. We already know of a continuous, incompressible fluid filling all space, and we call it the ether. Let us suppose that it is composed of, and by electromotive force analyzable into, two constituents; let these constituents cling together with a certain tenacity, so that the medium shall have an electromotive elasticity, though it is mechanically quite fluid; and let each constituent pos-

sess inertia, or something so like inertia as to produce similar effects. Making these hypotheses, electrical effects are to a certain extent explained. Not ultimately, indeed—few things can be explained ultimately: not even as ultimately as could be wished; for the nature of the connection between the two constituents of the ether, and between the ether and gross matter—the nature of the force, that is, and the nature of the inertia—remains untouched. This is a limitation to be clearly admitted; but if that were the only one—if all else in the hypothesis were true—we should do well, and a distinct step would have been gained. It is hardly to be hoped that this is so—hardly to be expected that the bald statement above is more than a kind of parody of the truth; nevertheless, supposing it only a parody, supposing what we call electromotive elasticity and inertia are things capable of clearer conception and more adequate statement (§ 156), yet, inasmuch as they correspond to and represent a real analogy, and inasmuch as we find that a medium so constructed would behave in a very electrical manner, and might in conjunction with matter be capable of giving rise to all known electrical phenomena, we are bound to follow out the conception into other regions, and see whether any other abstruse phenomena, not commonly recognized as electrical, will not also fall into the domain of this hypothetical substance and be equally explained by it (§ 8). This is what we shall now proceed to do.

120. Before beginning, however, let me just say what I mean by "electromotive elasticity." It might be called chemical elasticity, or molecular elasticity.

There is a well-known distinction between electromotive force and ordinary matter-moving force. The one acts upon electricity, straining or moving or, in general, "displacing" it; the other acts upon matter, displacing it. The nature of neither force can be considered known, but crudely we may say that as electricity is to matter, so is electric force to common mechanical force; so also is electric elasticity to the common shape-elasticity or rigidity of ordinary matter; so perhaps, once more, may electrical inertia be to ordinary inertia.

Inertia is defined as the ratio of force to acceleration; similarly electric inertia can be defined as the ratio of electromotive force to the acceleration of electric displacement. It is quite possible that electric inertia and ordinary inertia are the same thing, just as electric energy is the same with mechanical energy. If this were known to be so, it would be a step upward towards a mechanical explanation; but it is by no means necessarily or certainly so; and whether it be so or not, the analogy undoubtedly holds, and may be fruitfully pursued.

And as to "electromotive elasticity," one may say that pure water or gas is electromotively elastic, though mechanically limpid; each resists electric forces, up to a certain limit of tenacity, beyond which it is broken; and it recoils when they are withdrawn. Glass acts in the same way, but that happens to be mechanically elastic too. Its mechanical elasticity and tenacity have, however, nothing to do with its electric elasticity and tenacity.

We perceive in a general way why fluids can be electrically, or chemically, or atomically elastic: it is because their molecules are doubly or multiply composed; and the constituent atoms cling together, while the several molecules are free of one another. Mechanical forces deal with the molecule as a whole, and to them the substance is fluid; electrical or chemical forces deal with the constituents of the molecule, setting up between them a shearing strain and endeavouring to tear them asunder. To such forces, therefore, the fluid is elastic and tenacious, up to a certain limit. Extend this view of things to the constitution of the ether, and one has at least a definite position whence to proceed further.

121. It may be convenient here to say that a student might find it a help to re-read Parts I. and II. in the light of what has just been said: remembering that, for the sake of simplicity, only the simple fact of an elastic medium was at first contemplated and insisted on; no attempt being made to devise a mechanism for its elasticity by considering it as composed of two constituents. Hence the manifest artificiality of such figures as Fig. 6, p. 35, where fixed beams are introduced to serve as the support of the elastic connexions. But it is pretty obvious now, and it has been already indicated in Fig. 7A, p. 41, that a closer analogy will be obtained by considering two sets of beads, arranged in alternate parallel rows, connected by elastic threads, and displaced simultaneously in opposite directions. A still further progressive analogy is attempted in Fig. 46, p. 201. We have gradually passed, therefore, from a sort of one-fluid theory to a modified two-fluid theory;

believing it to be, in some sense or other, nearer the truth.

Recovery of the Medium from Strain

122. We have now to consider the behaviour of a medium endowed with an elastic rigidity, $4\pi/\kappa$, and a density, $4\pi\rho$, subject to displacements or strains. One obvious fact is that when the distorting force is removed the medium will spring back to its old position, overshoot it on the other side, spring back again, and thus continue oscillating till the original energy is rubbed away by viscosity or internal friction. If the viscosity is very considerable, it will not be able so to oscillate; it will then merely slide back, in a dead-beat manner, towards its unstrained state; taking a theoretically infinite time to get completely back, but practically restoring itself to something very near its original state in what may be quite a short time. The recovery may in fact be either a brisk recoil or a leak of any degree of slowness, according to the amount of viscosity as compared with the inertia and elasticity (§ 19).

The matter is one of simple mechanics. It is a case of harmonic motion modified by a friction proportional to the speed. The electrical case is simpler than any mechanical one, for two reasons: first, because so long as 'capacity' is constant (and no variation has yet been discovered) Hooke's law will be accurately obeyed—restoring force will be accurately proportional to displacement; secondly, because for all conductors which obey Ohm's law (and no true conductor is known to disobey it) the friction force is accurately proportional to the first power of velocity.

123. There are two, or perhaps one may say three, main cases. First, where the friction is great. In that case the recovery is of the nature of a slow leak, according to a decreasing geometrical progression or a logarithmic curve; the logarithmic decrement being independent of the inertia, and being equal to the quotient of the elasticity and the resistance coefficients.

As the resistance is made less, the recovery becomes quicker and quicker, until inertia begins prominently to assert its effect, and to lengthen out the time of final recovery once more, by carrying the recoiling matter beyond its natural position, and so prolonging the disturbance by oscillations. The quickest recovery possible is obtained just before these oscillations begin; and it can be shown that this is when the resistance coefficient is equal to twice the geometric mean of the elasticity and the inertia. One may consider this to be the second main case. The recoil is then exactly dead-beat, and occurs in the minimum of time.

The third principal case is when the resistance is quite small, and when the recovery is therefore distinctly oscillatory. If the viscosity were really zero, the motion would be simply harmonic for ever, unless some other mode of dissipating energy were provided; but if any such mode is provided, or if the viscosity has a finite value, then the vibrations will be simply harmonic with a dying out amplitude, the extremities of all the swings lying on a logarithmic curve. In such a case as this, the rate of swing is practically independent of friction; it depends only on elasticity and inertia; and, as is well known for simple harmonic motion, the time of a complete swing is 2π times the square root of the ratio of inertia and elasticity coefficients.

124. Making the statement more electrically concrete, we may consider a circuit with a certain amount of stored-up potential energy or electrical strain in it; for instance, a charged Leyden jar provided with a nearly complete discharge circuit. The main elastic coefficient, here, is the reciprocal of the capacity of the jar: the more capacious the jar—the more "pliable" it is—the less force of recoil for a given displacement; so that capacity is the inverse of rigidity. The main inertia coefficient is that which is known electrically as the "self-induction" of the circuit: it involves the inertia of all the displaced matter and ether—of everything which will be moved or disturbed when the jar is discharged. It is not a very simple thing to calculate its value in any given case; still it can be done, and the general idea is plain enough without understanding the exact function and importance of every portion of the surrounding space. (See Appendix.)

Corresponding, then, to the well-known simple harmonic $T = 2\pi\sqrt{\frac{m}{k}}$, we have, writing L for the self-induction or inertia of the circuit, and S for its capacity or inverse elasticity constant,

$$T = 2\pi\sqrt{LS}.$$

This, therefore, is the time of a complete swing.

Directly the jar is discharged, these oscillations begin, and they continue like the vibrations of a tuning-fork until they are damped out of existence by viscosity and other modes of dissipation of energy.

125. But now just consider a tuning-fork. Suppose its substance were absolutely unviscous, would it go on vibrating for ever? In a vacuum it might: in air it certainly would not. And why not? Because it is surrounded by a medium capable of taking up vibrations and of propagating them outwards without limit. The existence of a vibrating body in a suitable medium means the carving of that medium into a succession of waves, and the transmission of these waves away into space or into absorbing obstacles. It means, therefore, the conveyance away of the energy of the vibrating body, and its subsequent appearance in some other form wherever the radiating waves are quenched (§ 141).

The laws of this kind of wave-propagation are well known; the rate at which waves travel through the medium depends not at all on any properties of the original vibrating body, the source of the disturbance; it depends solely on the properties of the medium, if it be homogeneous. They travel at a rate precisely equal to the square root of the ratio of its elasticity to its density.

Although the speed of travel is thus fixed independently of the source, the length of the individual waves is not so independent. The length ot the waves depends both on the rate at which they travel and on the rate at which the source vibrates. It is well known, and immediately obvious, that the length of each wave is simply equal to the product of the speed of travel into the time of one vibration.

126. But not every medium is able to convey every kind of vibration. It may be that the mode of vibration of a body is entirely other than that which the medium surrounding it can convey: in that case no dissipation of energy by wave-propagation can result, no radiation will be excited. The only kind of radiation which common fluids are mechanically able to transmit is well known: it is that which appeals to our ears as sound. The elasticity, concerned in such disturbance as this, is mere volume elasticity or incompressibility. But electrical experiments (the Cavendish experiment, §§ 4 and 14 A, and Faraday's ice-pail experiment) prove the ether to be enormously—perhaps absolutely—incompressible; and if so, such vibrations as these would travel with infinite speed and not carve proper waves at all.

Conceivably (I should like to say probably) *gravitation* is transmitted by such longitudinal impulses or thrusts, and in that case it is nearly or quite instantaneous; and the rate at which it travels, if infinite, can be determined by a still more accurate repetition of the Cavendish experiment (the *electrical* one, not the customary gravitation-constant determination) than has yet been made. But true radiation transmitted by the ether cannot be of this longitudinal character. The elasticity possessed by the ether is of the nature of rigidity: it has to do with shears and distortions; not mechanical stresses —to them it is quite limpid and resistless—but electromotive stresses: it has an electrical rigidity, and it is this which must be used in the transmission of wave-motion.

But the oscillatory discharge of a Leyden jar is precisely competent to apply to the ether these electromotive vibrations; it will shake the medium in the mode suitable for transmission; and accordingly, from a discharging circuit, waves of electrical distortion, or transverse waves, will spread in all directions, at a pace depending on the properties of the medium.

Thus, then, even with a circuit of perfect conductivity the continuance of the discharge would be limited, the energy would be dissipated; not by friction—there would in such a circuit be no direct production of heat—it would be dissipated by radiation, dissipated in the same way as a hot body cooling, in somewhat the same way as a vibrating tuning-fork mounted on its resonant box. The energy of the vibrating body would be transferred gradually to the medium, and would by this be conveyed out and away; its final destination being a separate question, depending on the nature and position of the material obstacles it meets with. (See § 160; and also a lecture on Discharge of Leyden Jar, below.)

CHAPTER XIII

CONSTANTS OF THE ETHER

Velocity of Electrical Radiation.

127. THE pace at which the radiation-waves travel, depends, as we have said, solely on the properties of the medium, solely on the relation between its elasticity and its density. The elasticity considered must be of the kind concerned in the vibrations; but the vibrations are in this case electrical, and so electrical elasticity is the pertinent kind. This kind of elasticity is the only one the ether possesses, of finite value, and its value can be measured by electrostatic experiments. Not absolutely, unfortunately: only the relative elasticity of the ether as modified by the proximity of gross substances has yet been measured; its reciprocal being called their specific inductive capacity, or dielectric constant, κ. The absolute value of the quantity κ is at present unknown, and so a convention has arisen whereby in air it is called 1. This convention is the basis of the artificial electrostatic system of units. No one supposes, or at least no one has a right to suppose, that its value is really 1. The only rational

guess at ethereal rigidity is one by Lord Kelvin, long ago,[1] which, if we reckon it as $4\pi/\kappa$, is equivalent to saying that in air the value of κ is probably not greater than 140. Whether known or not, and at present it is certainly not known, the absolute value of the dielectric constant is manifestly a legitimate problem, which may any year be solved. It now seems more likely to be a totally different order of magnitude from the above—something exceedingly small.

The other thing on which the speed of radiation waves depends, is the medium's density—its electric density, if so it must be distinguished. Here again we do not know its absolute value. Its relative or apparent amount inside different substances is measured by magnetic experiments, and called their specific magnetic capacity, or permeability, and is denoted by μ.

Being unknown, another convention has arisen, quite incompatible with the other convention just mentioned, that its value in air shall be called 1. This convention is the basis of the artificial electro-magnetic system of units—volts, ohms, amperes, farads, and the like. Both of these conventions cannot be true: no one has the least right to suppose either true. A rational guess at an upper limit for ethereal free density was made by Lord Kelvin, on the basis of a reasonable maximum amplitude for waves of light; and on this estimate the value of μ in air would come out not less than 8×10^{-24}. On the other hand, a great deal of still

[1] *Trans. R. S. Edin.* xxii. 60; see also article "Ether," in the *Encyc. Brit.*; and the concluding line in Vol. III. of *Mathematical and Physical Papers.*

more recent work suggests that the density of the ether is exceedingly great—much denser than of any known material—and accordingly that its rigidity must be enormous. See Chap. XVII.

128. Very well, then; it being clearly understood that these two great ethereal constants, k or $\frac{1}{\kappa}$, and μ, are neither of them at present known, but are both of them quite knowable, and may at any time become known when a suitable experiment has been devised, it remains to express the speed of wave transmission in terms of them. But it is well known that this speed is simply the square root of the ratio of elasticity to density, so

$$v = \sqrt{\frac{k}{\mu}}, \text{ or } \frac{1}{\sqrt{(\kappa\mu)}}.$$

This then is the speed with which waves leave the discharging Leyden jar circuit, or any other circuit conveying alternating or varying currents, and travel out into space.

Not knowing either κ or μ, we cannot calculate this speed directly, but we can try to observe it experimentally.

129. The first and crudest way of making the attempt would be to arrange a secondary circuit near our oscillating primary circuit, and see how soon the disturbance reached it. For instance, we might take a nearly closed loop, make it face a Leyden jar circuit across a measured distance, and then look for any interval of time between the spark of the primary discharge and the induced spark of the secondary circuit; using a revolving mirror or what we please.

But in this way we should hardly be able to detect any time at all: the propagation is too quick.

130. Since this was first written, Dr. Hertz, of Karlsruhe, has succeeded in making a measure of velocity on this very plan. He did not indeed actually measure the time which elapsed between the closing of the primary circuit and the start of the induced current in the secondary, nor did he use an ordinary Leyden; but he converted the advancing waves from an electrically oscillating arrangement, excited by means of an induction coil, into stationary waves, by means of reflection at a plane metallic wall. Just as waves travelling along a rope or stretched cord are converted into stationary waves, or nodes and loops, by the interference of direct and reflected pulses: reflection taking place from the fixed end of the cord; so waves advancing from an electrostatic oscillator, or charged body connected with the terminals of an induction coil, were reflected at the wall of the room (lined with sheet zinc on purpose to make it a conductor, and therefore a good reflector, see § 164). Then interference with the direct waves converted them into stationary nodes and loops: the interval between two nodes being half a wave-length.

By now moving the secondary circuit about, between the primary and the wall, places of maximum and minimum disturbance could be found, and thus the wave-length measured. By calculating the oscillation period of the primary circuit (or part-circuit, for it was unclosed) an indirect measure of the velocity of propagation was arrived at. So far as could be told, it agreed with measurements made by other means, such as those now to be described.

131. We might next make use of the principle of the electric telegraph, viz. the propagation of a disturbance round a single circuit from any one point of origin. Consider a large closed circuit, either conveying or not conveying a current: introduce at any one point a sudden change—a sudden E.M.F., for instance, or a sudden resistance if there be a current already. Out from that point a disturbance will spread into the ether, just as happens in air when a blow is struck or gun-cotton fired. A regular succession of disturbances would carve the ether into waves: a single disturbance will merely cause a pulse or shock; but the rate of transmission is the same in either case, and we may watch for the reception of the pulse at a distant station. If the station has to be very distant in order to give an appreciable lapse of time, a speaking-tube is desirable to prevent spreading out in all directions—to concentrate the disturbance at the desired spot. What a speaking-tube is to sound, that is the wire of the circuit—the telegraph-wire—to ethereal pulses.

It is a curious function, this of the telegraph wire: it does not *convey* the pulses, it directs them. They are conveyed wholly by the ether, at a pace determined by the properties of the ether, modified as it may be by the neighbourhood of gross matter. Any energy which enters the wires is rapidly dissipated into heat, and gets no further: it is the insulating medium round it which transmits the pulses to the distant station.

All this was mentioned in Part III., and an attempt was made to explain the mechanism of the process, and to illustrate in an analogical way what is going on (Chap. XI.).

The point of the matter is that currents are not propelled by end-thrusts, like water in a pipe or air in a speaking-tube, but by lateral propulsion, as by a series of rotating wheels with their axes all at right angles to the wire, surrounding it as a central core, and slipping with more or less friction at its surface. This is characteristic of ether modes in general: the ether does not convey longitudinal waves or end-thrust pulses, like sound, but it conveys transverse vibrations of lateral pulses, like light (§ 42).

132. Without recapitulating further, we can perceive then that the transmission of the pulse round the circuit to its most distant parts depends mainly on the medium surrounding it. The process is somewhat as follows:—Consider two long straight parallel wires, freely suspended, and at some great distance joined together. At the near end of each, start equal opposite electromotive impulses, as by suddenly applying to them the poles of a battery; or apply a succession of such pulses by means of an alternating machine. Out spread the pulses into space, starting in opposite phases from the two wires, so that at a distance from the wires the opposite pulses interfere with each other, and are practically non-existent; just as but little sound is audible at a distance from the two prongs of a freely suspended tuning-fork. But near the wires, and especially between them, the disturbance may be considerable. The energy emitted by the source as it reaches each wire is dissipated, and so a fresh supply

of energy goes on continually arriving at the wires, always flowing in from outside, to make up the deficiency. If the wires are long enough, hardly any energy may remain by the time their distant ends are reached; but whatever there is will still be crowding in upon the wires and getting dissipated, unless by some mechanism it be diverted and utilized to effect some visible or audible or chemical change, and so to give the desired signal (§ 107).

133. Now the pace at which this transmission of energy goes on in the direction of the wires is pretty much the same as in free space.[1] There are various circumstances which can retard it; there are none which can accelerate it. The circumstances which can retard it are, first, constriction of the medium by too great proximity of the two conducting wires, as, for instance, if they consist of two flat ribbons close together with a mere film of dielectric between, or if one be a small-bore tube and the other its central axis or core. In such cases as this the general body of ether takes no part in the process, the energy has all to be transmitted by the constricted portion of dielectric, and the free propagation of ethereal pulses is interfered with: the propagation is then no longer a true wave-propagation, it approximates more or less closely to a mere diffusion creep: rapid it may be, and yet without definite velocity; like the conduction of heat, or like the diffusion of a salt into water. One well-known effect of this is to merge successive disturbances into one another, so that their individuality, and consequently the distinctness of signalling, is lost.

[1] Appendix (*o*).

134. Another circumstance which can modify rate of transmission of the pulses is ethereal inertia in the substance of the conducting wires: especially extra great inertia; as, for instance, if they are made of iron. For the dissipation of energy does not go on accurately at their outer surface, it has usually to penetrate to a certain depth; and, until it is dissipated, the fresh influx of energy from behind does not fully occur. Now, so long as the value of μ for the substance of the wires is the same as that of air or free space, no important retardation is thus caused, unless the wires are very thick; but directly the inertia in the substance of the wires is some hundred or thousand times as big as that outside, it stands to reason that more time is required to get up the needful magnetic spin in its outer layer; and so the propagation of pulses is more or less retarded. At the same time this circumstance does not alter the character of the propagation, it does not change it from true wave velocity to a diffusion, it leaves its character unaltered; and so the signals, though longer in coming, may arrive quite clear, independent, and distinct. It is much the same, indeed, as if the density of the surrounding medium had been slightly increased.

I have several times mentioned the name of Prof. Poynting as one who has developed Maxwell's equations, and thrown great light upon the mode in which electro-magnetic energy is transmitted; in the same connexion, and also still more prominently in connexion with the general theory of telegraphy and of electro-magnetic waves, I must mention with due emphasis the name of Mr. Oliver Heaviside, the scope of whose mathematical investigation into these difficult fields of research is remarkable.

135. These then are the main circumstances which affect the rate of transmission of a pulse from one part of a closed circuit to another:—extra inertia, or so-called magnetic susceptibility in the conducting substance, especially in its outer layers; and undue constriction or throttling of the medium through which the disturbance really has to go. Both these circumstances diminish the rate of transmission; and one (the last mentioned) modifies the law, and tends to obliterate individual features and to destroy distinctness.

Of course, besides these, the nature of the insulating medium will have an effect on the rate of propagation; but that is obvious all along; it is precisely the rate at which any given medium transmits pulses that we want to know, and on which we are thinking of making experiments. If we use gutta-percha (more accurately the ether inside gutta-percha) as our transmitting medium in an experiment, we are not to imagine that we have obtained a result for air.

136. The circumstances we have considered as modifying the rate of transmission are both of them adventitious circumstances, independent of the nature of the medium; and they are entirely at our own disposal. If we like to constrict our medium, or to use thick iron wires, we can do so, but there is no compulsion; and if we wish to make the experiment in the simplest manner, we shall do no such thing. We shall use thin copper wires (the thinner the better), arranged parallel to one another a fair distance apart,

and we shall then observe the time which an electromotive impulse communicated at one end takes to travel to the other. Instead of using two wires, we may if we like use what comes to much the same thing, viz. a single wire suspended at a reasonable height above the ground, as in a common land telegraph ; with circuit completed through the earth.

The experiment, if it could be accurately made, would result in the observation of a speed of propagation equal to 3×10^{10} centimetres (300,000 kilometres, or about 185,000 miles per second. The actual speed in practice may be less than this, by reason of the various circumstances mentioned, but it can never be greater. This, then, is the rate of transmission of transverse impulses, and therefore of transverse waves, through ether as free as it can be easily obtained.

Electric Waves along Wires.

137. In 1888 I succeeded in making a rough preliminary determination on this very plan ; but avoided the necessity for excessive lengths of wire, by using the principle of reflection and interference to obtain stationary waves in a pair of parallel wires of known length attached as lateral appendages to a Leyden jar circuit : such waves being excited at every discharge—an arrangement afterwards improved by Prof. Lecher. Experiments on these stationary waves in wires, observation of their nodes and loops, and measurements of their wave-length, were going on at Liverpool, simultaneously with, but independently

of, the experiments of Hertz in Carlsruhe on waves in space; and they were both described to the British Association at Bath in 1888.[1] Alternating pulses travelled along the wires, and were reflected at their far ends, just as pulses travel along a string attached to a tuning-fork in Melde's experiment. Reflection of the pulses at the free ends of the wires is not accomplished without a considerable recoil or kick, which can be observed by the brightness of the brush or the length of spark it gives. The length of the wires, or else the size of the discharging circuit, is adjusted until the recoil kick is a maximum, and the length of each wire is then considered to be half a wave-length. Knowing the rate of oscillation proper to the particular Leyden jar circuit employed, a determination of the velocity of the pulses can at once be made. It agrees with what is said above.

Added 1906.—This is the experiment of the recoil kick, described more in detail to the Royal Society in 1891 (*Proc. Roy. Soc.* vol. l. p. 23), and now applied in various systems of syntonized wireless telegraphy, as well as in D'Arsonval's apparatus for medical electrification at high frequency—the special appliance commonly used being often called an Oudin resonator.

In all these cases there is a long wire appendage to an oscillating Leyden jar discharging circuit, the wire in some cases being coiled compactly, and reinforcing the effect by its own self-induction; in other cases

[1] Lodge, *Phil. Mag.* August 1888; and *Electrician* of 1888 and 1889, especially vol. xxi. pp. 607—9. See also *Proc. Roy. Soc.* vol. l.; and Appendix (*o*) below.

being extended up into the air to a considerable elevation. A development of the above idea of transmitting waves along a pair of wires, reflecting them and observing the loops and nodes, so as to measure their length—using vacuum-tubes and other detectors—is now well known, and is commonly referred to as Prof. Lecher's method.[1]

138. There are many methods known to physicists by which an indirect experimental determination of this velocity of pulses along wires can be made. These methods have been more largely practised than the one described, but they do not determine directly the speed with which electrical pulses or waves travel: they directly determine the ratio of elasticity to density, or, what is the same thing, the product $\kappa\mu$; and it is left to theory to say that this is really the velocity of electrical pulses in free ether. It is unnecessary to say more about these plans here. They are generally referred to as methods of determining the ratio "v," or the number of electrostatic units of quantity in an electro-magnetic unit; which is a roundabout and forced mode of expression, but it serves.

The oscillatory discharge of a Leyden jar has been applied by Lodge and Glazebrook to determine the above ratio "v." See Stokes Memorial Volume (Camb. Phil. Soc., Univ. Press, 1899).

[1] The waves on wires described by the writer to the British Association in 1888 (See *Electrician*, 14 Sept. 1888, vol. xxi. p. 608) were exhibited with luminous nodes and loops, to the Physical Society of London in June 1891; as partially reported under an erroneous heading in the *Electrician*, vol. xxvii. p. 200. See also § 198, and *Nature*, vol. xxxix. p. 548.

CHAPTER XIV

ELECTRICAL RADIATION, OR LIGHT

139. HAVING now described one or two possible methods of measuring the velocity of electric wave propagation, and therefore at least the *ratio* of the two ethereal constants k and μ (or, what is the same thing, the product of the two constants κ and μ), we return to the consideration of an ordinary small discharging Leyden jar or other alternating current circuit of a moderate size, it may be a few yards or a foot or an inch in diameter.

If the alternating currents are produced artificially by some form of alternating machine, their "frequency" is, of course, arbitrary; but if they be automatically caused by the recoil of a given Leyden jar in a given circuit, their frequency—the reciprocal of their time-period—is, as we have already said (§ 124),

$$\frac{1}{2\pi\sqrt{(LS)}} \text{ per second}:$$

where L is the electrical inertia, or self-induction, of the circuit; and where S is the capacity, or reciprocal of the elasticity-constant, of the jar.

140. It is not convenient here to go into the determination of the quantity L, but roughly one may say that for an ordinary open single-loop circuit it is a quantity somewhat comparable with ten or twelve times its circumference multiplied by the constant μ.[1]

The value of S has to do with the area, A, and thickness, z, of the dielectric of the condenser; being, as is well known, $\frac{A}{4\pi z}$ multiplied by the constant κ.

The product LS in the above expression contains therefore two factors, each of linear dimensions, expressing the sizes of circuit and jar; and likewise contains a factor $\mu\kappa$ expressing the properties of the surrounding medium. Hence, so far as the ether is concerned, the above expression for frequency of vibration demands only a knowledge of the *product* of its two constants κ and μ; and since this is known by the previous velocity experiments, it is easy to calculate the rate of oscillation of any given condenser-discharge. It is also easy to calculate the wave-length; for if there are n waves produced per second, and each travels with the velocity v, the length of each wave is $\frac{v}{n}$.

Hence the wave-length is $2\pi\sqrt{\left(\frac{L}{\mu}\cdot\frac{S}{\kappa}\right)}$.

141. Now, if we go through these numerical calculations for an ordinary Leyden jar and discharger, we shall find waves something like, say, 50 or 100 yards long. They may plainly be of any length, according

[1] See Appendix (*e*).

to the size of the jar and the size of the circuit; the bigger both these are the longer will be the waves:—

A condenser of 1 microfarad capacity, discharging through a coil of self-induction 1 henry, will give rise to ether waves 1900 kilometres or 1200 miles long; and the rate of its oscillation is 160 complete swings per second.

A common pint Leyden jar, discharging through a pair of tongs, may start a system of ether waves each not longer than about 15 or 20 metres; and its rate of oscillation will be something like ten million per second.

A tiny thimble-sized jar overflowing its edge may propagate waves only about 2 or 3 feet long. (See also §§ 143, 157 and 158, and Appendix (*k*)).

141 A. Professor J. J. Thomson has shown that when electricity oscillates from pole to pole of a conducting sphere, the waves emitted are 1·4 times the diameter of the sphere in length. I have succeeded in recognizing waves emitted by spheres only 2 inches in diameter; but it is easier to get them clearly from bigger spheres. The waves emitted by spheres 6 inches or a foot in diameter, when their electricity is disturbed by a sudden spark, are easily recognizable several yards away.[1]

When the earth receives a spark, as a flash of lightning, its charge may oscillate between Antipodes and back 17 times a second. The time of one electric oscillation on the sun is 6¼ seconds; and the waves

[1] See *Nature*, vol. xli. p. 462.

are therefore a little over a million miles long. These great waves are possibly part of the cause of our terrestrial "magnetic storms."

142. The oscillations of current, thus recognized as setting up waves, have only a small duration, unless there is some means of maintaining them. How long they will last depends partly upon the conductivity of the circuit; but even in a circuit of infinite conductivity they must die out, if left to themselves, from the mere fact that they dissipate their energy by radiation. One may get 10 or 20, or perhaps even 100, perceptible oscillations of gradually decreasing amplitude, but the rate of oscillation is so great that their whole duration may still be an extremely small fraction of a second. For instance, to produce ether waves a metre in length requires 300,000,000 oscillations per second.

To keep up continuous radiation naturally requires a supply of energy, and unless it is so supplied the radiation rapidly ceases. Commercial alternating machines are artificial and cumbrous contrivances for maintaining electrical vibrations in circuits of finite resistance, and in despite of loss by radiation.

In most commercial circuits the loss by radiation is so small a fraction of the whole dissipation of energy as to be practically negligible; but we are not limited to the consideration of commercial circuits, or to alternating machines as at present invented and used. It may be possible to devise some less direct method—some chemical method, perhaps—for supplying energy to an oscillating circuit, and so converting what would be a mere discharge or flash into a continuous source of radiation.

143. So far we have only considered ordinarily practicable electrical circuits, and have found their waves in all cases pretty long, but getting distinctly shorter the smaller we take the circuit. Continue the process of reduction in size further, and ask what sized circuit will give waves 6000 tenth-metres (three-fifths of a *micron*, or 25 millionths of an inch) long. We have only to put $2\pi\sqrt{\left(\frac{L}{\mu}\cdot\frac{S}{\kappa}\right)} = 0{\cdot}00006$; and we find that the necessary circuit must have a self-induction, in electro-magnetic units, and a capacity, in electrostatic units, such that their geometric mean is 10^{-5} centimetre (one-tenth of a micron). This gives us at once something near atomic dimensions for the circuit, and suggests immediately that those short ethereal waves which are able to affect the retina, and which we are accustomed to call "light," may be really excited by electrical oscillations or surgings in circuits of atomic dimensions (§§ 157–9).

If after the vibrations are once excited there is no source of energy competent to maintain them, the light-production will soon cease, and we shall have merely the temporary phenomenon of phosphorescence; but if there is an available supply of suitable energy the electrical vibrations may continue, and the radiation may become no longer an evanescent brightness, but a steady and permanent glow.

Velocity of Electrical Radiation compared with Velocity of Light, in Free Space and in Material Substances.

144. We have thus imagined the now well-known Maxwellian theory of light, viz. that it is produced by electrical vibrations, and that its waves are electrical waves.

But what justification is there for such an hypothesis beyond the mere fact which we have here insisted on, viz. that waves in all respects like light-waves except size, *i.e.* transverse vibrations travelling at a certain pace through ether, can certainly be produced temporarily in practicable circuits by familiar and very simple means, and *could* be produced of exactly the length proper to any given kind of light if only it were feasible to deal with circuits ultra-microscopic in size? The simplest point to consider is: Does light travel at the same speed as the electrical disturbances we have been considering? We described one method of measuring how fast electrical radiation travels in free space, and there are many other methods: the result was 300,000 kilometres per second. Does light travel at the same pace?

Methods of measuring the velocity of light have long been known, and the result of those measurements in free space or air is likewise 300,000 kilometres a second. The two velocities agree in free space. Hence surely light and electrical radiation are identical.

145. But there is a further test. The speed of electrical radiation was not the same in all media: it

depended on the electrical elasticity and the ethereal density of the transparent substance; in other words, it was equal to the reciprocal of the geometric mean of its specific inductive capacity and its magnetic permeability—

$$v = \frac{1}{\sqrt{(\kappa\mu)}}.$$

Now, although the absolute value of neither κ nor μ is known, yet their values relatively to air are often measured, and are known for most substances.

Also, it is easy to compare the pace at which light goes through any substance with its velocity in free space: the operation is called finding the refractive index of a substance. The refractive index means, in fact, simply the ratio of the velocity of light in space to its velocity in the given substance. The reciprocal of the index of refraction is therefore the relative velocity of light. Calling the index of refraction n, therefore, we ought, if the electrical theory of light be true, to find that $n^2 = \kappa\mu$; or that the index of refraction of any substance is the geometric mean of its electrostatic and magnetic specific capacities.

146. That this is precisely true for all substances cannot at present be asserted. There are some substances for which it is very satisfactorily true: there are others which are apparent exceptions. It remains to examine whether they are not only apparent but real exceptions, and, if so, to what their exceptional behaviour is due.

It must be understood what the essential point is. It has been proved by various methods, and with greater approach to exactness as the accuracy of the methods is improved, that electrical disturbances—such as the long waves emitted by any alternating machine—travel through air or free space with exactly the same velocity as light ; in other words, that there is no recognizable difference in speed between waves several hundred miles long and waves so small that a hundred thousand of them can lie in an inch. This is true in free ether, and it is a remarkable fact. If it proves anything concerning the structure of the ether, it proves that it is continuous, homogeneous, and simple beyond any other substance ; or at least that if it does possess any structural heterogeneity, the parts of which it is composed are so nearly infinitesimal that a hundred miles and a hundred-thousandth of an inch are quantities of practically the same order of magnitude so far as they are concerned : its parts are able to treat all this variety of wave-length in the same manner.

But directly one gets to deal with ordinary gross matter we know that this is certainly not the case. Ordinary matter is composed of molecules which, though small, are far from being infinitesimal. Atoms are much smaller than light-waves, indeed, but not incomparably smaller. Hence it is natural to suppose that the ether as modified by matter will be modified in a similarly heterogeneous manner ; and will accordingly not be able to treat waves of all sizes in the same way.

The speed of all waves is retarded by entering gross matter, but we should expect the smallest waves to be retarded most. The phenomenon is well marked, even within the range of such light-waves as can affect the retina: the smaller waves—those which produce the sensation of blue—are more retarded, and travel a little slower through, say, glass or water, than the somewhat larger ones which produce the sensation of red. This phenomenon has long been known, and is called dispersion. One result of it is that it is not always easy to say at what rate waves a few inches or a few yards or miles long ought to travel, merely by knowing at what rate the ultra-microscopic light-waves travel.

147. But there is even more to be said than this. There is not only dispersion, there is selective absorption possessed by matter: not only does it transmit different-sized waves at different rates, but it absorbs and quenches some much faster than others. Few substances, perhaps none, are equally transparent to all sizes of waves. Glass, for instance, which transmits readily the assortment of waves able to affect the retina, is practically quite opaque to waves two or three times as long or as short. And whenever this selective absorption occurs, the laws of dispersion are extraordinary—so extraordinary that the dispersion is often spoken of as "anomalous"; which of course means, not that it is lawless, but that its laws are complicated. Dispersion in any case is an obscure and little understood subject, but dispersion modified by selected absorption is still worse.[1] Until the theory of dispersion is better understood, no one is able to say at what speed waves of any given length ought to

[1] It was Dr. John Hopkinson who called attention to the applicability of this fact to the present subject (*B. A. Report*, 1886, page 309).

travel. One can only examine experimentally at what rate they *do* travel. This has been done for long electrical waves, and it has been done for short light-waves: in the case of some substances the speed is the same, in the case of others it is different. But that the speed should be different is, as I have now explained, very natural, and can by no means be twisted into an admission that light-waves and electrical waves are not essentially identical. That the speed of both should agree at all is noteworthy; the agreement appears to be exact in air, and practically exact in such simple substances as sulphur, and in the class of hydrocarbons known as paraffins; whereas in artificial substances like glass, and in organic substances like fats and oils, the agreement is less perfect.

148. So much for the vital question of the speed at which electrical and optical disturbances travel. In some cases the speeds are accurately the same, in no case are they entirely different; and in those cases where the agreement is only rough, an efficient and satisfactory explanation of the difference is to hand, in the very different lengths of wave which have at present been submitted to experiment. To compare the speeds properly, we must learn either to shorten electrical waves, or to lengthen light-waves, or both, and then compare the two things together when of the same size.

It cannot be seriously doubted that they will turn out identical.

Manufacture of Light

149. The conclusions at which we have arrived, that light is an electrical disturbance, and that light-waves are excited by electric oscillations, must ultimately, and may shortly, have a practical import.

Our present systems of making light artificially are wasteful and ineffective. We want a certain range of oscillation, between 700 and 400 billion vibrations per second: no other is useful to us, because no other has any effect on our retina; but we do not know how to produce vibrations of this rate.[1] We can produce a definite vibration of one or two hundred or thousand per second; in other words, we can excite a pure tone of definite pitch; and we can command any desired range of such tones continuously, by means of bellows and a keyboard. We can also (though the fact is less well known) excite momentarily definite ethereal vibrations of some million per second, as I have explained at length; but we do not at present know how to maintain this rate at all continuously. To get much faster rates of vibration than this we have to fall back upon atoms. We know how to make atoms vibrate: it is done by what we call "heating" the substance; and if we could deal with individual atoms unhampered by others, it is possible that we might get a pure and simple mode of vibration, if we had any means of violently disturbing or 'clanging' them. It is possible, but unlikely; for atoms, even when isolated, have a

[1] The number of vibrations per second needed to generate visible light may be represented by the number of vibrations executed by a tuning-fork sounding a note two octaves above the middle C, continuing for 12,000 years.

multitude of modes of vibration special to themselves, of which only a few are of practical use to us, and we do not know how to excite some without also the others. However, we do not at present even deal with individual atoms; we treat them crowded together in a compact mass, so that their modes of vibration are really infinite.

We take a lump of matter, say a carbon filament or a piece of quick-lime, and by raising its temperature we impress upon its atoms higher and higher modes of vibration—not transmuting the lower into the higher, but superposing the higher upon the lower—until at length we get such rates of vibration as our retina is constructed for, and are satisfied. But how wasteful and indirect and empirical is the process. We want a small range of rapid vibrations, and we know no better than to make the whole series leading up to them. It is as though, in order to sound some little shrill octave of pipes in an organ, we were obliged to depress every key and every pedal, and to blow a young hurricane.

150. I have purposely selected as examples the more perfect methods of obtaining artificial light, wherein the waste radiation is only useless and not noxious. But the old-fashioned plan was cruder even than this: it consisted simply in setting something burning; whereby not only the fuel but the air was consumed; whereby also a more powerful radiation was produced, in the waste waves of which we were content to sit stewing, for the sake of the minute, almost infinitesimal, fraction of it which enabled us to see.

Every one knows now, however, that combustion is not a pleasant or healthy mode of obtaining light ; but everybody does not realize that neither is incandescence a satisfactory or unwasteful method which is like to be practised for more than a few decades, or perhaps a century.

Look at the furnaces and boilers of a great steam-engine driving a group of dynamos, and estimate the energy expended ; and then look at the incandescent filaments of the lamps excited by them, and estimate how much of their radiated energy is of real service to the eye. It will be as the energy of a pitch-pipe to an entire orchestra.

It is not too much to say that a boy turning a handle could, if his energy were properly directed, produce quite as much real light as is produced by all this mass of mechanism and consumption of material.

151. There might, perhaps, be something contrary to the laws of Nature in thus hoping to get and utilize some specific kind of radiation without the rest, but Lord Rayleigh has shown in a short communication to the British Association at York[1] that it is not so, and that therefore we have a right to try to do it.

We do not yet know how, it is true, but it is one of the things we have got to learn.

Any one looking at a common glow-worm must be struck with the fact that not by ordinary combustion, nor yet on the steam-engine and dynamo principle, is that easy light produced. Very little waste radiation is there from phosphorescent things in general.

[1] *B. A. Report*, 1881, p. 526.

Light of the kind able to affect the retina is directly emitted; and for this, for even a large supply of this, a modicum of energy suffices. Cf. § 200.

Solar radiation consists of waves of all sizes, it is true; but then solar radiation has innumerable things to do besides making things visible. The whole of its energy is useful. In artificial lighting nothing but light is desired; when heat is wanted it is best obtained separately by combustion. And so soon as we clearly recognize that light is an electrical vibration, so soon shall we begin to beat about for some mode of exciting and maintaining an electrical vibration of any required degree of rapidity. When this has been accomplished, the problem of artificial lighting will have been solved.

Mechanism of Electrical Radiation.

152. In forming a mental image of an electrical wave, we have to note that three distinct directions are involved. There is (1) the direction of propagation—the line of advance of the waves; (2) the direction of the electric displacements, at right angles to this; and (3) the direction of the magnetic axis, at right angles to each of the other two.

One may get a rough mechanical idea of the process of electrical radiation (at any rate in a plane) by means of the cog-wheel system already used in Part III. Imagine a series of elastic wheels, in one plane, all geared together, and let one of them be made to twist to and fro on its axis; from it, as centre, the disturbance will spread out in all directions, each wheel being made to oscillate similarly and to transmit its oscillation to the next. Looking at what is happening at a distance from the source: we shall see the pulses travelling, say, from left to right, while the electrical displacement is up and down, and the oscillating axes of the wheels are to and fro, or at right angles to the plane containing the wheels. It is therefore appropriately spoken of as electro-magnetic radiation rather than merely as electric radiation. The energy of the electrostatic strain is just as great as that of the electro-magnetic motion; in fact, the energy alternates from the potential to the kinetic form, or *vice versâ,* at every quarter swing, just like every other case of vibration; and on the average the two energies, in any considerable portion of space in which the waves are travelling, are necessarily exactly equal. If they are not equal, there will be reflection and complications.

153. In ordinary cases, the oscillations are all very small. For just consider that the wheel-work extends right away to infinity in all directions; how is any moderate force going to make one of these wheels oscillate? If they were rigid it would be impossible, but as they are elastic it is possible, though only with a very small amplitude of vibration; and it sets up a strain all round, which rapidly spreads out, as we have said, in all directions from the source. If the source were inclosed in a perfect conductor of moderate dimensions—if, for instance, we proceed to rotate to and fro one of a bounded series of

wheels, such as those inside the empty contour of Fig. 38—we can do it easily: the wheels are then limited in number, and can be easily got to oscillate considerably by a feeble source of disturbance.

This is commonly spoken of as concentration of light by reflection: the conductor is said to act as a perfect mirror; and, since none of the light escapes, any amount of illumination can be produced inside a closed spherical mirror of perfect conductivity. Such illumination would not be much use, however; for, directly a bit of matter is introduced to receive the benefit of it, dissipation goes on at its surface, and the violence of the ethereal disturbance is brought down to something more moderate. Nevertheless, even when dissipation is allowed, and when the reflecting surface is by no means perfectly conducting, but is bright silver, which is the best conductor we know, a considerable increase in illumination is caused: by reflection, if we choose to say so—by limitation, in at least some directions, of the extent of ethereal medium to be affected by a given source, as we might now prefer to express it (§ 164).

154. Prof. Fitzgerald, of Dublin, devised a model of the ether, which by help of a little artificiality represents the two kinds of displacement—the electric and magnetic—very simply and clearly.

His wheels are separated from one another by a certain space, and are geared together by elastic bands. They thus turn all in one direction, and no mention need be made of positive and negative electricity as separate entities.

But, the wheels being massive, a rotatory disturbance given to one takes time to spread through the series, at a pace depending on the elasticity of the bands and the inertia of the wheels; and during the period of acceleration one side of every elastic is stretched, while the other side is relaxed and therefore thickened. This thickening of the elastics goes on in one direction, and corresponds to an electric displacement in that direction; the direction being

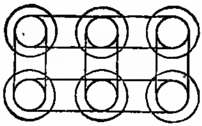


FIG. 48.—Fitzgerald's Ether Model. A set of massive-rimmed brass wheels on fixed pivots with their axles connected by common elastic bands. If the bands are taken off any region, it becomes a perfect conductor, into which disturbances cannot penetrate. (Cf. Fig. 38.)—*Proc. Roy. Dub. Soc.*, January 1885.

perpendicular both to the direction of advance of the disturbance and to the axes of the wheels. A row of wheels corresponds to a section of a wave-front; the displacements of india-rubber and the rotating axes, *i.e.* the electric and the magnetic disturbances, both lie in the wave-front.

155. Clerk Maxwell's originally suggested representation was not unlike this.[1] It consisted of a series of massive wheels, connected together not by a series of elastic bands but by a row of elastic particles or "idle wheels." These particles represented "electricity"; their displacement during the period of acceleration corresponding to the one-sided thickening of the elastic bands in Fitzgerald's model. The object of the idle wheels was to enable all the main

[1] *Phil. Mag.* April 1861.

wheels to rotate in the same sense, as desiderated in Fig. 35, p. 173.

Added 1906.—It is worth while to reconsider Maxwell's model in the light of modern electron theory, and to realise how near the truth his intuition led him.

I have proposed to contemplate a double series of wheels geared directly into one another, representing positive and negative electricity respectively, because it seems to me that so many facts point to the existence of these two entities; and because then no distinction has to be drawn between one part of the medium which is ether and another part which is electricity, but the whole is ether and may be also electricity; while, nevertheless, a much-needed distinction can be drawn between a motion of the ether as a whole, and a relative motion of its component parts: a distinction between forces able to move ether—*i.e.* to displace the centre of gravity of some finite portion of it—and forces which shear it and make its components slide past each other in opposite senses; these latter forces being truly electromotive (§ 120).

156. If it be asked how the elasticity of the ether is to be explained, we must turn to the vortex sponge theory, suggested by Prof. Fitzgerald,[1] as well as by Prof. Hicks [2] and recently elaborated by Lord Kelvin.[3] But this is too complicated a matter to be suited for popular exposition just at present. It must suffice

[1] *Proc. R. Dub. Soc.* Jan. 1885. See also his Collected Memoirs.

[2] *Brit. Assoc. Report*, 1885, Aberdeen, p. 930.

[3] *Ibid.* 1887, Manchester, p. 486. Also *Phil. Mag.* October 1887.

to indicate that the points here left unexplained are not necessarily at the present time unexplainable, but that the explanations have not yet been so completely worked out that an easy grasp can be obtained of them by simple mechanical illustrations and conceptions. At the same time, the general way in which motion is able to simulate the effects of elasticity will be found popularly illustrated, by help of gyrostats, in Lord Kelvin's article "Elasticity" in the *Encyclopædia Britannica*;[1] and the fact that elastic rigidity of a solid can be produced by impressing motion on a homogeneous and otherwise structureless fluid must be regarded as one of the most striking among his many fundamental discoveries.

We have found it necessary all through Part III. to imagine the ether as composed of cells containing electricity in rotation, and the act of magnetization as consisting in facing these whirls round. Lord Kelvin has taught us that a medium containing whirls like this will simulate the behaviour of an elastic solid, and in fact that whirling motion is all that is required to explain elasticity (Fig. 46). With this hint, which might be developed at greater length, I must leave this part of the subject.

157. We have seen that, to generate radiation, an electrical oscillation is necessary and sufficient; and we have attended mainly to one kind of electric oscillation, viz. that which occurs in a condenser circuit when the distribution of its electricity is suddenly altered—

[1] Also in a volume of the Nature Series—*Popular Lectures and Addresses*, vol. i. "The Constitution of Matter."

as, for instance, by a discharge (§§ 124, 141). But the condenser circuit need not be thrown into an obviously Leyden jar form; one may have a charged cylinder with a static charge accumulated mainly at one end, and then suddenly released. The recoil of the charge is a true current, though a weak one; a certain amount of inertia is associated with it, and accordingly oscillations will go on, the charge surging from end to end of the cylinder, like the water in a tilted bath suddenly levelled: though the electrical surgings in this case are few.

In a spherical or any other conductor, the like electric oscillations may go on; and the theory of these oscillations has been treated with great mathematical power both by Sir Wm. Niven and by Prof. Lamb.[1]

Essentially, however, the phenomenon is not distinct from a Leyden jar or condenser circuit; for the ends of the cylinder have a certain capacity, and the cylinder has a certain self-induction; the difficulty of the problem may be said to consist in finding the values of these things for the given case. The period of an oscillation may still be written $2\pi\sqrt{(LS)}$; only, since L and S are both very small, the "frequency" of vibration is likely to be excessive. And when we come to the oscillation of an atomic charge the frequency may perhaps surpass the rate of vibration which can affect the eye. The damping out of such vibrations, if left to themselves, will be also a very rapid process, because the initial energy is but small. It can be calculated that the oscillation of an atomic

[1] *Phil. Trans.* 1881 and 1883. Also by Prof. J. J. Thomson, *Math. Soc. Proc.* April 1884.

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charge would give rise to ultra-violet rays. It is probably because these ultra-violet rays synchronize with the period of vibration of atomic charges that they have such extraordinarily powerful chemical effects (§ 187).

157A. The waves of visible light, if produced by electric oscillation in atoms, must be caused, not by simple oscillations as in conducting spheres, but by surgings in conducting channels, more after the fashion of a Leyden jar circuit. But it may be held more probable that the vibrations to which ordinary light is due are mechanical vibrations of the substance of the atoms, and that the electrical disturbance accompanying it and recognized by the retina is a secondary effect. Light is now believed to be emitted by perturbations in the orbital revolution of electronic constituents of an atom.

I have also pointed out [1] that the rods and cones in the retina are of a diameter suitable for responding directly to electric oscillations of the frequency of visible light; and by means of a graduated series of metallic cylinders facing a source of electric radiation end-on, have so to speak imitated a retina which is able to select and respond to vibrations of assorted pitch, after the manner of Corti's fibres in the ear. (See Fig. 60 below.) But at present there is no physiological basis for such an assortment of size among the rods and cones as would correspond to the three colour sensations red, green, and violet. Perhaps it will be looked for.

The correspondence of the diameter of the rods

[1] *Nature*, vol. xli. p. 462, March 1890.

and cones to the wave-length of ordinary light may be accidental, but it seems hardly likely to be mere coincidence.

In all probability sight is a chemical sense, some molecular complexes being shaken asunder by the impact of synchronous ether waves, and thus stimulating the associated nerve-fibres. The nourishment supplied by the tissues may be trusted to build up the substances again almost as fast as they are shaken asunder; leaving, however, a little margin for lag, to correspond to the observed fact of retinal "fatigue."

158. Whether the charge oscillates in a stationary conductor, or whether a charged body vibrates as a whole, it equally constitutes an alternating current and can equally well be treated as a source of radiation. Now when we were considering the subject of electrolysis, we were led to think of molecules as composed of two atoms or groups of atoms, each charged with equal quantities of opposite kinds of electricity. Under violent disturbance we may suppose the components of the molecules to be set in vibration—the rate of vibration depending on and being characteristic of the contents of the particular molecule. The atoms being charged, however, an electric radiation is excited and propagated outwards. These vibrations would appear to be often of the frequency suited to our retina; hence these vibrating atoms indirectly constitute our usual source of light. The "frequency" of the visible radiation can be examined and determined by optical means (some form of interference experiment, usually a diffraction grating), and hence many of the rates of vibration

possible to the atoms of a given molecule under given circumstances become known: and this is the foundation of the science of spectroscopy.

It is possible that the long duration of some kinds of phosphorescence may be due to the atoms receiving indirectly some of the ethereal disturbance, and so prolonging it by their inertia, instead of leaving it to the inertia of the ether alone. It is possible also that the definite emissivity of some fluorescent substances is due to periods of vibration proper to their atoms, which, being disturbed in an indirect way by receipt of radiation, re-emit the same radiation in a modified, and, as it were, laden manner.

159. To get some further idea concerning the way in which an oscillating charge, or an oscillating charged body, can propagate radiation, refer back to Fig. 39, Part III., and imagine the rack oscillating to and fro. It will produce rotatory oscillation in the wheels gearing into it, these again in the next, and so on. If the wheel-work were rigid, the propagation would go on at an infinite speed to the most distant wheels; but if it be elastic, then the pace of propagation depends on the elasticity and the density, in a way we have already said enough about. The line of rack is the direction of electric oscillation, the axes of the wheels the direction of magnetic rotatory oscillation, and at right angles to both these is the direction of advance of the waves. True, the diagram is not a space representation, it is a mere section, and is only a crude suggestion of a mechanical analogy to what may be taking place.

The wheels, being perfectly geared together and into the rack, represent an insulator or dielectric; there is no slip or frictional dissipation of energy—in other words, there are no true electric currents. The electric oscillation is a mere displacement-oscillation due to elasticity and temporary give of the elastic wheels; whereby, during each era of acceleration, they are thrown slightly into the state represented in Fig. 46 as contrasted with Fig. 37.

Effects of encountering a New Medium.

160. Now contemplate an advancing system of waves, and picture their encounter with an obstacle; say, a medium of greater density, or less elasticity, or both. If the new medium is a perfect insulator, it must be considered as having its wheels thoroughly geared up, both with each other and with those of the initial medium, so that there is no slip or dissipation of energy at the surface. In this case none of the radiation will be lost: some will be reflected, and some transmitted, according to ordinary and well-known mechanical laws. The part transmitted will suddenly begin to travel at a slower pace, and hence if the incidence were oblique would pursue a somewhat different path. Also, at the edges of the obstacle, or at the boundary of any artificially limited portion of the wave, there will be certain effects due to spreading out and encroaching on parts of the medium not lying in the direct path. These refraction and diffraction effects are common to all possible kinds of wave propagation, and there is nothing specially necessary to be said concerning

electrical radiation on these heads which is not to be found in any work on the corresponding parts of optics, except that the velocity in every non-absorptive substance is characterized by the two ethereal constants, the electric κ and the magnetic μ; being equal, in fact, to the reciprocal of their geometric mean.

161. Concerning the amount and direction of the reflected vibrations there is something to be said, however, and that something very important;[1] but it is no easy subject to tackle, and I fear must be left, so far as I am concerned, as a distinct, but perhaps subsequently-to-be-filled-up, gap.

If the gearing between the new medium and the old is imperfect—if, for instance, there were a layer of slippery wheels between them, representing a more or less conducting film—then some of the radiation would be dissipated at the surface, not all would be reflected and transmitted, and the film would get to a certain extent heated. By such a film the precise laws of reflection might be profoundly modified, as they would be also if the transition from one medium to another were gradual instead of abrupt. But all these things must remain, for the present, part of the unfilled gap.

Electric Radiation encountering a Conductor.

162. We will proceed now to the case of a *conducting* obstacle—that is, of waves encountering a medium whose electrical parts are connected, not by elasticity but by friction. It is plain here that not only at the

[1] Lord Rayleigh, *Phil. Mag.* Sept. 1888.

outer layer of such a medium, but at every subsequent layer, a certain amount of slip will occur during every era of acceleration, and hence that in penetrating a sufficient thickness of a medium endowed with any metallic conductivity the whole of the incident radiation must be either reflected or destroyed: none can be transmitted (§ 104).

Refer back to Fig. 43, and think of the rack in that figure as oscillating. Through the cog-wheels the disturbance spreads without loss, but at the outer layer of the conducting region A B C D a finite slip occurs, and a less amount of radiation penetrates to the next layer, E F G H, and so on. Some thickness or other, therefore, of a conducting substance must necessarily be impervious to electric radiation: that is, it must be opaque. And since a good conductor dissipates very little energy, it will not act by absorbing the radiation, but will reflect it. (See §§ 153 and 164.)

Conductivity is not the sole cause of opacity. It would not do to say that all opaque bodies must be conductors. But conductivity is a very efficient cause of opacity, and it is true to say that all conductors of electricity are necessarily opaque to light; understanding, of course, that the particular thickness of any homogeneous substance which can be considered as perfectly opaque must depend on its conductivity. It is a question of degree, and a minute but specifiable fraction of an original disturbance may be said to get through any obstacle. Practically, however, it is well known that a thin, though not the thinnest, film of metal is quite impervious to light.

163. The statement that conductivity is not the sole

cause of opacity has reference to the kind of opacity caused by heterogeneity. A confused mass of perfectly transparent substance may be quite opaque; witness foam, powdered glass, chalk, etc.

Hence, though a transparent body must indeed be an insulator, the converse is not necessarily true; an insulator need not necessarily be transparent. A homogeneous, flawless insulator must, however, be transparent to some, though not necessarily to all, wave-lengths. A homogeneous and flawless opaque body, if really opaque to all wave-lengths, must be a conductor.

These, then, are the simple connexions between two such apparently distinct things as conducting power for electricity and opacity to light, which Maxwell's theory points out; and it is possible to calculate the theoretical opacity of any given simply-constructed substance by knowing its specific electric conductivity. There are, however, reasons for asserting that the opacity as so calculated does not agree very well with that actually observed. There is a field for work here.[1]

Fate of the Radiation.

164. To understand what happens to radiation impinging on a conducting body, it is most simple to proceed to the limiting case at once and consider a perfect conductor. In the case of a perfect conductor the wheels are connected not even by friction; they

[1] For a further discussion of opacity, see Lodge, *Phil. Mag.* April 1899.

are not connected at all. Consequently the slip at the boundary of such a conductor is perfect, and there is no dissipation of energy accompanying it. The blank space in Fig. 38 represented a perfectly conducting layer. Ethereal vibrations impinging on a perfect conductor practically arrive at an outer confine of their medium : beyond, there is nothing capable of transmitting them ; the outer wheels receive an impetus which they cannot get rid of in front, and which they therefore return back, the way it came, to those behind them : the radiation is totally reflected. It is like what happens when a sound-pulse reaches the open end of an organ-pipe ; like what happens when sound tries to go from water to air ; like the last of a row of connected balls along which a knock has been transmitted ; except that in the case of these longitudinal pulses the phase is reversed, whereas for transverse pulses under the same circumstances it is just not reversed. Our massive elastic wheels, especially the wheels of Fig. 48, are able to represent the act of reflection quite properly.

165. The reflected pulses will be superposed upon and interfere with the direct pulses, and accordingly, if the distances are properly adjusted, we can have the familiar formation of fixed nodes and stationary waves (§ 130).

166. The point of main interest, however, is to notice that a perfect conductor of electricity, if there were such a thing, would be utterly impervious to light : no light could penetrate its outer skin, it would all be reflected back : the substance would be a perfect reflector for ether waves of every size.

Thus with a perfect conductor, as with a perfect non-conductor, there is no dissipation. Radiation impinging on them is either all reflected, or some reflected and some transmitted. It is the cases of intermediate conductivity which destroy some of the radiation and convert its ethereal vibrations into atomic vibrations, *i.e.* which convert it into heat.

167. The mode in which radiation or any other electrical disturbance diffuses with continual loss through an imperfect conductor can easily be appreciated by referring to § 103 again. The successive lines of slip, A B C D, E F G H, &c., are successive layers of induced currents. An electromotive impulse loses itself in the production of these currents, which are successively formed deeper and deeper in the material, according to laws of diffusion.

If the waves had impinged on one face of a slab, a certain fraction of them would emerge from the other face—a fraction depending on the thickness of the slab, according to a logarithmic or geometrical-progression law of decrease. (See also Chap. XVI.)

It may occur to a student to ask what happens to the *energy* of light in cases of "interference." Interference is often popularly expressed by saying that two lights under certain conditions, when superposed, produce darkness; two sounds produce silence, and so on. Hence it is natural to inquire what becomes of the energy. The answer is that in all such cases the energy is merely redistributed and localized, not affected in quantity. Interference phenomena always distribute themselves in bands, either in space or time. In the case of light there are visible "interference-bands," the light being removed from certain dark strips and piled up in intermediate extra-luminous strips, but the total illumination is unaltered ; it is only a question of distribution. In the case of sound a similar phenomenon shows itself as "beats," and the periods of silences are compensated by extra loudness in the alternating sounds. The same is true of the criss-cross pattern when surface waves of water, generated by throwing in two stones, cross each other. It is a familiar fact that after the crossing the waves proceed uninjured and unaffected. Interference is not the same as destruction ; the interference is only local and temporary.

CHAPTER XV

ELECTRIC AND MAGNETIC INFLUENCES ON LIGHT

168. WE must now mention one or two phenomena which depend entirely upon a modification of ether by the neighbourhood of matter, and which we have reason to believe would not occur in free ether at all. These are the optical phenomena of Faraday and Kerr, and the electric phenomenon of Hall.

Faraday discovered, long before there was any other connexion known between electricity and light—except indeed the familiar luminous phenomena which accompany electric discharges of various kind—that the plane in which light-vibrations occur could be rotated by transmitting light through certain magnetized substances along the lines of magnetic force. To make this effect easily manifest, it is necessary to use plane-polarized light, and to transmit it through a fair length of magnetized substance, analyzing it after emergence, and showing that, though it remains plane-polarized, the plane has been rotated,—possibly through a right angle or more.

Now in a general way it is easy to imagine that, inasmuch as something of the nature of a rotation is going on in a magnetic field round the lines of force, vibrations travelling into such a field along these lines should be twisted round corkscrew fashion and emerge vibrating in a different plane. But on trying to follow out this process into detail, it turns out not quite so simple a matter. It has, however, no business to be a very simple and obvious consequence of the existence of a magnetic rotation round the rays of light, else would it occur in free space, and in the same direction in all media. But the facts are that in free space—that is, in free ether—it does not occur at all; and the direction of rotation is not the same for all media: substances can, in fact, be divided into two groups, according to the way in which given magnetization shall rotate the plane of polarized light passing through them.

169. Similar statements can be made concerning the electrostatic optical effect discovered by Dr. Kerr; who showed that plane-polarized light transmitted across the lines of force in an electrostatic field could, in certain media, come out elliptically polarized. Now, inasmuch as an electric field is a region of strain, and strain in transparent bodies is well known to make them slightly doubly refracting and able to turn plane-polarized into elliptically polarized light, it is very easy to imagine such a result in an electric field to be natural and probable. But the explanation is not so simple as that, else it ought to be a large effect, occurring in all sorts of media in the same direction, and likewise in free space. But the facts are that it does not occur at all in free space, and it occurs in different

senses in different substances; so that again they can be grouped into two classes, according to the sign of the Kerr effect.

Thus, then, the rotatory effect of a magnetic field upon light, discovered by Faraday, and the doubly refracting effect of an electrostatic field upon light, discovered by Kerr, agree in this: that they are both small or residual effects, depending on the existence of a dense or material medium, and both varying in sign according to the nature of the medium.

170. The only substance in which the Faraday effect is large, is iron; including with iron the other highly magnetic substances. The discovery of the effect in these bodies was likewise made by Kerr. The difficulty of dealing with them is that they are very opaque, and hence that the merest film of them can be used. The film can be used either by way of transmission or by way of reflection, it matters not which, but reflection is the way in which it was first done. Light reflected from the polished face of a magnet has indeed barely penetrated at all into the substance of the iron before being sent back; still, it has penetrated deep enough to be distinctly rotated by the tremendous magnetic whirl which it finds there.

171. All these highly magnetic substances are metallic conductors, and are therefore very opaque. Whether there is any real connexion between high magnetic susceptibility and conductivity is more than I can say. But it is quite natural, and indeed necessary, that the greatest portion of light should be reflected on entering a highly magnetic medium; because in such a medium the ethereal density, $4\pi\mu$,

is so great, and hence the velocity of wave transmission must undergo a sudden and immense decrease —a circumstance always causing a great amount of reflection ; just as when sound tries to pass from any one medium to a much denser one.

But the opacity of iron and other magnetic substances may be explained by the mere fact of their conducting power, just like other metals, and no noteworthy effect of their large value of μ need be detectable optically.

If a non-conducting, highly magnetic, substance could be found, it would probably reflect a great deal of light at its surface, though it would not dissipate that which entered it. Such a substance would be most interesting to submit to experiment, but perhaps its existence presupposes a combination of impossible properties. Certainly it has not yet been discovered.

As to the phenomenon detected by Hall, it appears intimately associated with that of Faraday, and it will be most simple to omit all reference to it for the present.

172. A general idea of what is happening in the Faraday and Kerr phenomena can be given thus.

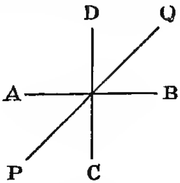


FIG. 49.

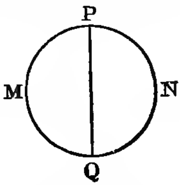


FIG. 50.

A simple vibration, like a pendulum-swing, or any other oscillation in one plane, can be resolved into two others in an infinite variety of ways; just as one force can be resolved into any number of pairs of equivalent forces. The two most useful modes of analyzing a simple vibration into a pair of constituents are these: (1) two equal components, likewise plane vibrations, each inclined at 45° to the original,—as when P Q is resolved into A B and C D (Fig. 49); and (2) two equal circular or rotatory oscillations in opposite directions,—as when P Q is resolved into P M Q and P N Q (Fig. 50). The first method of resolution is useful in explaining Kerr's effect, the second in explaining Faraday's.

Of the two component vibrations, A B and C D, into which P Q can be supposed analyzed, let some cause, no matter what, make one gain upon the other, so that in travelling along a line perpendicular to the paper one goes a little the quicker: the effect at once is to change the character of the vibration into which they will recompound. After the gain, they no longer reproduce the original simple vibration P Q: they give rise to elliptic, or it may be to circular, vibrations; this last, if the retardation is equal to a quarter period.

These are matters fully treated in any elementary treatise on polarized light, and they are quite easily illustrated by means of a simple pendulum. We may assume them known.

Similarly with the second system of analyzing the vibration into two opposing circular ones. If the components travel through any interposed medium at the same rate, they will, on emergence, reproduce the original vibration in its original position; but if one travels quicker than the other, they recombine into a vibration of the same character as at first, but turned through a certain angle. Thus, anything which retards one of the *rectangular* components behind the other changes the character of the vibration from plane into elliptical; while anything which retards one of the *circular* components behind the other leaves the character of the vibration unaltered, but rotates it through a certain angle.

173. So far we have said nothing but the simplest mechanics. The next point to consider is, What determines the rate at which light travels through any substance? This we have discussed at length (§ 128), and shown to be $\frac{1}{\sqrt{(\kappa\mu)}}$. Anything which increases either the electric or the magnetic permeability of the medium decreases the velocity of light. Now, when a medium is already subject to a violent strain in any one direction, it is possibly less susceptible to further strain in that direction and responds less readily. Not necessarily so at all: such an effect would only be produced when the strain was excessive, when the medium was beginning to be overdone, and when its properties began thereby to be slightly modified. There are reasons for believing the specific inductive capacity of most media to be very constant; of some media, perhaps, precisely constant; but if there were any limit beyond which the strain could not pass, it is probable that on nearing the limit the specific inductive capacity would be altered—possibly increased, possibly diminished—one could hardly say which. Quincke has investigated this matter, and has shown that the value of κ is affected by great electric strain.

Suppose now that a dielectric is subject to a violent electrical stress, so that its properties along the lines of force become slightly different from its properties at right angles to those lines. The value of κ will not be quite the same along the lines of strain as across them, and accordingly the rectangular component of a vibration resolved along the lines of force will travel rather quicker or rather slower than the component at right angles; because the velocity of transmission depends upon κ, as already explained: such a medium at once acquires the necessary doubly-refractive character, and will show Kerr's effect.

174. Similarly with magnetization. It is well known that for many media μ is not constant. Take iron, for instance. For very small magnetizing forces the susceptibility is moderate, and increases as they increase; at a certain magnetization it reaches a maximum, and then steadily decreases. But not only is it thus very inconstant, its ascending and descending values are not the same. To forces tending to magnetize it more, the susceptibility has one value; to forces tending to demagnetize it, it has another and in general smaller value. This property has been specially studied by Ewing, and has been called by him "hysterēsis." Slightly susceptible substances cannot be magnetized to anything like the same extent, and hence the property in them has been less noticed, perhaps not noticed at all. Nevertheless it must exist in every substance which exhibits a trace of permanent magnetism, and every substance I have tried appears to show some such trace.[1]

[1] See *Nature*, vol. xxxiii. p. 484.

175. The direction of rotation will depend on whether the value of μ is greater for small relaxations, or for small intensifications, of magnetizing force; and diamagnetic substances may be expected to be opposite in this respect to paramagnetic ones. Any substance for which μ is absolutely constant, whatever the strength of magnetic polarization to which it is submitted, can hardly be expected to exhibit any hysterēsis; the ascending and descending curves of magnetization will coincide, being both straight lines, and such a substance will show no Faraday effect. Similarly, any substance for which κ is absolutely constant, whatever the electric polarization to which it is submitted, can show no Kerr's effect. Free space appears to be of this nature; and gases approach it very nearly, but not quite.

In iron, μ is greater for an increasing than for a decreasing force, as is shown by the loops in Ewing's curves; hence the circular component agreeing in direction with the magnetizing current will travel slower than the other component, and hence the rotation in iron will be against the direction of the magnetizing current. The same appears to hold in most paramagnetic substances, and the opposite in most diamagnetic; but the mere fact of paramagnetism or diamagnetism is not sufficient to tell us the sign of the effect in any given substance. We must know the mode in which its magnetic permeability is affected by waxing and by waning magnetization respectively.

Possible Electrical Method of detecting the Faraday Effect.

176. Thus far we have considered the rotation of electric displacement by a magnetic field as being examined optically; the displacements being those concerned in light, and the rotation being detected by a polarizing analyzer suitable for determining the direction in which the vibrations occur, before and after the passage of light through a magnetized substance. This is the only way in which the effect has at present been observed in transparent bodies. But we ought not to be limited to an optical method of detection.

Electrical displacements are easily produced in any insulator, and if it be immersed in a strong magnetic field, so that the electric and magnetic lines of force are at right angles to each other, every electric disturbance ought to experience a small rotation. A steady strain will not be affected; it is the variable state only which will experience an effect; but every fresh electric displacement should experience a slight rotatory tendency, just like the displacements which occur in light.

Now to rotate a displacement A B into the position A C requires the combination with it of a perpendicular displacement B C (Fig. 51). Hence the effect of the magnetic field upon an electric displacement, A B, may be said to be the generation of a small perpendicular E.M.F., B C, which, compounded with the original one, has the resultant effect A C. It will be only a temporary effect, lasting while the displacement is being produced, and ceasing directly a steady state of strain is set up.

An inverse E.M.F., A D, will be excited by the same magnetic field directly the displacement is reversed.

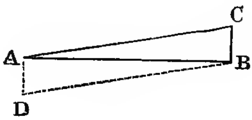


Fig. 51.

And so, if a continual electric oscillation is kept up between A and B in a magnetic field, an accompanying very minute transverse oscillation may be expected and may be looked for electrically.

Some such arrangement as that here shown (Fig. 52) may be employed: a square of heavy glass, perforated with four holes towards the centre, supplied

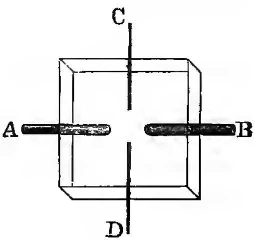


Fig. 52

with electrodes: one pair of electrodes, A, B, to be connected with the poles of some alternating machine, and the other pair, C, D, connected to a telephone or other detector of minute oscillatory disturbance. So soon as a strong steady magnetic field is applied, by placing the glass slab between the poles of a strong magnet, the telephone ought to be slightly affected by the transverse oscillations. This effect has not yet been experimentally observed, though at Liverpool I had a bored piece of glass ready to look for it, for some time, but it seems to me a certain consequence of the Faraday rotation of the plane of polarization of light.

Hall Effect.

177. Although the existence of this transverse E.M.F., excited by a magnetic field in substances undergoing varying electric displacement, has at present only been detected optically in transparent bodies, *i.e.* in insulators, yet in conductors the corresponding effect with a steady current has been distinctly observed electrically. By many persons it had been looked for (by Prof. Carey Foster and the writer, among others, though unfortunately they were not sufficiently prepared for its extreme smallness); by Prof. E. H. Hall, then at Baltimore, was it first successfully observed.

In conductors it is natural to use a conduction-current instead of a displacement-current. A steady current can be maintained in a square or cross of gold-leaf, or other thin sheet of metal, between the electrodes A, B; and a minute transverse E.M.F. can be detected, causing a very weak steady current through a galvanometer connected to the terminals C, D, so soon as a strong magnetic field is applied perpendicularly to the plate. Fig. 53 will sufficiently indicate the arrangement. The poles of the magnet are one above and one below the paper.

In iron it is easy to see which way the transverse E.M.F. ought to be found. It has been shown (§ 175) that a displacement will be rotated in iron against the magnetizing current; hence to rotate the displacement A B to A C (Fig. 51) requires in iron a clockwise magnetizing current. Such a current, or, what is the same thing, a south pole below the paper, a north pole

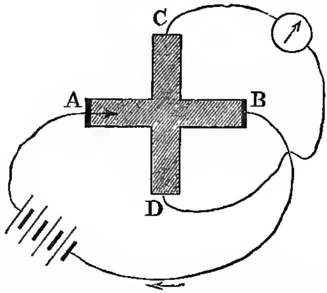


FIG. 53.—The direction of the transverse E.M.F. excited by the earth's vertical magnetic field in this conductor, conveying a current as shown, is C D if it represents gold, D C if it represents iron.

above, excites, in the cross of Fig. 53, an E.M.F. in the direction D C; and this by Ampère's rule is just the direction in which the conductor itself is urged by the magnetic forces acting on the current-conveying substance. Most diamagnetic substances should exhibit a transverse E.M.F. in the opposite sense. This transverse E.M.F., excited in conductors conveying a current in a magnetic field, is the effect known by the name of Hall. It is, as Prof. Rowland and others have pointed out, intimately connected with the Faraday rotation of light. (Cf. Fig. 51.)

178. Unfortunately a pure and simple Hall effect is a difficult thing to observe. Magnetism affects the conductivity of metals in a rather complicated manner; and strains affect their thermo-electric properties. Now a metal conveying a current in a magnetic field is certainly more or less strained by mechanical forces; and hence heat will be developed unequally in different parts, by a sort of Peltier effect; and the result of this will be to modify the resistance in patches, and so to produce a disturbance of the flow which may easily result partly in a transverse E.M.F. This has been pointed out by Mr. Shelford Bidwell.

The more direct effect of magnetism on conductivity may be negligibly small in many metals, but in bismuth it is certainly large. Both of these spurious effects seem to be large in bismuth, and probably quite mask any true Hall effect there may be in that metal. In all cases the existence of these spurious effects makes it difficult to be sure of the magnitude and sign of the real rotational effect.

179. But, it may be asked, what right have we to distinguish between a real and a spurious Hall effect? If a transverse E.M.F. can be predicted by reason of known strains and thermo-electric properties, as well as by known rotation of light effects, why should the two things be considered different? Why should they not be different modes of regarding one and the same phenomenon?

In other words, may not the Faraday rotation of light be due to infinitesimal temporary strains and heatings in the medium, caused by the fact that minute electric displacements are occurring in a violent magnetic field? May not the Hall effect also be accounted for by the action of magnetism on thermo-electric properties? These are questions capable of being answered by a quantitative determination of the amounts and direction of the effects to be expected, and a comparison with those actually observed. I do not know of data, at present obtained, sufficient to enable us to answer it. If their answers should turn out in the affirmative, several apparently distinct phenomena will be linked together.

In the *Philosophical Magazine* for May 1885, Mr. Hall gives some more measurements, showing that in bismuth the effect is enormous, and in the same direction as in copper, whereas in antimony it is also great and in the same direction as in iron. All these things seem to point to some thermo-electric connexion.

Effect of Magnetic Field on Resistance.

179A. Another interesting effect of magnetism upon conductors, which demands more theoretical attention than it has yet received, is the change in conductivity which metals exhibit when subjected to a magnetic field across the current flow. An indication of this phenomenon was detected by Professor S. P. Thompson in 1883 during a plotting of equipotential lines in a metal sheet immersed in a magnetic field. The resistance of tin and gold appeared to decrease about a third and two-thirds of one per cent., and that of iron seemed to increase about two parts in ten thousand.

These results were communicated as a paper to the

Physical Society of London on March 22, 1884, but it was not published.

In the same year, quite independently, Righi discovered a much larger effect in bismuth, as well as in other metals. In bismuth the effect is so remarkable that Lenard converted it into a method of quickly measuring the strength of a magnetic field, by observing its effect on the resistance of a flat spiral of bismuth wire, inserted between the pole pieces.

The resistance of bismuth, whether pure or not, increases when it is placed in a magnetic field, especially when the magnetic field crosses the line of current. In the latter case the increase of resistance can be as much as one-eighth of its value.

Lenard found the resistance of a spiral of bismuth wire, placed normal to the magnetic lines of force, to increase from 1, its normal value, to 1·32 for a field of 8000 c.g.s., and 1·8 for a field of 16000 c.g.s.

When a bismuth wire is parallel to the lines of force, the change is distinctly less; and he considered that he observed some difference between the resistance to alternating and that to direct currents.

Other Outstanding Problems.

184. Outstanding problems bristle all over the subject, and if I pick out any for special mention it will only be because I happen to have made some experiments in their direction myself, or otherwise have had my thoughts directed to them.

Referring back to § 66 at the end of Part II., a "current regarded as a moving charge," it is natural to ask, Is this motion to be absolute, or relative to the ether only, or must it be relative to the indicating magnetometer? In other words, if a charged body and a magnetic needle are flying through space together, as, for instance, by reason of the orbital motion of the earth, will the needle experience any deflecting couple?

It is one of many problems connected with the ether and its motion near gross matter—problems which the experiment of Fizeau (showing that a variable part of ether was bound with matter and transmitted with it, while another constant portion was free and blew through it) began to illuminate:—aberration problems such as exercised the genius of Sir George G. Stokes; problems connected with the motion of ether near great masses of matter, like those which Michelson so skilfully attacked experimentally; it is among these that we must probably relegate the questions whether absolute or relative motion of electric charges is concerned in the production of magnetic field, and what absolute motion through the ether precisely means. (*Phil. Mag.* Oct. 1898.)

186. Then, again, there is the influence of light on conductivity. Annealed selenium, and perhaps a few other things, improve in conductivity enormously when illuminated. The cause of this is unknown at present, and whether it is a general property of matter, possessed by metals and other bodies to a slight degree, is uncertain; for the experiments of Börnstein, with an affirmative result for the case of metals, have been seriously criticised.

Even though metals show no effect, yet electrolytes might possibly do so, but the effect, if any, is small;

and it is particularly difficult in their case to distinguish any direct radiation effect from the similar effect of mere absorbed radiation or heat.

The writer has found that a glass test-tube kept immersed in boiling water conducted distinctly better when the blinds of a room were raised than when they were lowered, though nothing but diffuse daylight fell upon it. But as the effect could have been produced by a rise in temperature of about the tenth of a degree, and as the absorption of diffuse daylight is competent to produce a rise of temperature as great as this in the glass of a thermometer-bulb, even though immersed in boiling water, he feels constrained to regard the result, though very clear and distinct, as after all a negative one, and has accordingly not published it.

187. The fact that ultra-violet waves have a period of vibration synchronous with probable electric vibration in molecules (§ 157) seems to cause a multitude of effects now being discovered. Hertz noticed that the light of one spark influenced another at a distance, so that a sparking interval was virtually shortened when illuminated. Wiedemann and Ebert have further investigated this, and obtained several interesting results, distinctly proving that it is ultra-violet light which is effective. Hallwachs has discovered that a clean metallic plate can become electrified when light falls upon it. And there are a number of other similar facts, some long known, some recent, which all illustrate the molecular effects of light. It appears probable that they all depend on some synchronized disturbance set up in the constitution

of atoms or molecules. These physical effects appear to be of the same order as those other familiar but vaguely grasped facts summed up under the category of the chemical or actinic power of light. For that light affects silver salts, ebonite, hydrogen, and chlorine, &c., is an old story. Some progress is now likely to be made in ascertaining the precise mode in which these changes occur (§ 33); cf. Lecture VI. below.

188. Before 1888 I should have put in a prominent position among outstanding problems the production of electric radiation of moderate wave-length; and the performance, with this radiation, of all the ordinary optical experiments — reflection, refraction, interference, diffraction, polarization, magnetic rotation, and the like (§ 1). But a great part of this has now been done, and so these things come to be mentioned under a different heading:—

Electric Waves in Space.

"Conclusion" seemed an absurd word to write in 1889, when the whole subject was astir with life, and when every month seemed to bring out some fresh aspect, to develop more clearly some already glimpsed truth. The only proper conclusion to a book dealing with electricity at such a time was to herald the advent of the very latest discoveries, and to prepare the minds of readers for more.

189. Referring back to Chap. XIV., to §§ 1 and 8, and all Part IV., we spoke confidently of a radiation being excited by electric oscillations, a radiation which travelled at the same rate as light, which was reflected

and refracted according to the same laws, and which, in fact, was identical with the radiation able to affect our retina, except in the one matter of wave-length. Such a radiation, the world now knows, was definitely obtained and examined by Dr. Hertz, at Karlsruhe, afterwards Professor at Bonn; and in Decemer, 1888, Prof. von Helmholtz communicated to the Physical Society of Berlin an account of Dr. Hertz's researches.

For electric waves along wires, observed by me in 1888 likewise, see Chap. XIII. above, pp. 235–7.

The step in advance which enabled Dr. Hertz to do easily that which others had long wished to do, was the invention of a suitable receiver. Light when it falls on a conductor excites first electric currents and then heat. The secondary thermal effect was what we had thought of looking for; but Dr. Hertz boldly took the bull by the horns, looked for the direct electric effect, and found it manifesting itself in the beautifully simple form of microscopic sparks across a gap between two conductors, or between the ends of a looped conductor.

He took a brass cylinder, some inch or two in diameter, and a foot or so long, divided into two halves with a small sparking interval between, and connected the halves to the terminals of a small induction-coil; every spark of the coil caused a charge in the cylinder to surge to and fro about five hundred million times a second, and to disturb the ether in a manner precisely equivalent to a diverging beam of plane-polarized light, with waves about thrice the length of the cylinder.

The radiation, so emitted, can be reflected by plane conducting surfaces, and can be concentrated by metallic parabolic mirrors; the mirror ordinarily used being a large parabolic cylinder of sheet zinc, with the electric oscillator situate along its focal line. By this means the effect of the wave could be felt at a fair distance, the receiver consisting of a synchronized pair of straight conductors with a microscopic spark-gap between them, across which the secondary induced sparks were watched for. By using a second mirror, like the first, to catch the parallel rays and reconverge them to a focus, the effect could be appreciated at a distance of 20 yards. If the receiving mirror were rotated through a right angle, it lost its converging power on this particular light.

Apertures in a series of interposed screens proved that the radiation travelled in straight lines (roughly speaking, of course).

A gridiron of metallic wires is transparent to the waves when arranged with the length perpendicular to the electric oscillations, but it reflects them when rotated through a right angle; so that the oscillations are proved to take place along the conducting wires. The wire grid thus represented a kind of analyser, and established the polarization of the radiation. The receiver itself also acted as analyser, for if rotated much it failed to feel the disturbance.

Conducting sheets, even thin ones, were very opaque to the electrical radiation; but non-conducting obstacles, even such as wood, interrupt it very little, and Dr. Hertz remarks, "not without wonder," that the door separating the room containing the source of radiation from that containing the detecting receiver might be shut without intercepting the communication. The secondary sparks were still observed.

But the most crucial test yet applied was that of refraction. A great prism of pitch was made, its faces more than a yard square, and its refracting angle about 30°. This being interposed in the path of the electric rays, they were lost to the receiver until it was shifted considerably. Adjusting it till its sparks were again at a maximum, it was found that the rays had been bent by the pitch prism, when set symmetrically, some 22° out of their original course; and hence that the pitch had an index of refraction, for these 2-foot waves, about 1·7.

190. These are great experiments. When the first edition of this book was written, the latest of them were but a month or two old, and they were only a beginning. Most of the experiments were simple, and had already been repeated.[1] They seem likely to settle many doubtful points. There has been a long-standing controversy in optics, nearly as old as the century, as to whether the direction of the vibrations was in, or was perpendicular to, the plane of polarization; in other words, whether it was the elasticity or the density of the ether which varied in dense media; or, in the language of Maxwell's theory whether it was the magnetic or the electric disturbance that coincided with that plane. This point had indeed, by the exertion of extraordinary genius, been

[1] See Fitzgerald and Trouton, *Nature*, Vol. xxxix. p. 391; also Dr. Dragoumis, on vacuum-tube detectors, *Nature*, Vol. xxxix. p. 548. Also Lodge and Howard, who concentrated the radiation by a suitable lens; *Phil. Mag.* July 1889.

almost settled already, through the consideration of common optical experiments; but now that we are able electrically to produce radiation with a full knowledge of what we are doing,—of its directions of vibration and all about it,—the complete solution of this and of many another recondite optical problem may be expected during the next decade to drop simply and easily into our hands. § 197 (see page 304).

We have now a real undulatory theory of light, no longer based on analogy with sound, and its inception and early development are among the most tremendous of the many achievements of the latter half of the nineteenth century.

In 1865, Maxwell stated his theory of light. Before the close of 1888 it is utterly and completely verified. Its full development is only a question of time, and labour, and skill. The whole domain of Optics is now annexed to Electricity, which has thus become an imperial science.

CHAPTER XVI

RECENT PROGRESS (1892)

191. THUS far in the first edition (1889). Since then much has been written concerning Hertz's experiments and the consequences deducible from them.[1] A brief account of the essential principles involved may be here suitable.

The discovery of Hertz, which made all the rest possible, was the fact that sparks could be excited in properly arranged conductors exposed to the electric radiation from an alternate current generator of sufficient rapidity. The oscillatory character of a Leyden jar discharge was referred to in § 19, and again in § 124; and the easiest way of displaying the spark-producing power of electric radiation is the plan I described in *Nature* of February 20, 1890, with the following diagram (Fig. 54).

[1] For instance, a set of three articles by Prof. Fitzgerald in *Nature*, vol. xliii. p. 536, and vol. xliv. pp. 12 and 31. Subsequently, in 1894, my own book "on the work of Hertz and his successors" appeared, as an expansion of a Royal Institution Lecture, and of a demonstration before the British Association at Oxford, showing how to signal by very small power to a fair distance, across space, using a Kelvin mirror-instrument as receiver.

Two similar Leyden jars are connected up to circuits of equal size ; but so that, while the circuit of A is interrupted by a spark gap, that of B is complete, the B circuit being conveniently adjustable in size, till it corresponds with the other, by means of a slider, S.

If, now, A is charged and discharged in the ordinary way, the oscillations at every discharge disturb the circuit of the jar B, exciting in it similar but feebler electric oscillations. If the two jars and their circuits are properly synchronized, as can be done by shifting

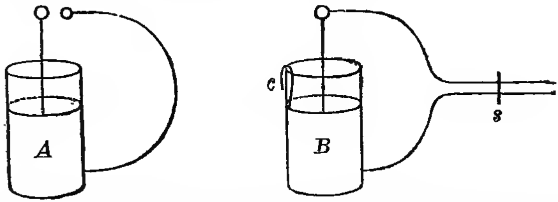


FIG. 54.—A couple of Leyden jars arranged so that a discharge in one causes the other short-circuited one to overflow aloog the easy tinfoil path, *c*. (See Lodge in *Nature*, vol. 41, p. 368. See also § 194.)

the slider S to and fro, the oscillations in B may be sufficiently violent to make it overflow. It cannot be expected to overflow its lip, unless this happens to be very much shallower than usual ; but a little tinfoil strip, *c*, pasted on the glass, and reaching over from the inner coating till it nearly touches the outer coating, provides an easy overflow path, of which the disturbance readily makes use. Accordingly, when the two circuits are arranged with their planes parallel, and their distance not more than two or three times their diameter, a bright little spark at the air-gap of the overflow path on the jar B can be seen at every discharge of the jar A.

A slight motion of the slider either way usually suffices to throw the jars out of tune, and to stop the effect.

192. The phenomenon is commonly spoken of as illustrating electric "resonance," which it certainly does very well; for the discharge of such a jar has many oscillations per spark, and accordingly there is opportunity for "beats" and destruction of incipient effect, unless the tuning is pretty exact; but the *name* "resonance" is too suggestive of some acoustic reverberation phenomenon to be very expressive. It is at present commonly used to express the sympathetic response of similarly tuned or timed vibrators in general, but even when thus used in acoustics it hardly conveys this meaning, except by reason of habit. The essential thing to be connoted is the synchronizing of the vibration-period of two things, and this is well expressed by the adjective "syntonic," which was suggested to me for the purpose by the late Dr. A. T. Myers. That which has been styled resonance I propose, therefore, in future, to call "syntony."

193. The alternations in the case of a circuit like this are what it is now customary to call moderately quick—for instance, about a million per second. It is easy to get them either slower or quicker. To get them quicker the wire part of the circuit may be diminished in length, and the coatings of the jar may be diminished in size and removed to a greater distance from each other.

The figures in the diagram below show the gradual transition from a Leyden jar to a Hertz oscillator as ordinarily made. The smaller and dumpier the arrangement the quicker will be its frequency of vibration. It is easy to make one to emit waves only a yard long, in which case its charge vibrates at the rate of three hundred million times a second. Quicker vibrators still can be obtained by using spheres. One sphere is sufficient, but sometimes several equal ones give a

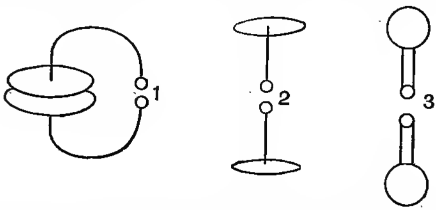


FIG. 55.—Showing the relationship between Hertz oscillator and Leyden jar.

stronger effect;[1] and I have succeeded in working with a sphere two inches in diameter, which vibrates twelve or thirteen times as rapidly as the one just mentioned above. But it is not feasible at present to produce recognisable vibrations of any such rate as a billion per second; whereas to affect the retina they must be at least 400 billions per second.[2]

194. Failing the retina, the principle of syntony enables waves to be detected: the "electric eye"

[1] See *Nature*, vol. xli. p. 462, March 1890. See also Fig. 64 below.

[2] A seconds pendulum beats a million times in twelve days; or a thousand million times in thirty years. A tuning fork sounding a note two octaves above middle C (one thousand a second) in thirty years vibrates a billion times. Hence before such a fork can execute the number of vibrations which are achieved in one second by dull red light a period of twelve thousand years must elapse.

being some conductor with the same rate of vibration. It may be alike in all respects, but usually there is a difference between sender and receiver. For instance, in Fig. 54, the circuit of the sender has a spark-gap

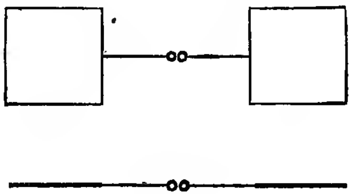


Fig. 56.

in it, but the circuit of the receiver must be closed; else the feeble beginnings of electric surgings, which are to be worked up by properly timed impulses, cannot occur. It is useless, therefore, to use as receiver a Leyden jar arranged like A, Fig. 54. The Leyden jar

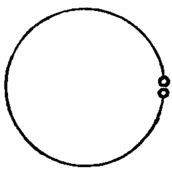


Fig. 57.

B must have its circuit carefully completed, and a side disturbance or overflow must be utilized as indication of the induced effect. (See Fig. 54.)

Some forms of Hertz oscillators, and methods for emitting from them a parallel beam, are shown in figures 56 to 58.

The circle in Fig. 57 represents primarily a *magnetic* receiver; for it is best held so that the magnetic oscillation occurs along its axis, *i.e.* perpendicular to its plane, and then sparklets or scintillæ may occur across its microscopic air-gap.

If the circle be turned so that the line joining its knobs is parallel to the *electric* force, this also can excite sparks; for it may be then regarded as a branched conductor, with one branch interrupted, and therefore ineffective. But as an explorer of electric force a linear receiver is simpler and is preferable. I commonly used a pair of stiff wires, each half a wave-length long, supported end to end on a long bar of mahogany, with their near ends pointed, and one of them movable in the direction of its length by a screw operating on it through a glass tube. With the wood near the points blackened and otherwise shaded from light, excessively minute sparks can be seen (Fig. 58).

A bulkier but more demonstrative receiver is an arrangement exactly like the oscillator, as in Fig. 56, but with an entire

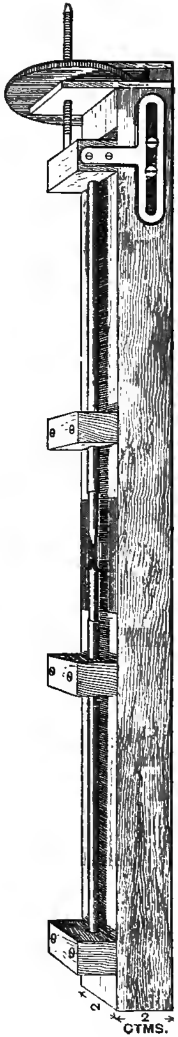


Fig. 58.—Linear receiver used by Lodge. A pair of copper wires each 26 centims. long, held in glass tubes a trifle shorter, and one of them movable by a screw with large head. Mounted on teak board 60 × 2 centims.

metal rod connecting the plates instead of one interrupted by knobs. Oscillations begin and increase in this, under the operation of syntony or resonance, and the consequent sparking or overflow can be detected by holding a penknife or other point to either of the plates.

A receiver exactly like an oscillator, with spark-gap in same position, really answers very fairly; but it

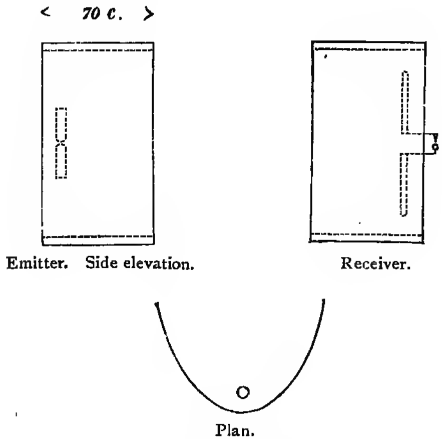


FIG. 59.—Small Hertz vibrater and receiver, arranged in focus of parabolic mirror for emission and reception of parallel beam.

must be responding to a subordinate oscillation, chiefly one in each half of the emitter; or else is not really syntonic. Precise tuning is never *very* important in these short-waved vibrators, because their rate of damping is so enormous. With greater capacity, as in the Leyden jars of § 191, tuning is essential.

195. Sometime as oscillator I used a simple sphere,

sparked to, on either side, by knobs connected with an induction coil; and a precisely similar sphere acted as receiver, a penknife being held to it or lightly dragged over it at the end of the proper diameter. The

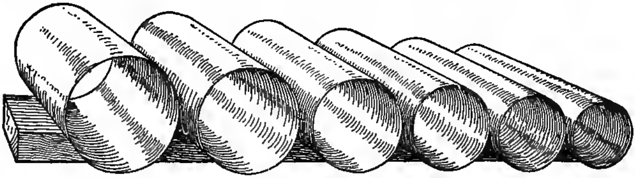


FIG. 60.—Lodge's Electric Retina—a set of copper cylinders 40 centims. long, and of diameters 14, 13, 12, 11, 10, 9 centims.; facing a source of radiation, as do the rods and cones in the eye, and responding by diametral electric vibration to the appropriate frequency. *Nature*, vol. 41, p. 462; cf. also p. 258 above.

arrangement was unexpectedly sensitive, and affords very short waves (Figs. 60, 61 and 64).

At a distance, it is easier to detect the radiation from a large vibrator, *i.e.* one possessing an extensive

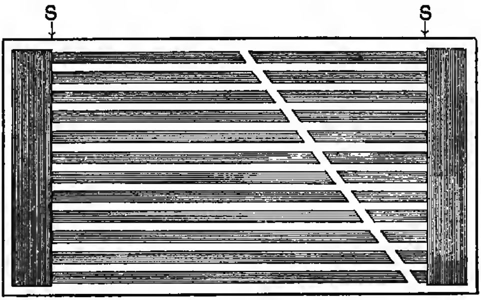


FIG. 61.—Robinson's electric harp, responding to vibrations through a considerable range of wave-length. Only a few of the tinfoil strips are shown. There are really fifty-one of them, closely packed together. Their length varies from about 30 centims. to 1 centim. The scintillæ occur at the razor-cuts marked S. The slant line of large gaps is simply to terminate the strips in a graduated series.

field, because of the greater initial energy electrostatically stored before a discharge begins, and because of its sort of "sounding-board" action; but there is no particular advantage in a great length of spark, for its resistance wastes energy. Half an inch or less is usually about the best length.

The smaller the oscillator, the more polished must be the knobs, else the requisite suddenness of start-

FIG. 62.—Small oscillator, drawn to scale $\frac{1}{8}$, used for experiments with the pitch lens. (Lodge and Howard, *Phil. Mag.*, July 1889. Rate of vibration, 300 million per second.

ing will not be attained. Excessively sudden disturbances are necessary to excite waves in such rapidly vibrating things. Otherwise, as when a beer-barrel is carefully tilted, the potential has time to equalize itself leisurely, and no waves are caused. Ultra-violet light falling on either knob, especially on the cathode,

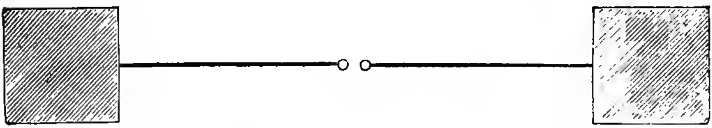


FIG. 63.—Gigantic oscillator, drawn to scale $\frac{1}{80}$, for violeot and distant effects. When this is excited by very large coil, most gas and water pipes in the building, and some wire fencing also, give off sparks to conductors brought close to them or to each other; and a telephone joined to any conductors in the neighbourhood is affected. See Lodge, on "Signalling across Space without Wires" (Electrician Co.) Rate of vibration, 10 million per second. Average radiation activity, while it lasts, 64 horse-power.

is to be avoided, for it enables the spark to occur too easily, and apparently with a less sudden breakdown. Anything of the nature of an electric brush or glow is especially deadly; and that is one reason, I think, why a Voss or Wimshurst machine is usually less effective than a coil, even if it be able to give as many sparks per second. The quality of the spark at the oscillator is very important, and is exceedingly capricious. Some days it declines to emit any reasonable amount of radiation, and on other days the receiver responds at surprising distances. Practice however, tends to reduce these caprices, and there is

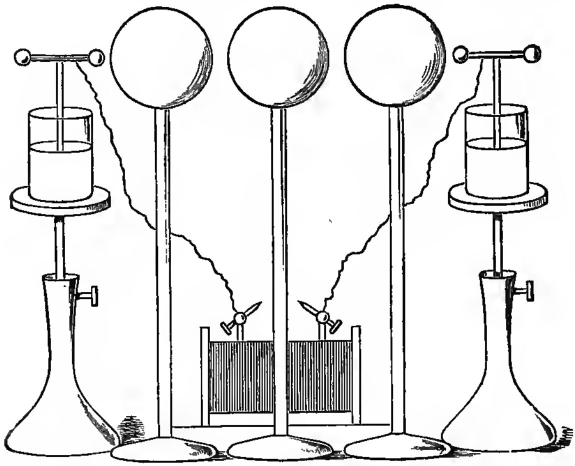


FIG. 64.—Arrangement for triple-sourced radiation from six-inch spheres; suitable for exciting the electric retina, Fig. 60. (*Nature*, vol. 41, page 462.)

seldom any difficulty in working with a good-sized oscillator, such as one with foot-disks a yard apart and connected by a rod and spark gap.

Process of Radiation.

196. Consider now in more detail what is happening. To and fro round the circuit of the jar A (Fig. 54) an electric current alternates, charging up the coatings

with alternately plus and minus charges. As a result of this electric current, a magnetic oscillation is going on along the axis of the circuit, perpendicular to the plane of the diagram; and this it is which may be thought of as disturbing the ether at a distance. It is, in fact, primarily a magnetic oscillator, and it excites induced currents in the ordinary way. But it does more than that; for it throws off true waves, which do not return to it, but convey its energy out into space.

A linear vibrator, as No. 3 in Fig. 55, may be called primarily an electric oscillator; for the electric surgings, from one end to the other and back, are the prominent feature. Its ends are alternately positive and negative at the end of each half-swing; and thence arises the electric strain which is felt by the surrounding ether. In mid-swing there is no electrostatic strain, but there is a linear current which exerts magnetic influence all round itself, causing circular lines of magnetic force surrounding the conductor.

Ring vibrators, such as No. 1, Fig. 55, or such as Fig. 57, only cause electric disturbance as a secondary consequence of the magnetic oscillations along their axis; which is their primary effect. Linear oscillators excite primarily an electric oscillation. But in neither case do the two occur simultaneously; one lags a quarter-period behind the other in time, just as the maximum velocity and maximum excursion of a simple pendulum differ by a quarter-period.

This lag is, however, strange to say, very soon made up or compensated by reason of a start in space. The magnetic disturbance being considered to start at the oscillator, the electric starts a quarter of a wave-length in advance; and accordingly, though it occurs a quarter-period later, the two travel together everywhere except within the first quarter wave-length. They are not, indeed, *coincident*, because they occur in planes at right angles to each other, but their maxima and zeros agree in position. If one is likened to a series of crests and troughs, the other is that same series rotated through a right angle.

But within the first quarter wave-length all this is different. The electric and magnetic forces there sometimes agree in phase and sometimes differ, one being occasionally even opposite in sign to the other.

This fact has important though not obvious consequences. In a varying electro-magnetic field, energy flows, as Poynting showed, in a direction determined by the direction of the electric and magnetic forces; it flows at right angles to both of them, and is reversed in direction if either of them is reversed in sign. Now, within the first quarter wave-length from an oscillator, the electric and magnetic forces sometimes have the same sign and sometimes opposite sign; hence the energy there oscillates to and fro; more, indeed, travels outward than returns, but some returns, and assists in maintaining the next oscillation.[1]

Beyond the first quarter wave-length, however, the magnetic and electric forces wax and wane together; neither is ever reversed without the other, and consequently the flux of energy there is steadily outward:

[1] Hertz's own treatment of the theory of these actions, with full diagrams, will be found translated by me in *Nature*, vol. xxxix. p. 451.

no more returns, but all travels out into space as radiation.

Whether it be much or little that thus travels out is a question of wave-length. With long waves the

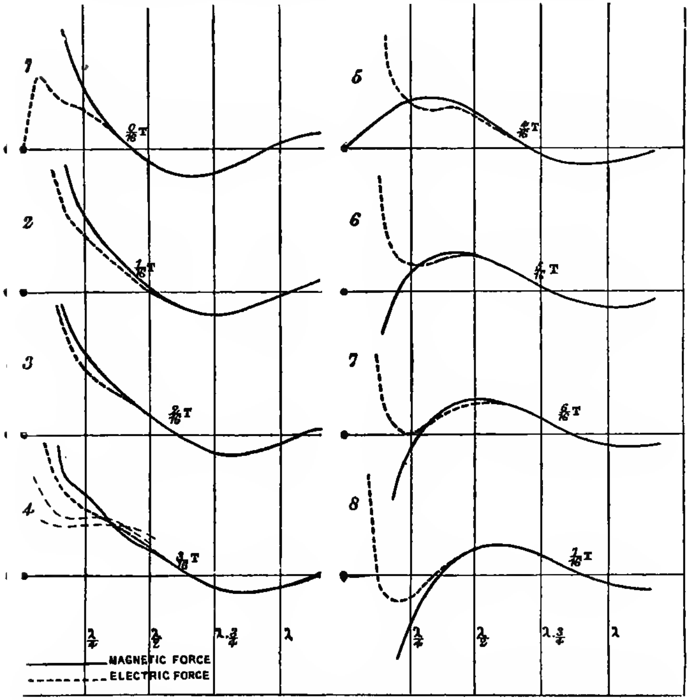


FIG. 65.—Diagram of the electric and magnetic forces concerned in radiation. (*Drawn by Mr. Trouton, see* Nature, vol. 42, p. 172.)

point of departure, or origin of radiation, is a long way from the vibrator, and accordingly the disturbance there is but slight. Most of the energy in that case returns to the oscillator, whose rate of damping will be controlled only by resistance and the production of local heat. Thus a commercial alternator, with frequency 100 per second, emits waves 3,000 kilometres (about 2,000 miles) long. Consequently, the radius where its energy begins to radiate away is something like the distance of the Shetlands from London; and accordingly no appreciable loss of energy is due to uncompensated emission of waves. But a small Hertz vibrator, whose wave-length is a few feet, radiates powerfully—far more powerfully than sunshine, for instance, while it lasts; and the rapid dying out of its vibrations is due almost entirely to this cause.

It is to be observed that the effective source of the emitted radiation is not at the oscillator itself, but at a quarter wave-length in advance of it. If it be assumed to start at the oscillator, the light will seem to travel too quickly; and this Hertz found to be the case. It travels with a quarter wave-length start, and so its phase at any distance is a quarter-period more than would have been expected.

The fact that there was this sort of quarter-wave acceleration of phase in ordinary light was discovered mathematically by Sir George Stokes,[1] and had become an accepted part of optics; the reason of it, in Maxwell's electric theory, is now clear.

Direction of Vibration.

197. The electric disturbance emitted by a linear oscillator, like that in Fig. 62, occurs parallel to the

[1] *Dynamical Theory of Diffraction*, 1849; *Stokes's Papers*, vol. ii. pp. 280, 321.

axis of the oscillator; the magnetic force is at right angles to it; and the direction of flow of energy, or ray, is out from the oscillator, perpendicular to both the electric and magnetic disturbances. Since the direction of vibration is thus definite, the beam is what is spoken of in optics as "polarized"; though whether the polarization retains its precision unimpaired to great distances may be uncertain.

An important experiment, on radiation thus obtained, was made by Mr. Trouton, in Prof. Fitzgerald's laboratory, Dublin,[1] to ascertain which is the plane of polarization, through the interposition of a non-conducting, *i.e.* transparent, obstacle in the beam, at appropriate obliquity, $\tan^{-1}\mu$. It is found that if, under these circumstances, the plane of incidence is arranged to coincide with the direction of the electric disturbance, none of the radiation is reflected; whereas, if the magnetic disturbance is in the plane of incidence, a portion of the radiation is reflected. Now, Fresnel—who was, of course, unacquainted with the fact that there are two distinct kinds of vibration to be attended to, and who treated light as if it were a mechanical disturbance in an elastic solid—surmised that the direction of vibration of light, reflected at the polarizing angle from a transparent substance, was perpendicular to the plane of incidence at which it was reflected. Hence we see that the disturbance contemplated by Fresnel corresponds to the electric disturbance; whereas the vibration contemplated in

[1] See lecture by Prof. Fitzgerald at the Royal Institution, March 21, 1890, reported in *Nature*, vol. xlii. p. 172. See also Mr. Trouton in *Nature*, vol. xxxix. p. 391.

the opposition theory advanced by McCullagh corresponds to the magnetic disturbance.

Thus Maxwell's theory that the magnetic force is in the plane of polarization is directly verified.

In most cases, as in the action of light on chemicals, diffraction by small particles, and so on, the electric oscillation is the more effective of the two; and it turns out to be this which has been properly treated as *the* direction of vibration by Stokes and others, from the point of view of the elastic solid theory.

When trying the experiment on reflection at the polarizing angle, it was found that a thin plate, such as a slab of glass, would not give any reflection; the reason being that its two surfaces are so close together that reflection from one is masked by interfering reflection from the other; just as happens in the black spot of Newton's rings. But by using as reflector a wall 3 feet thick the surfaces were farther separated; and, the transparency being imperfect, reflection from the back surface was also much weakened, so that uninterrupted reflection from the front surface could now be dealt with; and this it was which varied with the angle of incidence and with the direction of vibration relatively to the plane of incidence.

Mr. Trouton has tried a number of other interference experiments,[1] imitating Newton's rings, &c., and has obtained some diffraction phenomena when a reflector was smaller than a wave-length in size: obtaining results analogous to Stokes's "experimentum crucis" with respect to direction of vibration. The readiest way in which I obtained interference

[1] See *Nature*, vol. xl. p. 398; also *Phil. Mag.* July 1891.

effects was when using a spherical oscillator, a metal sphere about 6 inches in diameter supported by a glass rod 2 feet high on a teak table: one of those in Fig. 64. The receiver being a precisely similar sphere, it was found to respond at certain distances along the table and not at others; and moving it steadily and gradually towards the oscillator, from a distance of 12 feet, a succession of silences, or at least minima, were observed. On measuring the positions of these, they were found to correspond well with a difference in path amounting to one, three, and five half wave-lengths between the source and its image in the table.

The radiation from a sphere seems to me to be a purer tone, more monochromatic, than the radiation from a dumbbell-shaped conductor with a spark-gap in the middle of it. I prefer, as a rule, to have the spark-gap beyond the oscillator, instead of in the middle of it, and to depend on oscillations excited in a regularly-shaped conducting body when thus suddenly supplied with an electric charge.

Other Receivers or Detectors of Radiation.

198 Since Hertz's discovery that little sparks could be excited in a conductor exposed to electric radiation, various other methods of detecting radiation have been devised. Dr. Dragoumis, working in my laboratory, has used vacuum tubes, and has shown that they glow in the oscillating field near an electric vibrator without being attached to wires or any form of conductor;[1] also that they furnish

[1] *Nature*, vol. xxxix. p. 548.

a fairly convenient means of displaying Hertz's experiment to a small audience when attached to an ordinary syntonized receiver. They are not bright enough to be visible far away, nor except in a dark room; but when they contain some of Sir William Crookes's phosphorescent powders they are very fairly bright. The brightest I possess is one sent me in 1889 by Dr. Lenard, from Heidelberg, containing strontic sulphide rendered impure with calcic fluoride and a trace of copper, which last impurity seems necessary to the brilliant glow.[1] I estimate the light when its terminals are attached to the terminals of a small coil as about half a candle, and I have been accustomed to exhibit it to my class as possibly the embryo of the light of the future.

Sir W. Crookes long worked at the subject of phosphorescence with this idea in view; and Mr. Nikola Tesla constructed alternating dynamos of extraordinarily high frequency, which may be considered as a means of maintaining electric oscillations, and thereby making vacuum tubes and other bodies glow with considerable brightness, when connected with, or even when disconnected from, the source. The vapour of mercury has been shown by Cooper Hewitt to be very bright when conveying a steady current.

The oscillations maintained by Tesla's dynamos must at present be considered "slow," for they do not, I believe, rise to a hundred thousand per second; but they are vastly quicker than any which have been steadily *maintained* before. The Leyden jar and Hertz

[1] *Wied. Ann.*, xxxviii. p. 90; abstract in *Phil. Mag.* November 1889, p. 428.

vibrations, of millions or thousands of millions per second, do not last an appreciable instant of time. Three or four, or a few dozen, vibrations,—and they are done. The intervals for refreshment bear an appalling proportion to the moments of activity; even when hundreds of sparks are excited per second; hence it is that any illumination or other effect that they can produce is so feeble. To maintain them at their maximum intensity would indeed demand a good many horse-power; but the effects then obtainable would be prodigious.[1]

Another mode of detecting electric radiation is by its heating effects. The late Mr. Gregory, of Coopers Hill, constructed a very delicate arrangement of a fine wire attached to a spiral shaving and mirror, whereby extremely minute changes of length were translated into perceptible rotations. This receiver, held in an oscillating field with its length parallel to the direction of the electric disturbance, was heated by the electric currents induced in it, and produced a measurable deflection of a beam of light. Mr. Gregory's hope was with such an instrument to make a series of metrical determinations in the neighbourhood of a Hertz oscillator; but the difficulty of obtaining consistent results lay not in the receiver, which seemed well enough adapted for the purpose, but in the capricious behaviour of the spark at the emitter. If every spark could be depended on as being like every other, many difficulties and distrac-

[1] The power of tropical sunshine (by which I mean sunshine at the earth's distance, but unaffected by the British climate, natural or artificial) is about 2 horse-power per square yard.

tions, at that time inseparable from the experimental investigation of electric radiation, would cease. Recently by employing a series of very short air-gaps this difficulty has been largely overcome.

Another thermal method has been tried by several experimenters, viz. the interposition of a thermal junction in, or juxtaposition of it to, the thin wire receiver. This is heated by the induced currents, and can be connected with a galvanometer.

For making the effects merely visible at a distance, a method was discovered by Prof. Fitzgerald, who found that, if the two halves of an ordinary Hertz receiver were connected with a delicate fine wire galvanometer, its needle was disturbed whenever the little scintillæ occurred. A telephone does still better.

Similarly, Mr. Blyth, of Glasgow, has used a quadrant electrometer in the same sort of way; while Prof. Boltzmann made the little spark effect momentary contact between a charged jar and an electroscope, and thus display itself.

The effect observed by Fitzgerald depends on the induced electrostatic charging of the plates of the receiver connected through the galvanometer wire. If there is no spark, their charge and discharge quantities both pass through the galvanometer, and produce no effect; but, if they spark, the charge alone passes through it, and causes a minute effect.

I found something apparently of the same sort in some experiments on lightning guards. When the knobs of the guard were exceedingly close together, and were used to protect a galvanometer, that galvanometer was liable to capricious disturbance whenever sparks passed across the microscopic air-gap. If the air-gap was too big, there was nothing; and if it was too small, *i.e.* zero, there was nothing; but when just short of zero there was a very pronounced effect, and sometimes the jaws of the gap were found afterwards to be feebly at a single point cohering. [See *Journ. Inst. E.E.* April, 1890, vol. xix. pp. 352, 4].

Coherer.

199 This (published as above in 1892) was the beginning of what soon developed into the "coherer," which was the name I gave to the minute gap between a pair of metals in ostensible but incomplete contact. The slightest electric splash or scintilla across the gap caused cohesion, thereby establishing electric connexion, and enabling a battery current to pass and give any desired signal. The cohesion was easily broken again by a slight tap, which made it ready for a fresh signal. Already M. Branly, of Paris, had observed a similar effect with porphyrized copper and with metal filings; so, before long, in my laboratory, sometimes a coherer and sometimes a Branly filings tube was employed as the detector of electric wave radiation, as described in my book, published in 1894, called *The Work of Hertz and his Successors* [*or Signalling across Space without Wires*]; which was intended as a memorial to the great physicist Heinrich Hertz: these later developments being regarded as a legitimate and natural outcome of his work.

Since that time all these modes of detection, whether in the form of a single specially arranged contact-gap, or the form of a multiplicity of loose contacts, have been called "coherers" indiscriminately; and in 1896 Signor Marconi came to this country for the purpose of applying the device to official and commercial wireless telegraphy, which he has done with conspicuous success.

Luminescence.

200 The fact that the light of phosphorescence—such light as that of the glow-worm, for instance—is far more economical than any other known kind of luminescence (in other words, consists wholly of the kinds able to affect the retina, and of little else, as mentioned in § 151) has now been directly ascertained by Prof. Langley, of the Smithsonian Institute, Washington.[1]

He has examined the spectrum of a firefly with his bolometer, and found that the whole intensity of radiation is concentrated in its visible portion; while of infra-red or ultra-violet rays there is hardly a trace. It is, perhaps, rather singular that the eyes of fireflies—to which this light is of course intended to appeal—should thus prove to respond to just the same wave-lengths as do ours. Without this fact it would have been rash to assert that other animals might not often be emitting radiation, unperceived by us, but visible enough to them. The observation of Prof. Langley, although it does not of course negative this possibility, yet seems to me to render it improbable, and to suggest that the molecular structures adapted to respond to light in animal tissues are fairly definite, and not susceptible of variety.

[1] Langley and Very, "On the Cheapest Form of Light, from Studies at the Allegheny Observatory," *Phil. Mag.* September 1890, p. 278.

The structures susceptible to light in vegetable economy also respond to much the same range of vibration; for plants are injured by ultra-violet light of too high an order, such as is given by the electric arc, and I believe that chlorophyll is not known to be affected by infra-red rays. The range of vision of algæ and other subaqueous vegetation has not, I think, yet been ascertained.

Opacity.

201 The possibility of experimenting with radiations of great variety of wave-length throws a new meaning on the subject of opacity. It is well known that thin layers of anything, even gold if thin enough, will transmit some light, but that in sufficient thickness most things become opaque.

Opacity, however, on Maxwell's theory, ought to depend, not only on the nature of the medium, but also on the frequency of vibration of the light which is trying to penetrate it. For the quenching takes place after a certain number of vibrations, and not instantaneously. Suppose a substance so opaque as to destroy or reflect the greater part of an incident beam in the course of three vibrations, it must depend entirely on the wave-length of those vibrations how great a thickness is needed to be effectively opaque. If the waves are each the hundred-thousandth of an inch in length, like ordinary light, a mere film is sufficient. If the waves are each a foot long, then a wall a yard thick would be necessary.

And if the wave-lengths are reckoned in miles, no practicable thickness will stop them.

So it is experimentally found.

Hertz waves can get through deal doors and stone walls—not, of course, without some loss,—but they are stopped dead by a copper plate, or even by tinfoil. I am unable to detect them on the other side of paper covered with Dutch metal, when they are emitted by a small sphere; but a coating of plumbago lets them partially through. Very long waves, such as are emitted by an electro-magnet fed with an ordinary alternating current, can get through not only walls and buildings, but through sheet copper; though again not without some loss. And if the copper be thick enough, not very much will get through. A *perfect* conductor, if such a thing existed, would reflect and stop everything, however thin it might be. Still slower waves, such as are generated by slowly waving a magnet about, can get through copper of any reasonable thickness, and affect compass needles on the other side. But the more rapidly the magnet moves, the more will its effect be screened; and the best way of showing the experiment is not to move the magnet, but the copper. Lord Kelvin has inclosed a fixed magnet in a thick copper box, and shown that when the box is revolved a compass needle outside is much less deflected then when it is stationary.[1]

M. Pictet at Berlin ascertained that screens are singularly transparent to the "heat" radiation emitted by bodies 200 Centigrade degrees below zero.

[1] *Proc. Roy. Soc.*, vol. xlix. p. 422.

Thus there are all possible gradations of opacity, depending on the frequency of the incident vibration. To very long waves almost everything is transparent. To very short waves almost everything is opaque.[1]

Pressure of Light.

202 Maxwell predicted that light falling upon a reflecting metallic surface must repel it or press upon it with a minute but calculable force. Thus tropical sunshine falling normally on a square centimetre of silver must press on it with about the ten-thousandth part of a dyne: that being about the force needed to reverse the tide of energy. The pressure of sunlight on the whole earth amounts to about 100,000 tons weight. On a small enough dust particle in a comet's tail the solar radiation could overpower the solar gravitative attraction and drive the tail away from the sun.[2]

This pressure, though looked for by Sir William Crookes, had not in 1892 been detected with ordinary light, because it is altogether masked by the far greater effect of the air molecules, which cannot be got rid of, however good the so-called vacuum be made. Sir William Crookes, indeed, was fortunate enough to discover this molecular effect, and to invent the radiometer. If the direct light effect is ever to be seen, it must either be looked for with a

[1] For a full discussion of "opacity," see Lodge, Presidential address to Physical Society, 1899 (*Phil. Mag.* April 1899).

[2] See note by the writer at Cardiff, 1891, reported briefly in *Nature*, vol. xliv. p. 454. I find that Prof. Fitzgerald had discussed the same thing before (*Proc. Roy. Dub. Soc.* May 1882).

very bright surface; or else with some black surface not beaten back by rebounding molecules.

But there is no real need to hesitate about the reality of the direct light effect, because, by using longer waves, it becomes very conspicuous.

It is, indeed, essentially nothing else than the fact discovered by Faraday as to the odd behaviour of metallic masses near the pole of a magnet: the effect described and illustrated in Fig. 28, p. 151.

A copper disk held near a magnet fed by an alternating current is repelled by reason of the currents induced in it, and by their reaction on the field. That is precisely why light exerts pressure on a conducting surface. It induces currents in it and then repels them because it disagrees with them in phase. The repulsion of a disk near an alternating magnet is not, indeed, a steady or one-directioned effect; there may be moments of attraction, but on the whole there is distinct balance of repulsion, and repulsion alone is observed if the alternations are rapid and sinuously regular.

The strength of the alternating currents now readily available has enabled Prof. Elihu Thomson to throw this kind of repulsion into various striking forms, making it support rings, rotate spheres, and exert forces expressible in pounds weight.

Added 1906.—Recently (1904) Messrs. Nicholls and Hull in America have succeeded in verifying the existence of Maxwell's light-pressure, and in measuring its amount. They avoided the radiometer-like effect by adjusting the vacuum so as to give as nearly as possible zero molecular disturbance; since the effect of residual air changes sign at a certain stage of exhaustion. They thus were able to show that light exerted a normal pressure on absorbing or reflecting surfaces, of amount equal to that predicted by Maxwell.

Prof. Poynting of Birmingham has now gone further, and perceived that there must be a tangential force; or surface drag, when light impinges on an absorbing surface obliquely ; and that this is easier to observe than the normal pressure, since it is less perturbed by other causes. For a reflecting surface it is zero, because the direct and reflected beams act oppositely in a tangential direction, while their normal pressures are added. By suspending a couple of small surfaces on a quartz fibre, in such a way that the normal forces neutralize each other while the tangential forces co-operate, Poynting has measured this tangential or grazing force of light, and shown that its order of magnitude also corresponds with theory (*Phil. Trans.* 1904, vol. ccii. page 537).

Future Experiments.

203 Experiments on optical "dispersion," with a view of understanding the mechanism of the process, and affording information concerning the interaction of material atoms and the ether in which they are embedded, have not at present, so far as I know, been made. But Fitzgerald and Trouton have suggested filling pitch or paraffin with bullets, or some such plan, and studying the behaviour of a prism of it to Hertz waves of assorted wave-lengths not enormously

greater than the size of the metallic balls embedded in the transparent substance.

They have also many instructive ideas on the subject of maintaining an electrical vibration of a high degree of frequency,[1] without those disastrous intervals of darkness, or silence, or rest, which at present exist between one spark and the next: intervals which are to the time of one vibration as a year is to a minute. You cannot expect to make much impression on the universe by a performance, however brilliant, of five minutes' duration repeated once a year.

Progress towards the direct manufacture of light, suggested in §§ 149–151, is thus apparently going on in two different directions. One is by the attempt to construct mechanism, or discover principles, able to cause and maintain electric oscillations of the desired frequency; the other is to depend on the properties of certain molecules disturbed and thrown into vibration by comparatively slow electric oscillations and thus caused to phosphoresce.

This last may seem a short cut to the desired result, but it has rather too strong a family likeness to the present blindfold method of coaxing molecules to radiate, viz. by jogging them with heat, to be quite satisfactory. The direct maintenance method may lie dormant longer, and be farther from the achievement of success, but it seems to have a deeper comprehension of actual conditions latent within it.

This latter method fails at present from insufficient frequency; the phosphorescence method fails at present from insufficient intensity.

[1] *e.g.* Abstract in *Nature*, vol. xlv. p. 358.

CHAPTER XVII

MOST RECENT VIEWS CONCERNING THE ETHER (1907)

204 HITHERTO, though we have constantly referred to the two ethereal constants μ and κ, we have spoken as if there were no clue to their values ; but quite recently I have come to the conclusion that facts now known enable us to make a reasonable and plausible estimate of the orders of magnitudes of these important quantities. This matter I will now explain, and incidentally will endeavour to indicate some of the steps whereby it is hoped ultimately to show how the whole of the material universe is conceivably explicable on the postulate of a continuous incompressible perfect fluid, thoughout space, possessing only the two fundamental attributes (*a*) inertia, and (*b*) intrinsic rotational kinetic energy,—the latter involving two related but opposite kinds of motion. Such an indication is perforce unsatisfactory and incomplete at present, and the chief feature of the present chapter must be an estimate of the orders of magnitude for the inertia and for the intrinsic energy per unit volume which will be needed in the explanation.

For the ideas of some eminent workers in this field reference may be made to the *Phil. Mag.* for April and June, 1907.

In conjunction with this chapter a perusal of the appended article, called "Lecture 5," below, "On the Interstellar Ether," is recommended; and the author feels it not improbable that some vital or psychical consequences of considerable importance—such, perhaps, as may have been intended by the authors of "The Unseen Universe"—may sooner or later flow from the immense ethereal energy and density which physicists are now challenged to contemplate or controvert. (See also Appendix *s*).

Structure of the Ether.

205 What, then, is the conclusion of the whole matter, so far as a conclusion is possible at present?

The material universe seems to consist of a perfectly continuous incompressible and inextensible medium, filling all space without interstices or breach of continuity;—not of a molecular or discrete structure, and as a whole completely at rest: as frictionless moreover, and unresisting to all ordinary motion of what we call matter through it, as is the mathematical conception—a perfect fluid. But in spite of immobility as a whole, it possesses that property of "rigidity," or elastic resilience to "shear," which is characteristic of what we ordinarily call a solid; wherefore it would appear that it must be, throughout, in such a state of excessively fine-grained turbulent motion as would confer this property upon it. And the resilience is so complete and instantaneous, without any delay or permanent set, that the elasticity must be described as "perfect." It is the gyrostatic kind of elasticity, discovered dynamically and applied ethereally by Lord Kelvin, whereby a perfect fluid can kinetically acquire some of the properties of a perfect solid. (See § 156, Chap. XIV. p. 256, above.)

It is well known that every solid possesses two kinds of elasticity—elasticity of bulk and elasticity of shape. The first or volume elasticity may also be called "the incompressibility," and is common to all forms of matter—fluid as well as solid. In the case of the ether, however, the value of this quantity appears to be infinite: it is, at any rate, greater than we have as yet been able to appreciate by specially directed experiments,—meaning especially the Cavendish experiment referred to in §§ 4 and 14A. The elasticity of figure, or shape-elasticity, is only possessed by solids, and is technically called "rigidity"; it is small in the case of india-rubber, great in the case of steel or glass; it is the property on which spiral springs and torsion-balances depend. The two kinds of elasticity are quite independent of each other—quite independent also of anything akin to viscosity, which in the case of the ether appears to be zero.

Now something analogous to shape-elasticity the ether possesses. It does not possess ordinary mechanical rigidity, because that is an affair of molecules; but it possesses something which may be called an electric rigidity, or electromotive elasticity. It is identical with the electromotive elasticity of a dielectric,—it is the property which causes recoil after charge; and it has been denoted by $4\pi/\kappa$, where κ is the absolute

Faraday's dielectric constant, or specific inductive capacity, for free space.

The property thus analogous to rigidity, or shape-elasticity, is accompanied by another property, akin to inertia. This is the property to which magnetism is due; it is a magnetic inertia, to pair with electric rigidity, and it has been denoted throughout by $4\pi\mu$, where μ is the absolute magnetic permeability of free space. The self-induction or quasi-inertia associated with every electric current, of which $4\pi\mu$ is the non-geometrical and essential factor, is explicable, up to a point, as due to the magnetic field excited by electric motion; but it would seem as if ultimately it must necessarily be dependent on an unexplained and fundamental kind of inertia possessed by the ether itself; so that the ether may be said to have a certain density, or mass per unit volume,—a massiveness so like ordinary material specific-gravity or density that we have to call it by the same name.

By reason of these two properties—electric elasticity and magnetic density—transverse electromagnetic waves are transmitted through and by the ether, at a perfectly definite and known speed. This speed of wave propagation is far greater than any we are accustomed to in connexion with matter; and if ever the motion of matter can be made to approach this speed, it must encounter a reaction, or impedance, or opposition to further acceleration, which ultimately, in the limit, amounts to a practically infinite obstruction at the actual critical speed.

X This obstruction is not of the nature of friction,—it is not resistance proportional to the velocity, or in any way dependent on the velocity: it solely opposes acceleration, and is of the nature of impedance or inertia.

The fact of inertia enables an oscillatory wave-process to go on in the ether, and endows those oscillations with a particular kind of alternating kinetic, as well as with potential, energy.

The energy of strained or distorted ether is always potential energy, and is all the potential energy there is; but accessible or convertible kinetic energy is usually only possessed by those individualised and discriminated regions, or ethereal structures, which possess the power of locomotion, and which in their aggregate appeal to our senses as "matter."

During the passage of waves, the ethereal medium is sheared to and fro; not with any movement as a whole, but with equal opposite movement of two aspects, or elements, or conditions, of its structure: such shear being equivalent to what is called an electric displacement, and being subject to a restoring force accurately proportional to that displacement.

This elasticity is "perfect" in free space, apart from matter; until a critical shear, of unknown value, is reached. If strained beyond that, it may be supposed that a separation, or dislocation, or decomposition, of the ether into two components or constituents would occur;—constituents generated, as it were, by means of the shear, and probably not existing, as such, in the unperturbed ether. One of these components we call positive, and the other negative, electricity. Once formed they do not disappear again: they may combine—or approach each other so closely that they neutralize each other's effects at a distance; but they are still readily separable by electromotive force. They do not combine in the sense of destroying each other,—they do not re-form the original substance out of which they were produced.

The negative electricity, when separated, is freely mobile and easily isolated: it is what we experience as an electron. The positive constituent does not appear thus in an isolated manner, but is only known to exist in a mass,—a mass very like a hydrogen atom —possibly an inseparable aggregate of opposite charges matted together and going about as a whole. Some of these aggregates may unite into larger ones; others, when too large, may split up into smaller ones; and so finally a set of sub-permanent stable aggregates are formed which we recognize as the atoms of the so-called "elements" of matter: each with its appropriate degree of stability.

These masses or aggregates may temporarily acquire, or may lose, one or more of the free electrons; and by thus becoming amenable to electrical or chemical attractions and repulsions, constitute what we call "ions," so long as the unbalanced or electrified condition lasts.

Massiveness of the Ether.

206 Each electron, moving like a sphere through a fluid, has a certain mass associated with it; dependent on its size, and, at very high speeds, on its velocity also.

Now how shall that mass be treated?

Shall we deal with it on the analogy of a sphere moving through a perfect irrotational liquid, without examining into details any further?

Or shall we consider it as generating circular lines of magnetic induction by its movement, by reason of the rotational properties of the ether, and attribute all its inertia to the magnetic whirl thus caused round its path: possibly treating the whirl as an actual circulation of fluid excited by the locomotion?

Both methods may be adopted, to see whether they will agree.

Now treating it by the first method, and considering the electron merely as a sphere moving through a perfect liquid, its behaviour is exactly as if its mass were increased by half that of the fluid displaced and the surrounding fluid were annihilated. It has been argued in § 126, from the result of the Cavendish surface-charge experiment, and from the phenomena of gravitation, that the ether is incompressible, to a high degree of exactness; and accordingly the density of fluid inside and outside an electron must be the same. So that, treating it in this simplest fashion, the resultant inertia is half as great again as that of the volume of fluid corresponding to the electron: that is to say, is $2\pi\rho a^3$, where ρ is the uniform density. If an electron is of some other shape than a sphere, then the numerical part is modified, but remains of the same order of magnitude.

Now treat it by the other, or magnetic whirl, method.

Let a spherical electron e of radius a be flying at speed u, so that the magnetic field at any point, $r\ \theta$, outside, is

$$H=\frac{eu\sin\theta}{r^2},$$

and the energy per unit volume everywhere is $\mu H^2/8\pi$.

It has been shown by Lord Kelvin, Mr. Heaviside, G. F. FitzGerald, and Prof. Larmor, that a magnetic field may be thought of, hypothetically, as a circulation of fluid along the lines of magnetic induction—which are always closed curves—at some unknown velocity w.

Consider the energy per unit volume anywhere: it can be represented by the equivalent expressions

$$\tfrac{1}{2}\rho w^2=\frac{\mu H^2}{8\pi}=\frac{\mu}{8\pi}\,\frac{e^2u^2\sin^2\theta}{r^4};$$

wherefore

$$\frac{w}{u}=\sqrt{\left(\frac{\mu}{4\pi\rho}\right)}\cdot\frac{e\sin\theta}{r^2}.$$

On the cog-wheel analogy (§ 113) the highest velocity will be that in contact with the moving charge; and there is some reason to suppose that the maximum velocity w at the equator of the moving sphere may be equal to the speed u. Elsewhere it will decrease with the inverse square of the distance, just as H decreases.

But without any hypothesis, if there be a circulation at all, its velocity must be a maximum at the equator of the sphere, where $r=0$ and $\theta=90$; so, calling this w_0,

$$\frac{w_0}{u}=\sqrt{\frac{\mu}{4\pi\rho}}\cdot\frac{e}{a^2},$$

and

$$\frac{w}{w_0}=\frac{a^2 \sin \theta}{r^2},$$

and therefore the major part of the circulation is limited to a region not far removed from the surface of the electron.

The energy of this motion is

$$\tfrac{1}{2}\rho\int_0^\pi\int_a^\infty w^2 \, . \, 2\pi r \sin \theta \quad r d\theta \, . \, dr,$$

whence, substituting the above value of w, the energy comes out equal to $\frac{4}{3}\,\pi\rho a^3 w_0^2$.

Comparing this with a mass moving with speed u,

$$m=\frac{8}{3}\pi\rho a^3\left(\frac{w_0}{u}\right)^2.$$

This agrees with the simple hydrodynamic estimate of effective inertia if $w_0=\frac{1}{2}\sqrt{3}u$; that is to say, if the whirl in contact with the equator of the sphere is of the same order of magnitude as the longitudinal rack-motion or cog-wheel spin (§ 99) at the same place.

Now for the real relation between w_0 and u we must make a hypothesis. If the two are considered equal, the effectively disturbed mass comes out as twice that of the bulk of the electron. If w_0 is much smaller than u, then the mass of the effectively disturbed fluid is much less even than the bulk of an electron; and in that case the estimate of the fluid-density ρ must be exaggerated enormously, in order to supply the required energy. It is difficult to suppose the equatorial circulation w_0 *greater* than u, since it is generated by it; and it is not unreasonable to treat them both as of the same order of magnitude. So, taking them as equal,

$$e = a^2\sqrt{\frac{4\pi\rho}{\mu}}$$

and m = twice the spherical mass.

Hence all the estimates of the effective inertia of an electron are of the same order of magnitude, being all comparable with that of a mass of ether equal to the electron in bulk.

This would also be the conclusion drawn, if, instead of integrating the magnetic energy from a to infinity, we integrated from a to a larger radius b, or say na; the inertia would then come out

$$\tfrac{2}{3}\mu e^2\left(\frac{1}{b} - \frac{1}{a}\right) \quad \text{or} \quad \frac{2(n-1)}{3n}\frac{\mu e^2}{a},$$

and be still of the same order of magnitude for all reasonable values of n; the reason being that all the effective disturbance is concentrated in the neighbourhood of the charge.

Now the linear dimension of an electron is 10^{-13} centimetre diameter, and its mass is of the order 10^{-27} gram, being about the 1/700th part of the atom of hydrogen. Consequently, if its mass were due to its contents, the density of its material must be of the order

$$10^{-27} \div 10^{-39} = 10^{12} \text{ grams per cubic centimetre.}$$

This, truly, is enormous, but any reduction in the estimate of the circulation speed, below that of an electron, would only go to increase it; and since electrons move sometimes at a speed not far below that of light we cannot be accused of underestimating the probable velocity of magnetic spin by treating it as of the same order of magnitude, at the bounding surface of the electron: a relation suggested, though not enforced, by the cog-wheel and gyrostat analogy.

Incidentally, we may notice how enormous is the magnetic field surrounding the equator of an electron moving along an axis with, say, one-thirtieth the speed of light: it amounts to 10^{15} C.G.S. lines per sq. centimetre. And the magnetic energy there is correspondingly enormous, being 4×10^{28} ergs per c.c. At the velocity of light it would equal the constitutional energy of the ether itself.

The centrifugal force of the whirl outside a flying electron, treating it as that of a set of concentric spherical shells, is

$$F=\int_a^\infty \tfrac{2}{3}\cdot 4\pi r^2 dr\cdot \rho\frac{w^2}{r},$$

where w = the equatorial speed $=\frac{a^2}{r^2}u$.

Wherefore $$F=\tfrac{4}{3}\pi\rho a^2u^2=\frac{mu^2}{a};$$

that is to say the same force as would be exerted on its constraints by a particle of the same mass as an electron revolving in its own circumference at its own speed.

At one-thirtieth the speed of light, this amounts to about ten grams weight distributed over the surface of the electron. At the speed of light this also rises to the critical 10^{33} dynes per sq. centimetre, corresponding to the ether's intrinsic energy.

Value of the Ethereous[1] *Constants.*

207 It has been argued throughout the book that the ethereons density is what we know in magnetism as $4\pi\mu$; wherefore an approximate estimate of the absolute value of the magnetic constant μ for free space, on this view, is 10^{11} grams per c.c.

Using the value $4\pi\mu=\rho$, we get for the charge of an electron $e=4\pi a^2$, or comparable to its superficies.

The speed with which waves travel through the medium is the square root of 10^{21} C.G.S.; consequently the elasticity of the ether must be of the order 10^{33} dynes per square centimetre; and it is what in static electricity we denote by $4\pi/\kappa$. Wherefore an approximate estimate of the absolute value of Faraday's dielectric constant, κ, for free space, is 10^{-32} cubic centimetre per erg.

In other words, the intrinsic energy of constitutional motion of the ether, to which its rigidity is due, is of the order 10^{33} ergs or 10^{26} Joules per cubic centimetre —about a hundred foot lbs. per atomic volume; which is equivalent to the output of a million horse-power

[1] *Note on the word Ethereous.*—The usual word "ethereal" suggests something unsubstantial, and is so used in poetry; but for the prosaic treatment of Physics it is unsuitable, and etheric has occasionally been used instead. No just derivation can be given for such an adjective, however; and I have been accustomed simply to spell etherial with an *i* when no poetic meaning was intended. This alternative spelling, I am told by a Scholar, is not incorrect; but he points out that Milton uses the variant "ethereous," in a sense suggestive of something strong and substantial (*Par. Lost*, vi. 473). This word, therefore, can be employed to replace "ethereal" in physics: especially as the ether is now turning out to be by far the most substantial body known,—in comparison with which the hitherto contemplated material universe is like a vapour of extreme tenuity,—a barely perceptible filmy veil.

working for forty million years, in every cubic millimetre of space. It can otherwise be expressed as the energy of a thousand tons per cubic millimetre, moving with the velocity of light; but of course the motion really contemplated is all internal and circulatory.

Transmission of Waves.

208 Wherever electrons and atoms exist, they modify the ether in their immediate neighbourhood, so that waves passing through a portion of space containing them are affected by their presence, as if the ether were more or less loaded by them; because the electric displacements which go on in the unseparated and still perfectly united constituents of free ether are also shared to some extent by the separated peculiarities, especially by those of the electrons which are not too embedded in or surrounded by a positive charge—for instance, like a nucleus in a shell. These might be inert, and without influence on the light, except as small fixed mechanical obstructions; but all those charges which possess externally-reaching lines of force must share in the motion of the waves, without having the requisite amount of resilience to compensate for their inertia; consequently they, to that extent, constitute a retarding, and either an absorbing or a reflecting, agency.

Furthermore, their motions of vibration and rotation during the epochs of acceleration, however caused, encounter the inertia of the medium, and thereby excite waves in it—waves of oscillatory electric displacement with magnetic concomitant;—and this electromagnetic radiation is transmitted out into space. But it is insignificant in amount unless the acceleration is violent; it is proportional to the square of the acceleration.

The positive and negative constituents, when they combine or cohere, do not destroy each other and revert into plain ether again; on the contrary, they retain their individuality and persist, in either a combined or separate state. We do not know how to produce or to destroy these peculiarities; and though atoms of matter are composed of them, and though all electrical phenomena and the excitation of radiation are due to their presence and behaviour, it is no more and perhaps not much less correct to say that the main bulk of the ether is composed of them, than it is to say that actual sodium and chlorine exist in undissociated common salt. These elements only make their appearance when the original substance is decomposed. But certainly matter can be dissociated with extreme ease, whereas the dissociation of ether is unknown and hypothetical, save as represented by its apparent results.

Nevertheless, it must be the case that the slight, almost infinitesimal, shear, which goes on in the light wave, is of the nature of incipient and temporary electric separation; and all electromotive force *tends* to drive one constituent in one direction and the other in the other; thus beginning that individualisation or separate manifestation of the two ingredients, without a knowledge of which the original fluid would have appeared to be of a perfectly uniform and homogeneous character.

It is quite possible that the actually double aspect of ether is not only manifested, but really generated, by an electromotive force applied to it, just as the elastic recoil is so generated. It appears possible that a sufficiently violent E.M.F., applied to the ether by some method unknown to us at present, must be the kind of influence necessary to shear it beyond the critical value and leave its components permanently distinct; such constituents being opposite electric charges, which, when once thoroughly separated, only combine to form matter, and do not recoil into ordinary ether again.

Hypothetical Longitudinal Stress.

209 Every attempt at separation of this kind, even if no stronger than exists in ordinary light, seems to be accompanied by a slight longitudinal force at right angles both to the displacement and to the orbital axis of the excursion—a force which is known as the normal pressure of light, or Maxwell's pressure, perpendicular to an advancing wave-front: the inertia of the constantly encroached upon region of free ether having the effect of momentum. Cf. § 202.

If the disturbance could be made so extreme as to result in permanent dislocation, this pressure might leave behind it, as permanent residue, a longitudinal pressure, extending throughout space inversely as the distance; whereby all the dislocated material would thereafter be urged together with a force which we know as gravitation, proportional to the rate of variation of this pressure, and proportional in any piece of matter to the number of dislocated centres which go to compose it, and therefore proportional to its mass, irrespective of secondary accidents of a physical or chemical constitution. See Appendix (*r*).

Amplitude of Light Wave.

210 If a is the amplitude of shear during the passage of a wave of light, and if u is the maximum velocity of recovery, then

$$\frac{u}{v} = 2\pi\frac{a}{\lambda},$$

where v is the velocity of light and λ the wave-length.

The total energy per unit volume is $\frac{1}{2}\rho u^2$, where ρ is the density of the medium ; for this represents twice the average kinetic energy, and of this quantity one-half is really kinetic, the other half potential.

Now direct thermal measurements such as those conducted by Pouillet give, as the energy of sunlight near the earth, 4×10^{-5} erg per c.c. ; and consequently in the region of intense light near the solar surface the energy of radiation must be about 2 ergs per cubic centimetre. There may be more intense light than this, but this is the most intense we know of ; so it is instructive to consider the amplitude of the shear corresponding to such violent illumination. Let us therefore put $\frac{1}{2}\rho u^2 = 2$, whence

$$u^2 = 4 \times 10^{-12}$$

It follows, therefore, that

$$u/v = \tfrac{2}{3} \times 10^{-16},$$

and accordingly the amplitude, of the most intense visible light we are acquainted with is only 10^{-17} of a wave-length. The maximum strain is 2π times this fraction; and so the tangential stress thus called out in the medium, its rigidity being 10^{33}, may be estimated as comparable with 10^{17} dynes per square centimetre, or 10^{11} atmospheres.

The ordinary electrostatic unit of charge, on this estimate of ethereous elasticity, becomes 10^{-16} square centimetre, or the superficial dimension of an atom. This also corresponds with the estimate above, that the electronic charge is equal to the superficies of an electron; since one should be 10^{10} times the other.

The pressure of light has been represented by Prof. Poynting as a travelling momentum, like that of a jet of water, resulting in a pressure ρcv; where c is the velocity of longitudinal motion or circulation in the light beam, and v is the velocity of light. Taking the pressure of intensest light as 2 dynes per square centimetre, this gives $c=\frac{2}{3}10^{-22}$ centimetre per second: excessively small, therefore, even in that extreme case.

Hypothetical Flow along Lines of Magnetic Induction.

211 It has long been a working hypothesis with some mathematical physicists (see, for instance, the April 1907 number of the *Philosophical Magazine*) that there was probably something of the nature of a flow—an ethereous flow—along lines of magnetic induction; and the fact that these are always closed curves, in all known circumstances, is in favour of such an idea. The energy of the field would then be attributed to

the energy of this flow; and though it is possible that the flow might be of the nature of components moving in opposite directions, the movement is hardly likely to be of this nature, since that would correspond with merely an electric current.

Fourteen years ago, in 1893, having rather perfect appliances for examining the effect of drift on the velocity of light, I carefully looked for some longitudinal flow along lines of magnetic force; repeating the experiments still more anxiously when I learnt that something of the kind was seriously suspected by Dr. Larmor.

Applying a field of 1400 C.G.S. units over a length of light path of about 14 metres in the aggregate, things were so arranged that a drift of 1 foot a second, or about 10^{-9}th of the velocity of light, would have been observed by a fractional shift of micrometically viewed interference bands, if it had occurred. But no effect whatever on the interference bands could be detected; nor was anything observed when—with less perfect vision, in that case, owing to increassd difficulties—the air along the field and path of light was replaced by bisulphide of carbon; except that, of course, if plane-polarised light was used, the plane was then rotated by a very large amount. Sufficient details of this series of negative experiments are given in the April 1907 issue of the *Philosophical Magazine.*

The result was to show that if the magnetic energy were to be accounted for in the assumed kinetic fashion, the density of the ether must be very considerable—in fact about 180 times that of water,—in order to give the actual energy with a velocity below what could be observed in this way.

I have now, however, as described above, made a theoretical estimate of the density of the ether—arriving at the tentative conclusion that it is of the order 10^{-12}—and we can therefore proceed to calculate what velocity of hypothetical ethereous drift is to be expected in any given magnetic field. It will come out, of course, exceedingly slow; for, on this view, the electromagnetic unit of field is $\mu^{-\frac{1}{2}}$, which equals 3×10^{-6} centimetre per second, and the velocity to be expected is the 2πth of that.

So, for instance, the field inside a solenoid, surrounded by a current of 100 amperes circulating 100 times round every centimetre of it, being $4\pi n_1 C$, will equal 12,000 C.G.S.; which corresponds with a velocity of 0·003 centimetre per second, or about 4 inches an hour. In fact the ampere-turns per inch, in any solenoid, measures the speed of magnetic circulation along its axis, no matter what the material of the core may be, in millimicrons per second.

When iron is substituted for air, the speed is the same; but the ethereous density is virtually increased, by the loading due to the molecular whirls in the iron.

It may seem difficult to reconcile this very slow velocity, in any ordinary field, with the great velocity of the very same character, already postulated in the immediate neighbourhood of an electron; where it is supposed that the magnetic circulation is equal to, or at any rate of the same order of magnitude as, the locomotion speed—which it is well known may easily be 1/30th of the velocity of light, without departing appreciably from the simply calculated inertia. But that great speed, in the immediate neighbourhood of an electron, can be fully admitted; and there is nothing really inconsistent in that with the slow speed observed at any ordinary distance. For instance, if, close to the equator of a flying electron, the ethereal magnetic speed is 1/30th of the velocity of light, or 10^9 centimetres per second; then, at a distance of 1 millimetre away, the speed is reduced to 10^{-24}th of that value, and is, therefore, even at that small distance, only 10^{-15} centimetre per second, or one-third of a micron per thousand years.

The speed at the axis of a solenoid is, of course, far greater than that, because of the immense number of electrons in any ordinary current surrounding it; but in order to get up a drift-velocity of 1 centimetre per second in a solenoid, a thousand amperes would have to circulate three thousand times round every centimetre of it; which seems hardly practicable.

The optical arrangements, in my experiment above spoken of, could doubtless be improved sufficiently to show an ether drift of 1 centimetre per second; but I do not see how to produce a field of the required intensity to give even this leisurely flow. Such a field would have to be about four million C.G.S. units, and must exist throughout a great length of air.

The experimental verification of the above theoretical estimate of ethereous density seems therefore to be beyond the reach of this form of experiment. Nevertheless, I feel reasonably convinced that there is a justification for assuming the ether to have properties such as can only for the present be represented, in analogy with the properties of matter, by saying that its behaviour consistently indicates something typified by its possession of an immense elasticity or rigidity, 10^{33} dynes per square centimetre, caused by its intrinsic constitutional energy; combined with a property analogous to, and resulting in, material inertia, and typified by attributing to it a density of the order 10^{12} grams per cubic centimetre. The ethereous property here called elasticity is certainly the source and origin of every kind of material elasticity and potential energy; for the only real static effect producible in the particles of matter is a change in their arrangement or configuration. All stress must exist really in the ether.

Although the experimental methods so far suggested have proved themselves unable to test the magnitudes involved in these high values, some other method of inquiry may be suggested, and the theory may yet be brought to the test of experiment.

Other Anticipations of Great Ether Density.

212 I pointed out in an appendix to my *Philosophical Magazine* paper for April 1907, that many great authorities had anticipated a high ethereous density, partly on the basis of a flow along magnetic lines of force. But Dr. O. W. Richardson of Princeton has since shown, in *Nature* vol. lxxvi. p. 78, that, without assuming a flow of that precise kind, a similar calculation may be made on another basis;

namely, the basis laid by J. J. Thomson, of a flow at right angles to both sets of lines of force and along the Poynting vector. This mode of regarding the matter results numerically in a density of the same order of magnitude as that given by the other calculation, and is therefore confirmatory of the general propositions sustained in the present chapter; though the question of how far the hypothetical magnetic flow here spoken of is a reality must be regarded as *sub judice*, and in fact as a question for the mathematical physicists who originated the idea. Prof. Larmor sustains the reality of such a flow, as a physical interpretation of mathematical results rigorously arrived at by the principle of "Least Action" (*Nature*, July 18, 1907, page 270); but it is desirable, before leaving the subject, briefly to indicate the other or alternative mode of regarding the matter, and of arriving at a not dissimilar conclusion, as popularly explained by J. J. Thomson in his American Lectures in the following way:—

Extracts from J. J. Thomson's book "Electricity and Matter" (1904).

"The momentum in unit volume of the medium is $4\pi\mu N^2 v \sin\theta$, and is in the direction of the component of the velocity of the Faraday tubes [lines of electric force] at right angles to their length. Now this is exactly the momentum which would be produced if the tubes were to carry with them, when they move at right angles to their length, a mass of the surrounding medium equal to $4\pi\mu N^2$ per unit volume, the tubes possessing no mass themselves and not carrying any of the medium with them when they glide through it parallel to their own length." . . . .

"We shall call the mass $4\pi\mu N^2$, carried by the tubes in unit volume, the mass of the bound ether. It is a very suggestive fact that the electrostatic energy, E, in unit volume is proportional to the mass of the bound ether in that volume . . . . thus E is equal to the kinetic energy possessed by the bound mass when moving with the velocity of light." . . . .

"On this view of the constitution of matter, part of the mass of any body would be the mass of the ether dragged along by the Faraday tubes stretching across the atom between the positively and negatively electrified constituents. The view I wish to put before you is that it is not merely a part of the mass of a body which arises in this way, but that the *whole* mass of any body is just the mass of ether surrounding the body which is carried along by the Faraday tubes associated with the atoms of the body. In fact, that all mass is mass of the ether, all momentum, momentum of the ether, and all kinetic energy, kinetic energy of the ether. This view, it should be said, requires the density of the ether to be immensely greater than that of any known substance."

Summary.

213 Thus, our hypothesis is as follows :—Throughout the greater part of space we find simple unmodified ether, elastic and massive, squirming and quivering

with energy, but stationary as a whole. Here and there, however, we find *specks of electrified ether*, isolated yet connected together by fields of force, and in a state of violent locomotion.

These 'specks' are what, in the form of prodigious aggregates, we know as "matter"; and the greater number of sensible phenomena, such as viscosity, heat, sound, electric conduction, absorption and emission of light, belong to these differentiated or individualized and dissociated or electrified specks, which are either flying alone or are revolving with orbital motion in groups. The "matter" so constituted,—built up of these well separated particles, with interstices enormous in proportion to the size of the specks, must be an excessively porous or gossamer-like structure, like a cobweb, a milky way, or a comet's tail; and the inertia of matter—that is, the combined inertia of a group of electrified ether particles— must be a mere residual fraction of the mass of the main bulk of undifferentiated continuous fluid occupying the same space; of which fluid the particles are hypothetically composed, and in which they freely move.

APPENDED LECTURES

The following lectures bearing on the subject of this book are here conveniently appended.)

LECTURE I

THE RELATION BETWEEN ELECTRICITY AND LIGHT [1]

WHEN a person is setting off to discuss the relation between electricity and light it is very natural and very proper to pull him up short with the two questions: What do you mean by electricity? and, What do you mean by light? These two questions I intend to try briefly to answer. And here let me observe that in answering these fundamental questions I do not necessarily assume a fundamental ignorance on your part of these two agents, but rather the contrary; and must beg you to remember that if I quote well-known and simple experiments it is for the purpose of directing attention to their real meaning and significance, not to their obvious and superficial characteristics: in the same way that I might repeat the exceedingly familiar experiment of dropping a stone to the earth if we were going to define what we meant by gravitation.

Now then we will ask first, What is Electricity? and the strict answer must be, We don't exactly know.

[1] Portions of a lecture delivered at the London Institution on December 16, 1880.

Well, but this need not necessarily be depressing. If the same question were asked about Matter, or about Energy, we should have likewise to reply, No one knows.

But then the term Matter is a very general one, and so is the term Energy. They are heads, in fact, under which we classify more special phenomena.

Thus if we were asked, What is sulphur? or What is selenium? we should at least be able to reply, A form of matter; and then proceed to describe its properties, *i.e.* how it affected our bodies and other bodies.

Again, to the question, What is heat? we can reply, A form of energy; and proceed to describe the peculiarities which distinguish it from other forms of energy.

But to the question, What is electricity? we have no answer pat like this. We cannot assert that it is a form of matter, neither can we deny it; on the other hand, we certainly cannot assert that it is a form of energy, and I should be disposed to deny it. It may be that electricity is an entity *per se*, just as matter is an entity *per se*.

Nevertheless I can tell you what I mean by electricity by appealing to its known behaviour.

Here is a battery—that is, an electricity pump: it will drive electricity along. Some people say that it generates electricity; but that is exactly what neither it nor anything else can do. It is as impossible to generate electricity in the sense I am trying to give the word, as it is to generate matter, though it is perfectly possible to generate heat, *e.g.* by simple friction: that is by converting some other form of energy into heat.

I want you then to regard this battery and all electrical machines and batteries as kinds of electricity pumps, which drive the electricity along through the wire very much as a water-pump can drive water along pipes; and that no electric machine can manufacture electricity, any more than a pump can manufacture water.

Conversely an electric motor driven by a current consumes none of the current; just as much flows away from it by the low-potential wire as was supplied by the high-potential wire. In this respect it is like a water-wheel or turbine, where the tail-water is equal in quantity to the head-water: the only loss being a loss of level and consequent loss of available energy.

Based on this conservation of current several attempts at perpetual motion were made at one time, by people with half knowledge, who conceived that the unexpended current from one motor could be used to drive another and so on *ad infinitum*; thus gaining any amount of energy from a single supply. This can be done if the electromotive force of the generator is high enough, but it must always exceed the sum of the back E.M.F.'s of all the motors; and accordingly the power that has to be expended, in driving the generator or dynamo, is always in excess of the power obtained from the series of motors; and in fact the series is no more efficient than a single good one which develops an adequate back E.M.F. The case is quite analogous to a pump used to elevate water, the high pressure water being then used to drive a turbine or series of turbines. It is only a case of transmission of power, with, of course, some loss in the process; though surprisingly little loss in the electrical case, if well designed.

While the flow of electricity is going on, the wire manifests a whole series of properties, which are called the properties of the current.

[Here were shown an ignited platinum wire, the electric arc between two carbons, an electric machine spark, an induction-coil spark, and a vacuum tube glow. Also a large nail was magnetized by being wrapped in the current, and two helices were suspended and seen to direct and attract each other.]

To make a magnet, then, we only need a current of electricity flowing round and round in a whirl. A vortex or whirlpool of electricity is, in fact, a magnet; and *vice versâ*. And these whirls have the power of directing and attracting other previously existing whirls according to certain laws, called the laws of magnetism. And, moreover, they have the power of exciting fresh whirls in neighbouring conductors, and of repelling them according to the laws of diamagnetism. The theory of the actions is known; though the nature of the whirls, as of the simple stream of electricity, is at present unknown.

[Here was shown a large electro-magnet and an induction-coil vacuum discharge spinning round and round when placed in its field (Fig. 24).]

So much for what happens when electricity is made to travel along conductors, *i.e.* when it travels along like a stream of water in a pipe, or spins round and round like a whirlpool.

But there is another set of phenomena, usually regarded as distinct and of another order, but which are not so distinct as they appear, which manifest themselves when you join the pump to a sheet of glass or any non-conductor and try to force the electricity through that. You succeed in driving some through, but the flow is no longer like that of water in an open pipe; it is as if the pipe were completely obstructed by a number of elastic partitions, or diaphragms. The water cannot move without straining and bending these diaphragms, and if you allow it, these strained partitions will recover themselves and drive the water back again. [Here was explained the process of charging a Leyden jar, and the model (Fig. 11, § 24) was shown.] The essential thing to remember is that we may have electrical energy in two forms, the static and the kinetic; and it is therefore also possible to have the rapid alternation from one of those forms to the other, called vibration.

Now we will pass to the second question: What do you mean by Light? And the first and obvious answer is, Everybody knows. And everybody that is not blind does know to a certain extent. We have a special sense-organ for appreciating light, whereas we have none for electricity. Nevertheless, we must admit that we really know very little about the intimate nature of light—very little more than about electricity. But we do know this, that light is a form of energy; and, moreover, that it is energy rapidly alternating between the static and the kinetic forms —that it is, in fact, a special kind of energy of vibration. We are absolutely certain that light is a periodic disturbance in some medium, periodic both in space and time; that is to say, the same appearances regularly recur at certain equal intervals of distance at the same time, and also present themselves at equal intervals of time at the same place; that in fact it belongs to the class of motions called by mathematicians undulatory or wave motions.

A row of a large number of equidistant similar pendulums serves well to illustrate a disturbance periodic both in space and time. The pendulums themselves, at rest, may be said to be periodic in space; like a row of palings, or a grating, or many other things. The motion of each pendulum separately is periodic in time, repeating itself at regular intervals called the time-period. If now such a set of pendulums be successively disturbed, one after the other, in quick succession, the resulting motion is periodic both in time and space; and if the experiment is neatly done by steadily withdrawing a deflector the series of swinging bobs will appeal to the eye very distinctly as a wave motion,—the waves advancing from one end of the row to the other, constantly coming in at one end and passing out at the other,—although manifestly there can be no material transfer.

The velocity of transmission in this case is somewhat arbitrary: it is equal to the wave-length divided by the time of swing, as usual, but the wave-length depends only upon the way the pendulums were set in motion; so that it is the rate of removal of the initial deflexion which determines the velocity. In that respect it does not correspond to natural waves in a medium; but it is otherwise a good illustration. It is instructive to remark that in this model the velocity is directly proportional to the wave-length; in large water waves the velocity is proportional to the square root of the wave-length; in sound and light waves it is independent of the wave-length—being determined solely by the properties of the medium, provided the medium is homogeneous. In so far as there is any dependence of speed on wave-length in the case of light, the result is dispersion, and the cause of it is a lack of homogeneity in the medium: for instance, a jelly with plums embedded in it is not a homogeneous medium. There are other cases known, where the velocity of a wave is actually greater as the wave-length is shorter; such cases can be found in minute ripples of liquid, and in the impulses transmitted by rigid bars.

The wave motion in a well-known model, called Powell's wave apparatus, results from the simple up-and-down motion popularly associated with the term *wave.* But when a mathematician calls a thing a wave he means that the disturbance is represented by a certain general type of formula; not that it is an up-and-down motion, or that it looks at all like those things on the top of the sea. The motion of the surface of the sea falls within that formula, and hence is a special variety of wave motion. But the term "wave" has acquired in popular use this signification and no other; so that when one speaks ordinarily of a wave, or undulatory motion, people immediately think of something heaving up and down, or even perhaps of something breaking on the shore. But when we assert that the form of energy called light is *undula-*

tory, we by no means intend to assert that anything whatever is moving up and down, or that the motion, if we could see it, would be anything at all like what we are accustomed to on the ocean. The kind of motion is unknown; we are not even sure that there is anything like "motion" in the ordinary sense of the word at all.

Now how much connexion between electricity and light have we perceived in this glance into their natures? Not much, truly. It amounts to about this: That on the one hand electrical energy may exist in either of two forms—the static form, when insulators are electrically strained by having had electricity driven partially through them (as in the Leyden jar), which strain is a form of energy because of the tendency to discharge and do work; and the kinetic form, where electricity is moving bodily along through conductors or whirling round and round inside them—which motion of electricity is a form of energy, because the conductors and whirls can attract or repel each other and thereby do work.

And, on the other hand, that light is the rapid alternation of energy from one form to another—from the static form where the medium is strained, to the kinetic form where it moves. It is just conceivable then that the static form of the energy of light is *electro*-static—that is, that the medium is *electrically* strained—and that the kinetic form of the energy of light is *electro*-kinetic—that is, that the motion is not ordinary motion, but electrical motion; in fact that light is an electrical vibration, not a material one.

On November 5, 1879, there died at Cambridge a man in the full vigour of his faculties—such faculties as do not appear many times in a century—whose chief work had been the establishment of this very fact, the discovery of the link connecting light and electricity; and the proof—for it certainly amounts to a proof—that they are different manifestations of one and the same class of phenomena: that light is, in fact, an electro-magnetic disturbance. The premature death of James Clerk Maxwell is a loss to science which appears at present utterly irreparable, for he was engaged in researches that no other man can hope as yet adequately to grasp and follow out: but fortunately it did not occur till he had published his book on *Electricity and Magnetism*, one of those immortal productions which exalt one's conception of the mind of man, and which has been mentioned by competent critics in the same breath as the *Principia* itself.

The main proof of the electro-magnetic theory of light is this. The rate at which light travels has been measured many times, and is pretty well known. The rate at which an electro-magnetic wave-disturbance would travel, if such could be generated, can be also determined by calculation from electrical measurements. The two velocities agree exactly. This is the great physical constant known as the ratio "*v*," which so many physicists have been measuring, and are likely to be measuring for some time to come.

Many and brilliant as were Maxwell's discoveries, not only in electricity, but also in the theory of the nature of gases, and in molecular science generally, I cannot help thinking that if one of them is more striking and more full of future significance than the rest, it is the one I have just mentioned—the theory that light is an electrical phenomenon.

The first glimpse of this splendid generalization was caught in 1845, five and thirty years ago, by that prince of pure experimentalists, Michael Faraday, His reasons for suspecting some connexion between electricity and light are not clear to us—in fact they could not have been clear to him; but he seems to have felt a conviction that if he only tried long enough. and sent all kinds of rays of light in all possible directions across electric and magnetic fields, in all sorts of media, he must ultimately hit upon something. Well, that is very nearly what he did. With a sublime patience and perseverance, which remind one of the way Kepler hunted down guess after guess in a different field of research, Faraday combined electricity, or magnetism, and light, in all manner of ways; and at last was rewarded with a result.

A singularly out-of-the-way result it seemed. First you have to get a most powerful magnet and very strongly excite it; then you have to pierce its two poles with tunnels, in order that a beam of light may travel from one to the other along the lines of force; then, as ordinary light is no good, you must get a beam of plane-polarized light and send it between the poles. But still no result is obtained; until, finally, you interpose a piece of a rare and out-of-the-way material which Faraday had himself discovered and made—a kind of glass which contains borate of lead, and which is very heavy, or dense, and which must be perfectly annealed.

And now, when all these arrangements are completed, what is seen is simply this, that if an analyzer is arranged to stop the light and make the field quite dark before the magnet is excited, then, directly the battery is connected and the magnet called into action, a faint and barely perceptible brightening of the field occurs ; which will disappear if the analyzer be slightly rotated. [The experiment was then shown.] Now no wonder that no one understood this result. Faraday himself did not understand it ; he seems to have thought that the magnetic lines of force were rendered luminous, or that the light was magnetized ; he had no clear idea of its real significance. Nor had anyone. Continental philosophers experienced some difficulty and several failures before they were able to repeat the experiment. It was in fact discovered too soon, before the scientific world was ready to receive it ; and it was reserved for Lord Kelvin briefly but clearly to point out, and for Clerk Maxwell more fully to develop, its most important consequences.

This is the fundamental experiment which probably suggested Clerk Maxwell's theory of light ; but of late years many fresh facts and relations between electricity and light have been discovered, and at the present time they are tumbling in in great numbers.

It was found by Faraday that many other transparent media besides heavy glass would show the phenomenon if placed between the poles : only in a less degree; and the very important observation that air itself exhibits the same phenomenon, though to an exceedingly small extent, has been made by Kundt and Röntgen in Germany.

Dr. Kerr, of Glasgow, has extended the result to opaque bodies, and has shown that if light be passed through magnetized *iron* its plane is rotated. The film of iron must be exceedingly thin, because of its opacity; and hence, though the intrinsic rotating power of iron is undoubtedly very great, the observed rotation is exceedingly small and difficult to observe; and it was only by very remarkable patience and care and ingenuity that Dr. Kerr obtained his result. Prof. Fitzgerald has examined the question mathematically, and has shown that Maxwell's theory would have enabled Dr. Kerr's result to be predicted.

Another requirement of the theory is that bodies which are transparent to light must be insulators or non-conductors of electricity, and that conductors of electricity are necessarily opaque to light. Simple observation amply confirms this; metals are the best conductors, and are the most opaque bodies known. Insulators such as glass and crystals are transparent, whenever they are sufficiently homogeneous; and the very remarkable researches of Prof. Graham Bell in the last few months (1880) have shown that even *ebonite*, one of the most opaque insulators to ordinary vision, is certainly transparent to some kinds of radiation, and transparent to no small degree.

[The reason why transparent bodies must insulate, and why conductors must be opaque, was here illustrated by mechanical models.

The model which represented a dielectric has already been depicted in Fig. 8; and when the cord threading all the elastically supported balls is vibrated, waves travel readily through it.

The model which represented a metallic conductor is shown here in Fig. 66. It has its wooden balls sliding on smooth brass rods so that they have no tendency to recoil to a settled position, but remain where placed. On shaking the cord connecting these

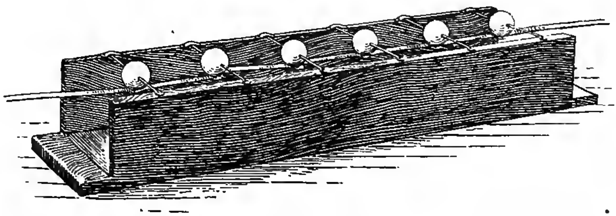


FIG. 66.—Rude model to pair with Fig. 8 (p. 43) and to call attention to some of the differences between a metal and an insulator.

balls, the waves penetrate a certain small depth into the medium, but fail to get through it.

The two models were connected in series, and waves which had been transmitted along the cord by one, were partly quenched, partly reflected, by the other.]

A further consequence of the theory is that the velocity of light in a transparent medium will be affected by its electrical strain-constant; in other words, that its refractive index will bear some close relation to its specific inductive capacity.

But there are a number of results not predicted by theory, and whose connexion with theory is not clearly made out. We have the fact that light falling on the platinum electrode of a voltameter generates a current; first observed, I think, by Sir W. R. Grove —at any rate it is mentioned in his *Correlation of Forces*—extended by Becquerel and Robert Sabine to other substances, and now being extended to fluorescent and other bodies by Prof. G. M. Minchin. And finally we have the remarkable action of light on selenium. The fact was discovered accidentally by an assistant in the laboratory of Mr. Willoughby Smith, who noticed that a piece of selenium conducted electricity very much better when light was falling upon it than when it was in the dark. The light of a candle is sufficient, and instantaneously brings down the resistance to something like one-fifth of its original value.

I could show you these effects, but there is not much to see; they are interesting phenomena, but their external manifestation is not striking—any more than Faraday's heavy glass experiment was.

The sensitiveness of selenium to light was utilized by Prof. Graham Bell in his ingenious invention, the photophone. By the kindness of Prof. Silvanus Thompson I have a few slides to show the principle of the invention, and Mr. Shelford Bidwell has been good enough to lend me his home-made photophone, which answers exceedingly well for short distances.

In conclusion I must just allude to what may very likely be the next striking popular discovery, viz., the transmission of light by electricity; I mean the transmission of such things as views and pictures by means of the electric wire. It has not yet been done, but it seems already theoretically possible, and it may very soon be practically accomplished.

LECTURE II

THE ETHER AND ITS FUNCTIONS[1]

THE idea of an ether is by no means a new one. As soon as a notion of the enormous extent of space had been grasped, by means of astronomical discoveries, the question presented itself to men's minds, What was in this space? was it full, or was it empty? and the question was differently answered by different metaphysicians. Some felt that a vacuum was so abhorrent a thing that it could not by any possibility exist anywhere,—that Nature would not be satisfied unless space were perfecly full. Others, again, felt that *empty* space could hardly exist, that it would shrink up to nothing like a pricked bladder unless it were kept distended by something material. In other words, they made 'matter' the condition of 'extension.' On the other hand, it was contended that, however objectionable the idea of empty space might be, yet emptiness was a necessity in order that bodies might have room to move; that, in fact, if all space were perfectly full of matter everything would be jammed

[1] Based on a lecture delivered at the London Institution on December 28, 1882.

together, and nothing like free attraction or free motion of bodies round one another could go on.

And indeed there are not wanting philosophers at the present day who still believe something of this same kind, who are satisfied to think of matter as consisting of detached small particles acting on one another with forces varying as some inverse power of the distance; and who, if they can account for a phenomenon by an action exerted across empty space, are content to go no farther, nor seek the cause and nature of the action more closely.

Now metaphysical arguments, in so far as they have any weight or validity whatever, are unconscious appeals to experience; a person endeavours to find out whether a certain condition of things is by him conceivable, and if it is not conceivable he has some *primâ facie* ground for asserting that it probaby does not exist. I say he has *some* ground, but whether it be much or little depends partly on the nature of the thing thought of, whether it be fairly simple or highly complex, and partly on the range of the man's own mental development, whether his experience be wide or narrow.

If a highly-developed mind, or set of minds, find a doctrine about some comparatively simple and fundamental matter absolutely unthinkable, it is an evidence, and is accepted as good evidence, that the unthinkable state of things is one that has no existence; the argument being that if it did exist, either it or something not wholly unlike it would have come within the range of experience. We have no further evidence than this for the statement that two straight lines cannot inclose a space, or that the three angles of a triangle are equal to two right angles.

Nevertheless there is nothing final about such an argument; all that the inconceivability of a thing really proves, or can prove, is that nothing like it has ever come within the thinker's experience; and this proves nothing as to the reality or non-reality of the thing, unless his experience of the same kind of things has been so extensive as to make it reasonably probable that if such a thing had existed it would not have been so completely overlooked.

The experience of a child or a dog, on ordinary scientific phenomena, therefore, is worth next to nothing; and as the experience of a dog is to ordinary science, so is the experience of the human race to some higher phenomena, of which they at present know nothing, and against the existence of which it is perfectly futile and presumptuous to bring forward arguments about their being inconceivable; as if they were likely to be anything else.

Now if there is one thing with which the human race has been more conversant from time immemorial than another, and concerning which more experience has been unconsciously accumulated than about almost anything else that can be mentioned, it is *the action of one body on another;* the exertion of force by one body upon another, the transfer of motion and energy from one body to another; any kind of effect, no matter what, which can be produced in one body by means of another, whether the bodies be animate or inanimate. The action of a man in felling a tree, in thrusting a spear, in drawing a bow; the action of the bow again on an arrow, of powder on a bullet, of a horse on a cart; and again, the action of the earth on the moon, or of a magnet on iron. Every activity, of every kind that we are conscious of, may be taken as an illustration of the action of one body on another.

Action at a Distance v. *Continuous Medium.*

Now I wish to appeal to this mass of experience, and to ask, Is not the direct action of one body on another across empty space, with no means of communication whatever,—is not this absolutely unthinkable? We must not answer the question off-hand, but must give it due consideration; and we shall find, I think, that wherever one body acts on another by obvious contact, we are satisfied and have a feeling that the phenomenon is simple and intelligible; but that whenever one body apparently acts on another at a distance, we are irresistibly impelled to look for the connecting medium.

If a marionette dances in obedience to a prompting hand above it, any intelligent child would feel for the wire; and if no wire or anything corresponding to it was discovered, would feel that there was something uncanny and magical about the whole thing. Ancient attempts at magic were indeed attempts to obtain results without the trouble of properly causing them, to build palaces by rubbing rings or lanterns, to remove mountains by a wish instead of with the spade and pickaxe, and generally to act on bodies without any real means of communication. And modern disbelief in magic is simply a statement of the conviction of mankind that all attempts in this direction have turned out failures, and that physical action at a distance is impossible.

If a man explained the action of a horse or a cart by saying that there was an attraction between them varying as some high direct power of the distance, he would not be saying other than the truth—the facts may be so expressed,—but he would be felt to be giving a wretchedly lame explanation, and any one who simply pointed out the traces would be going much more to the root of the matter. Similarly with the attraction of a magnet for a distant magnetic pole. To say that there is an attraction as the inverse cube of the distance between them is true, but it is not the whole truth; and we should be obliged to any one who will point out the traces, for traces we feel sure there are.

If any one tries to picture clearly to himself the action of one body on another without any medium of communication whatever, he must fail. A medium is instinctively looked for, in most cases; and if not in all, as in falling weights or magnetic attraction, it is only because custom has made us stupidly callous to the real nature of these forces.

When we see a vehicle bowling down-hill without any visible propelling force, we ought to regard it with the same mixture of curiosity and wonder as the Chinaman felt when he saw for the first time in the streets of Chicago a tram-car driven by a rope buried in a pipe underground. The attachment to these cars comes through a narrow slit in the pipe, and is quite unobtrusive. After regarding the car with open-mouthed astonishment for some time, the Chinaman made use of the following memorable exclamation, "No pushee—No pullee—Go like mad!" He was a philosophic Chinaman.

Remember, then, that whenever we see a thing being moved we must look for the rope; it may be visible or it may be invisible, but unless there is either "pushee" or "pullee" there can be no action. And if you further consider a pull it resolves itself into a push; to pull a thing towards you, you have to put your finger behind it and push; a horse is said to pull a cart, but he is really pushing at the collar; an engine pushes a truck by means of a hook and eye; and so on.

An experiment can here be conveniently shown to an audience, which emphasizes the above point of view. A lecturer can have a black wooden weight, attached by invisible thread to a stick; and after waving the stick about like a wand, with the thread slack, and exciting the derision of the audience at the idea that the mass would follow a wand, they can observe that unexpectedly it does so, whenever the thread—whose existence they are unaware of—is tightened.

The lecturer can then say that in all such cases a connecting medium should be searched for; and he can then proceed to feel for the thread and destroy the illusion.

He can subsequently employ a quite visible thread or piece of string for the same purpose, in which case there appears nothing mysterious; but by a few observations on the unknown nature of cohesion, he can emphasize the fact—for it is a fact—that the following of a whole because of the movement of a part, though an absurdly commonplace experience, is just as mysterious as anything else whose physical cause is unknown.

There is thus the further very important and difficult question as to why the parts hang together, and why when you push one part the rest follows. Cohesion is a very striking fact, and an explanation of it is much to be desired ;[1] I shall have a little more to say about it later (p. 369), but at present we have nothing more than an indication of the direction in which an explanation seems possible. We cannot speak distinctly about those actions which are as yet mysterious to us ; but concerning those which are comparatively simple and intelligible we may make this general statement : The only way of acting on a body directly is to push it behind.

There must be contact between bodies before they can directly act on each other ; and if they are not in contact with each other and yet act, they must both be in contact with some third body which is the medium of communication, the rope.

Consider now for an instant the most complex case, the action of one animate body on another not touching it. To call the attention of a dog, for instance, there are several methods : one plan is to prod him with a stick, another is to heave a stone at him, a third is to whistle or call, while a fourth is to beckon him by gesture, or, what is essentially the same process, to flash sunlight into his eye with a mirror.

[1] Chap. 16 in my book on "Electrons" above, may be referred to.

In the first two of these methods the media of communication are perfectly obvious—the stick and the stone; in the third, the whistle, the medium is not so obvious, and this case might easily seem to a savage like action at a distance, but we know of course that it is the air, and that if the air between be taken away, all communication by sound is interrupted. But the fourth or optical method is not so interrupted; the dog can see through a vacuum perfectly well, though he cannot hear through it; but what the medium now is which conveys the impression is not so well known. The sun's light is conveyed to the earth by such a medium as this across the emptiness of planetary space.

The only remaining typical plans of acting on the dog would be either by scent or by electric or magnetic attractions; and I would have you seek for the medium which conveys these impressions with just as great a certainty that there is one as you feel in any of the other cases.

Leaving these more mysterious and subtle modes of communication, let us return to the two most simple ones, viz. the stick and the stone. *These two are representative of the only possible fundamental mechanical modes of direct communication between distant bodies;* for we are inclined to believe that every more occult mode of purely physical action will ultimately resolve itself into one or other of these two. The stick represents the method of communication by continuous substance; the stone represents the communication by actual transfer of matter, or, as I shall call it, the projectile method.

There are no other known methods for one body to act directly on another than by these two—by continuous medium, and by projectile.

We know one clear and well-established example of the projectile method, viz. the transmission of pressure by gases. A gas consists of particles perfectly independent of each other, and the only way in which they can act on each other is by percussion. The pressure of the air is a bombardment of particles, and actions are transmitted through gases as through a row of ivory balls. Sound is propagated by each particle receiving what is virtually a knock and passing it on to the next; the final effect being much the same as if the first struck particles had been shot through the whole distance.

The explanation of the whole behaviour of gases in this manner is so simple and satisfactory, and moreover is so certainly the true account of the matter, that we are naturally tempted to ask whether this projectile theory is not the key to the universe, and whether every kind of action whatever cannot be worked out on this hypothesis of atoms blindly driving about in all directions at perfect random, and with complete independence of each other except when they collide. And accordingly we have the corpuscular theories of light and of gravitation: both account for their respective phenomena by a battering of particles. The corpuscular theory of gravitation is, however, full of difficulties; for it is not obvious, according to it, why the weight of a plate is the same when held edgeways as when held broadside on, in the stream of corpuscles; while it is surprising (as indeed it perhaps is on any hypothesis) that the weight of a body is the same in the solid, liquid, and gaseous states. It has been attempted to explain cohesion also on the same hypothesis, but the difficulties, which were great enough before, are now enormous; and to me at any rate it seems that it is only by violent straining and by improbable hypothesis that we can explain all the actions of the universe by a mere battery of particles.

Moreover, it is difficult to understand what the atoms themselves can be like; or how they can strike and bound off one another, without yielding to compression and then springing out again like two elastic balls; it is difficult to understand the elasticity of really ultimate hard particles. And if the atoms are not such hard particles, but are elastic and yielding, and rebound from one another according to the same sort of law that ivory balls do—of what are they composed? We shall have to begin all over again, and explain the cohesion and elasticity of the parts of the atom.

The more we think over the matter, the more are we compelled to abandon mere impact as a complete explanation of action in general. But if this be so we are driven back upon the other hypothesis—the only other—viz. communication by continuous medium.

We must begin to imagine a continuous connecting medium between the particles—a substance in which they are embedded, which penetrates into all their interstices, and extends without breach of continuity to the remotest limits of space. Once grant this, and difficulties begin rapidly to disappear. There is now continuous communication between the particles of bodies, and if one is pushed the others naturally receive the motion. The atoms of gas are impinging as before, but we have now a different idea of what impact means.

It is not likely that atoms of gas ever come into actual contact like two india-rubber balls. Mutual forces acting between two atoms can produce the effect of a rebound from a collision, without any actual contact; and these forces may be either attractive or repulsive. If attractive, their two paths or orbits will intersect, the particles swinging each other round at the nearest point in a ladies'-chain fashion. If the forces are repulsive, the two orbits do not intersect, but stand outside each other like the two branches of a hyperbola.

Gravitation is explicable by differences of pressure in the medium, caused by some action between it and matter not yet understood. Cohesion is probably explicable by residual electric affinity.[1]

Light consists of undulation or waves in the medium; while electricity is turning out quite possibly to be an aspect or individualised peculiarity of the very medium itself.

The medium is now accepted as a necessity by all modern physicists, for without it we are groping in the dark; with it we feel we have a clue which, if followed up, may lead us into the innermost secrets of Nature. It has as yet been followed up very partially, but I will try and indicate the directions in which modern science is tending.

[1] See Lodge in *Nature* (1904), vol. lxx. p. 176; also p. 76 above.

The name you choose to give to the medium is a matter of very small importance, but "the ether" is as good a name for it as another.

As far as we know, it appears to be a perfectly homogeneous, incompressible, continuous body, incapable of being resolved into simpler elements or atoms; it is, in fact, continuous, not molecular. There is no other body of which we can say this and hence the properties of ether must be somewhat different from those of ordinary matter. But there is little difficulty in picturing a continuous substance to ourselves, inasmuch as the molecular and porous nature of ordinary matter is by no means evident to the senses, but is an inference of some difficulty.

Ether is often called a fluid, or a liquid; and again it has been called a solid, and has been likened to a jelly, because of its rigidity; but none of these names is very much good; for all these are molecular groupings, and therefore not like ether. Let us think simply and solely of a continuous, frictionless medium possessing inertia—and the vagueness of the notion will be nothing more than is proper in the present state of our knowledge.

We have now to try and realize the idea of a perfectly continuous, subtle, incompressible substance pervading all space and penetrating between the molecules of all ordinary matter, which are embedded in it and connected with one another by its means. And we must regard it as the one universal medium by which all actions between bodies are carried on. This, then, is its function—to act as the transmitter of motion and of energy.

Transmission of Light.

Now consider the propagation of light.

Sound is propagated by direct excursion and impact of the atoms of ordinary matter. Light is not so propagated. How do we know this?

(1) Because of its speed, 3×10^{10} centimetres per second; which is greater than anything transmissible by ordinary matter.

(2) Because of the kind of vibration, as revealed by the phenomena of polarization.

The vibrations of light are not such as can be transmitted by a set of disconnected molecules; if by molecules at all, it must be by molecules connected into a solid, *i.e.* by a body with rigidity. Rigidity means active resistance to shearing stress, *i.e.* to alteration in shape; it is also called *elasticity of figure;* it is by the possession of rigidity that a solid differs from a fluid. For a substance to transmit vibrations *at all* it must possess inertia; transverse vibrations can only be transmitted by a substance possessing *also* the property of rigidity. All matter possesses inertia, but fluids possess only volume elasticity, and accordingly can transmit only longitudinal vibrations. Light consists of transverse vibrations; air and water have no rigidity, yet they are transparent, *i.e.* permit transverse vibrations; hence it must be the ether inside them which really conveys the motion, and the ether must have properties which, if it were ordinary matter, we should style *inertia* and *rigidity*. No highly rarefied air will serve the purpose; the ether must be a distinct body. Air may *exist* indeed in planetary space, even to infinity, but if so it is of almost infinitesimal tenuity. The density of ether is completely unknown; some physicists suspect that it is very great; others have surmised that it is exceedingly small.

Once given the density of the ether, its rigidity follows at once, because the ratio of the rigidity to the density is the square of the velocity of transverse wave propagation; viz. in the case of ether 9×10^{20}. The most rigid solid we know is steel; its rigidity is 8×10^{11} C.G.S. units. Neither steel nor glass, however, could transmit vibrations with anything like the speed of light, because of their great density. The rate at which transverse vibrations are propagated by crown glass is half a million centimetres per second—a considerable speed, no doubt, but the ether inside the glass transmits them 40,000 times as quick, viz. at twenty thousand million centimetres per second.

The ether outside the glass can do still better than this; it comes up to thirty thousand million, and the question arises what is the matter with the ether inside the glass that it can only transmit undulations at two-thirds the normal speed. Is it denser than free ether, or is it less rigid? Well, it is not easy to say, but the fact is certain that ether is somehow affected by the immediate neighbourhood of gross matter, and it appears to be concentrated inside it to an extent depending on the density of the matter. Fresnel's hypothesis is that the ether is effectively denser inside gross matter, that there is a sort of attraction between ether and the molecules of matter which results in an agglomeration or binding of some ether round each atom, and that this additional or bound ether belongs to the matter, and travels about with it. The *rigidity* of the bound ether Fresnel supposes to be the same as that of the free, except in some crystals.

If anything like this can be imagined, a measure of the relative density of the bound ether is easily given. For the inverse velocity-ratio of light is n (the index of refraction), and the density is inversely as the square of the velocity; hence the density-measure is n^2. The density of ether in free space being called 1, that inside matter has a density n^2, and the density of the bound portion of this is $n^2 - 1$.

This may all sound very fanciful, but something like it is sober truth; not as it is here stated very likely, but the fact that $\left(1 - \frac{1}{n^2}\right)$th of the whole ether inside matter is bound to it and travels with it while the remaining $\frac{1}{n^2}$th is free and blows freely through the pores, is fairly well established and confirmed by direct experiment.

Consider the effect of wind on sound. Sound is travelling through the air at a certain definite rate, depending simply on the average speed of the atoms in their excursions, and on the rate at which they therefore pass the knocks on; if there is a wind carrying all the atoms bodily in one direction, naturally the sound will travel quicker in that direction than in the opposite. Sound travels quicker with the wind than against it. Now is it the same with light? does it too travel quicker with the wind? Well that altogether depends on whether the ether is blowing along as well as the air; if it is, then its motion must help the light on a little; but if the ether is at rest, no motion of air or matter of any kind can make any difference. But according to Fresnel's hypothesis it is not wholly at rest nor wholly in motion; the free is at rest, the bound is in motion; and therefore the speed of light, with the wind, should be increased by an addition of $\left(1 - \frac{1}{n^2}\right)$th of the velocity of the wind.

Very small is this fraction for the case of air, whose n is but a trifle greater than 1; but for water the fraction is 7–16ths, and Fizeau thought this not quite hopeless to look for. He accordingly devised a beautiful experiment, executed it successfully, and proved that when light travels with a stream of water, 7-16ths of the velocity of the water must be added to the velocity of the light; and when it travels against the stream the same quantity must be subtracted, to get the true resultant velocity with which the light is travelling through space.

Arago suggested another experiment. When light passes through a prism, it is bent out of its course, by reason of its diminished velocity inside the glass, and the refraction is strictly dependent on the retardation. Now suppose a prism carried rapidly forward through space—say at the rate of nineteen miles a second by the earth in its orbit which is the quickest accessible carriage; if the ether is all streaming freely through the glass, light passing through the prism will be less retarded when going with the ether than when going against it, and hence the bending will be different.

Maxwell tried the experiment in a very perfect form, but found no difference. If all the ether were free there would have been a difference; if all the ether were bound to the glass there would have been a difference the other way; but according to Fresnel's hypothesis there *should* be no difference, because, according to it, the free ether, which is the portion in relative motion, has nothing to do with the refraction, it is the addition of the bound ether which causes the refraction, and this part is stationary relatively to the glass, and is not streaming through it at all. Hence the refraction is the same whether the prism be at rest or be in motion through space.[1]

Emission of Waves.

Let an atom embedded in ether be vibrating and sending out waves in all directions; the length of the wave depends on the period of the vibration, and different lengths of wave produce the different colour sensations. Now through free ether all kinds of waves travel at the same rate; not so through

[1] Several of this class of experiments have been recently performed with consummate skill and with refined appliances by Mr. Michelson in America. The result of his repetition of the Fizeau experiment is entirely confirmatory of Fizeau's result and of Fresnel's theory. The results of some of the other experiments, having reference to the theory of aberration and the motion of the ether near the earth, are at first sight more puzzling, and open up a large and important subject. [See Lord Rayleigh in *Nature*, vol. xlv., pp. 499, 549, "Aberration"; also Lodge, *Phil. Trans. Roy. Soc.*, 1893 and 1895.]

bound ether; inside matter the short waves are more retarded than the long, and hence the different sizes of waves can be sorted out by a prism. Now a free atom has its own definite period of vibration, like a tuning-fork, and accordingly sends out light of a certain definite colour or of a few definite colours, just as a tuning-fork emits sound of a certain definite pitch or of a few definite pitches called harmonics. By the pitch of the sound it is easy to calculate the rate of vibration of the fork; by the colour of the light one can determine the rate of vibration of the atom.

When we speak of the atoms vibrating, we do not mean that they are wagging to and fro as a whole; it is more likely that they are crimping themselves, that they are vibrating as a tuning-fork or a bell vibrates. It is now thought most likely that only a very small portion—only a constituent of the atom—is by its orbital motion, or series of motions, generating the waves. The free atoms of a gas vibrate in the simplest manner. It is only in the gaseous state, indeed, that we can study the rate of vibration of an atom; when atoms are packed closely together in a solid or liquid, they are cramped, and all manner of secondary vibrations are induced. Constrained vibrations are executed in every variety, but the simple periodicity of the free atom is lost.

To study the free atoms we take a gas—the rarer the better: heat it, or otherwise disturb it violently, so as to make the atoms clang against each other; and then sort out the waves it produces in the ether by putting a triangular prism of bound ether in their path.

The bound ether retards different waves differently, or "disperses" the light, sorting out its constituent waves along different paths, and thus analyzing it.

The result of the prismatic analysis is to prove that every atom of matter has its own definite rate of vibration, as a bell has; it may emit several colours, or only one, and the number it emits may depend upon how much it is struck (or heated); but, those it can emit are a perfectly definite selection, and depend in no way on the previous history of the atom. Every free atom of sodium, for instance, vibrates in the same way, and has always vibrated in the same way, whatever other element it may have been at intervals combined with, and whether it exists in the sun or in the earth, or in the most distant star. The same is true of every other kind of matter, each has its own mode of vibration which nothing but bondage changes; and hence has arisen a new chemical analysis, wherein substances are detected simply by observing the rate of vibration of their free atoms, a branch of physical chemistry called spectrum analysis.

The atoms are small bodies, and accordingly they or their effectively radiating constituent parts vibrate with inconceivable rapidity.

An atom of sodium vibrates 5×10^{14} times in a second; that is, it executes five hundred million complete vibrations in the millionth part of a second.

This is about a medium pace, and the waves it emits produce in the eye the sensation of a deep yellow.

4×10^{14} corresponds to red light, 7×10^{14} to blue.

An atom of hydrogen has three different periods, viz. 4·577, 6·179, and 6·973, each multiplied by the inevitable 10^{14}.

The number of vibrations or revolutions executed every second by a luminous atom exceed-5,000 fold the number of seconds of time which have passed since the Christian era.

Atoms may, indeed, vibrate more slowly than this, but the retina is not constructed so as to be sensible of slower vibrations; however, thanks to Sir W. Abney, there are ways now of photographing the effect of much slower vibrations, and thus of making them indirectly visible; so we can now hope to observe the motion of atoms over a much greater range than the purely optical ones, and so learn much more about them.[1]

The distinction between free and bound ether is forced on our notice by other phenomena than those of light. When we come to electricity we find that some kind of matter has more electricity associated with it than others, so that for a given electromotive force we get a greater electric displacement;—the electricity behaves as if denser in some kinds of matter than in others. The density of electricity in space being called I, that inside matter is called K, its specific inductive capacity. In optics the relative density of the ether inside matter

[1] Still more perhaps may we now hope from the modified line thermopile or Siemens pyrometer, which Prof. Langley so ably developed and used in a series of fine researches: the instrument which he calls the "bolometer." Or from Mr. Boys's still more recent "Radio-micrometer."

was n^2, the square of the index of refraction, p. 349. These numbers appear to be the same.

Is the ether electricity then? I do not say so, neither do I think that in that coarse statement lies the truth; but that they are connected there can be no doubt.

What I have to suggest is that positive and negative electricity together may make up the ether; or rather, that *the ether may be sheared by electromotive forces into what would become positive and negative electricity if they were really separated.* Transverse vibrations are carried on by shearing forces, acting in matter which resists them, because it or its ether possesses rigidity. The bound ether inside a conductor has no rigidity; it cannot resist shear; such a body is opaque. Transparent bodies are those whose bound ether, when sheared, resists and springs back again; such bodies are dielectrics.

We have no direct way of exerting force upon ether at all; we can, however, act on it in a very indirect manner, for we have learnt how to arrange matter so as to cause it to exert the required shearing (or electromotive) force upon the ether associated with it. Continuous shearing force applied to the ether in metals produces a continuous and barely resisted stream of the two electricities in opposite directions; or a conduction current.

Continuous shearing force applied to the ether in transparent bodies produces an electric displacement accompanied by elastic resilience, and thus all the phenomena of electric charge and induction (Chap. III.).

Some chemical compounds, consisting of binary molecules, *distribute* the bound ether of the molecule; at any rate as soon as it is split up by dissociation; and, instead of each nascent radicle or atom taking with it neutral ether, one takes a certain definite quantity of positive, the other the same amount of negative, electricity. In the liquid state the atoms are capable of locomotion; and a continuous shearing force applied to the ether, in such liquids, causes a continual procession of the matter and associated electricity—the positive one way, and the negative the other—and thus all the phenomena of electrolysis (Chap. IV.).

I do not say that the ether is actually composed of positive and negative electricity: but I do say that it possesses a structure such as enables it to transmit light—a structure which, when sheared or decomposed completely by electromotive forces, reveals constituents recognizable by us as positive and negative electricity respectively. We only know how to effect this decomposition in the presence of matter; and the positive appears always inseparable from atoms of matter. In free space the structure only quivers, with incipient separation, but never separates; unless perchance there is some such separation in 'globe lightning.'

Other Functions of the Ether.

But now, looking back to Fresnel's hypothesis of the extra density of ether inside gross matter, and also to the fact that it must be regarded as incompressible; the question naturally arises, How can it be condensed by matter or anything else. Perhaps it is not; perhaps matter only strains the ether towards itself, thus slackening its tension, as it were, inside bodies, not producing any real increase of density; and this is roughly McCullagh's form of the undulatory theory. In this form gravitation may be held to be partially explained; for two bodies straining at the ether in this way will tend to pull themselves together. Newton himself dimly suggested, in one of the queries appended to the later editions of his *Opticks*, that gravitation would be caused if only matter exerted a kind of tension on an all-pervading ether: the tension varying as the inverse distance, so that differences could vary as the inverse square (See Appendices *q* and *r*).

He did not follow the idea up, however, because he had then no other facts to confirm him in his impression of the existence of such an ether, or to inform him concerning its properties. We now not only feel sure that an ether exists, but we know something of its properties; and we also have learnt, from light and from electricity, that some such action between matter and ether actually occurs, though how or why it occurs we do not yet know. I am therefore compelled to believe that this is certainly the direction in which an ultimate explanation of gravitation is to be looked for.

In thinking over the Fresnel and McCullagh forms of the undulatory theory, with a view to the reconciliation between them which appears necessary and imminent, one naturally asks, Is there any such clear distinction to be drawn between ether and matter as we have hitherto tacitly assumed? may they not be different modifications, or even manifestations, of the same thing?

Again, when we speak of atoms vibrating, how can they vibrate? of what are their parts composed? If the atom is composed of electrons, then how is the ether modified so as to form an electron?

And now we come to one of the most remarkable and suggestive speculations of modern times—a speculation based on this experimental fact, that the elasticity of a solid may be accounted for by the motion of a fluid; that a fluid in motion may possess rigidity.

I said that rigidity was precisely what no fluid possessed; at rest this is true; in motion it is not true (§ 156).

Consider a perfectly flexible india-rubber O-shaped tube full of water; nothing is more flaccid and limp. But set the water rapidly circulating, and it becomes at once stiff; it will stand on end for a time without support; kinks in it take force to make, and are more or less permanent. A practicable form of this experiment is the well-known one of a flexible chain over a pulley, which becomes stiff as soon as it is set in rapid motion.

This is called a vortex stream-line, and a vortex is a thing built up of a number of such stream-lines. If they are arranged parallel to one another about a straight axis or core, we have a vortex cylinder, such as is easily produced by stirring a vessel of water or by pulling the plug out of a wash-hand basin; or such as are made in the air on a large scale in America, and telegraphed over here, when they are called "cyclones," or "depressions." The *depression* is visible enough in the middle of revolving water. These vortices are wonderfully permanent things, and last a long time, though they sometimes break up unexpectedly. Their energy is due to vapour condensation.

Vortices need not have straight cores: they may have cores of various ring forms, the simplest being a circle. To make a vortex ring we must take a plane disk of the fluid, and at a certain instant give to every atom in the disk a velocity forward, graduating the velocity according to its distance from the edge of the disk. We have as yet no means of doing this in a frictionless fluid, but with a fluid such as air and water it happens to be easy; we have only to knock a little of the fluid suddenly out of a box through a sharp-edged hole, and the friction of the edges of the hole does what we want. The central portion travels rapidly forward, and returns round outside the core, rolling back towards the hole. But the impetus sends the whole forward, and none really returns; it rolls on its outer circumference as a wheel rolls along a road. In a perfect fluid, under conceivable circumstances, it need not so roll forward, as there would be no friction; but in air or water a vortex ring has always a definite forward velocity, just as a locomotive driving-wheel has, when it does not slip on the rails.

We have in these rings a real mass of air moving bodily forward; and it impinges on the face, or on a gas flame, with some force. One is thus easily able to blow out a distant gas flame ten or twelve yards away by an invisible projectile of air. It is differentiated from the rest of the atmosphere by reason of its peculiar rotational motion. The ring may be rendered visible by means of smoke, but it is in no way improved by that addition except in the matter of visibility.

The cores of these rings are elastic—they possess rigidity; the circular is their stable form, and if this is altered, they oscillate about it. Thus when two vortex rings impinge, or even approach fairly near one another, they visibly deflect each other, and also cause each other to vibrate.

The theory of the impact or interference of vortex rings, whose paths cross but which do not come very near together, has been worked out by Prof. J. J. Thomson. It is quite possible to make the rings vibrate without any impact, by serrating the opening out of which they are knocked. The simplest serration of a circle turns it into an ellipse, and here you have an elliptic ring oscillating from a tall to a squat ellipse and back again. Here is a four-waved opening, and the vibrations are by this very well shown. A six-waved opening makes the vibrations almost too small to be perceived at a distance, but still they are sometimes distinct.

The rings vibrate very much like a bell vibrates: perhaps something like an atom vibrates. They have rigidity, although composed of fluid: they are composed of fluid in motion. These air vortices are imperfect, they increase in size, and decrease in energy; in a perfect fluid they would not do this, they would then be permanent and indestructible,—but then also you would not be able to make them.

Now does not the idea strike you that atoms of matter may be vortices like these—vortices in a perfect fluid, vortices in the ether. This was Lord Kelvin's theory of matter. It is not yet proved in what sense or with what modifications it is going to be true, but is it not highly beautiful? a theory about which one may almost dare to say that it deserves to be true? The atoms of matter, according to it, are not so much foreign particles embedded in the all-pervading ether, as portions of it, differentiated off from the rest by reason of their vortex motion, thus becoming virtually solid particles, yet with no transition of substance; atoms indestructible and not able to be manufactured, not mere hard rigid specks, but each composed of whirling ether; elastic, capable of definite vibration, of free movement, of collision. The crispations or crimpings of these rings illustrate the kind of way in which we may suppose an atom to vibrate. They appear to have all the properties of atoms except one, viz. gravitation; and before the theory can be accepted, I think it must account for gravitation. This intrinsic property of matter cannot be left over to be explained by an artificial battery of ultra-mundane corpuscles. We cannot go back to mere impact of hard bodies after having allowed ourselves a continuous medium. Vortex atoms, or corpuscles, must be shown to gravitate.

But then remember how small a force gravitation is. Ask any educated man whether two pound-masses of lead attract each other; and he will reply no. He is wrong, of course, but the force is exceedingly small. Yet it is the aggregate attraction of trillions upon trillions of atoms; the *slightest* effect of each upon the ether would be sufficient to account for gravitation; and no one can say that vortices do not exert some such residual, but uniform, effect on the fluid in which they exist, till second, third, and every other order of small quantities have been taken into account, and the theory of vortices in a perfect fluid worked out with the most final accuracy.

I have now endeavoured to introduce you to the simplest conception of the material universe which has yet occurred to man—the conception, that is, of one universal substance, perfectly continuous and homogeneous, save for its structural constitution, extending to the furthest limits of space of which we have any knowledge, existing equally everywhere; all at rest as a whole, but endowed with such intrinsic motion as enables it to transmit the undulations which we call light; other portions in a still more special state of rotational motion—in vortices or something equivalent—and differentiated permanently from the rest of the medium by reason of this motion.

These whirling portions may indirectly constitute what we call matter; their motion gives them rigidity, and of them our bodies and all other material bodies with which we are acquainted may be built up.

One continuous substance filling all space: which can vibrate as light; which, under certain unknown conditions, can be modified or analyzed into positive and negative electricity; which can constitute matter; and can transmit, by continuity and not by impact, every action and reaction of which matter is capable. This is the modern view of the Ether and its functions.

LECTURE III

THE DISCHARGE OF A LEYDEN JAR[1]

IT is one of the great generalizations established by Faraday that all electrical charge and discharge is essentially the charge and discharge of a Leyden jar. It is impossible to charge one body alone. Whenever a body is charged positively, some other body is *ipso facto* charged negatively, and the two equal opposite charges are connected by lines of induction. The charges are, in fact, simply the ends of these lines; and it is as impossible to have one charge without its correlative, as it is to have one end of a piece of string without there being somewhere, hidden it may be, split up into strands it may be, but somewhere existent, the other end of that string.

This, I suppose familiar, fact—that all charge is virtually that of a Leyden jar—being premised, our subject for this evening is at once seen to be a very wide one; ranging, in fact, over the whole domain of electricity. For the charge of a Leyden jar includes virtually the domain of electrostatics; while the discharge of a jar, since it constitutes a current, covers

[1] Delivered at the Royal Institution of Great Britain, on Friday evening, March 8, 1889.

the ground of current electricity,—all except that portion which deals with phenomena peculiar to steady currents. And since a current of electricity necessarily magnetizes the space around it, whether it flow in a straight or in a curved path, whether it flow through wire or burst through air, the territory of magnetism is likewise invaded; and inasmuch as a Leyden jar discharge is oscillatory, and we now know the vibratory motion called light to be really an oscillatory electric current, the domain of optics is seriously encroached upon.

But though the subject I have chosen would permit this wide range, and though it is highly desirable to keep before our minds the wide-reaching import of the most simple-seeming fact in connexion with such a subject, yet to-night I do not intend to avail myself of any such latitude; but shall keep as closely and distinctly as possible to the Leyden jar in its homely and well-known form, as constructed out of a glass bottle, two sheets of tinfoil, and some stickphast.

The act of charging such a jar I have permitted myself now for some time to illustrate, by the mechanical analogy of an inextensible endless cord, able to circulate over pulleys, and threading in some portion of its length a row of tightly-gripping beads, which are connected to fixed beams by elastic threads.

The cord is to represent electricity; the beads represent successive strata in the thickness of the glass of the jar, or, if you like, atoms of dielectric or insulating matter. Extra tension in the cord represents negative potential, while a less tension (the nearest analogue to pressure adapted to the circum-

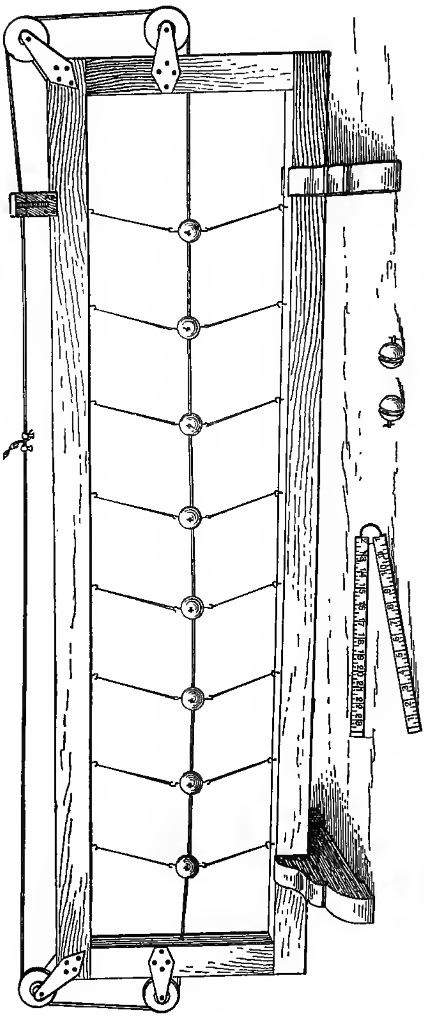


FIG. 67.—Actual model representing dielectric phenomena, as in Figs. 6 and 8, page 39. The cord is a piece of blind cord joined by a binding screw, and passing through a clip or clamp by which it can be fixed. The wooden balls have screws to grip on to it; or their grip can be relaxed to represent conduction. The balls lying on the table are made of lead, and when fixed on the vertical portions of the cord represent the effect of increase of self-induction. The wooden balls are hooked on to the frame by common elastic bands, which may be doubled or otherwise varied to represent differences in specific inductive capacity.

stances) represents positive potential. Forces applied to move the cord, such as winches or weights, are electromotive forces; a clamp or fixed obstruction represents a rheostat or contact-breaker; and an excess or defect of cord, between two strata of matter, represents a positive or a negative charge.

The act of charging a jar is now quite easily depicted as shown in the diagram.

To discharge the jar one must remove the charging E.M.F. and unclamp the brake, *i.e.* close the circuit. The stress in the elastic threads will then rapidly drive the cord back; but the inertia of the beads will cause it to overshoot the mark, and for an instant the jar will possess an inverse charge. Back again the cord swings, however, and a charge of same sign as at first, but of rather less magnitude, would be found in the jar if the operation were now suspended. If it be allowed to go on, the oscillations gradually subside, and in a short time everything is quiescent, and the jar is completely discharged.

All this occurs in the Leyden jar; and the whole series of oscillations, accompanied by periodic reversal and re-reversal of the charges of the jar, is all accomplished in the incredibly short space of time occupied by a spark.

Consider now what the rate of oscillation depends on. Manifestly on the elasticity of the threads and on the inertia of the matter which is moved. Take the simplest mechanical analogy, that of the vibration of a loaded spring, like the reeds in a musical box. The stiffer the spring and the less the load, the faster it vibrates. Give a mathematician these data, and he will calculate for you the time the spring takes to execute one complete vibration, the "period" of its swing. A wooden lath clamped in a vice, and loaded at the top with a flap of lead sheeting, illustrates the oscillations very well.

The electrical problem and the electrical solution are precisely the same. That which corresponds to the flexibility of the spring is in electrical language called static capacity, or, by Mr. Oliver Heaviside, permittance. That which corresponds to the inertia of ordinary matter is electro-magnetic inertia, or self-induction, or by Mr. Heaviside, inductance.

Increase either of these, and the rate of oscillation is diminished. Increasing the static capacity corresponds to lengthening the spring; increasing the self-induction corresponds to loading it.

Now the static capacity is increased simply by using a larger jar, or by combining a number of jars into a battery in the very old-established way. Increase in the self-induction is attained by giving the discharge more space to magnetize, or by making it magnetize a given space more strongly. For electro-magnetic inertia is wholly due to the magnetization of the space surrounding a current, and this space may be increased, or its magnetization intensified, as much as we please.

To increase the space we have only to make the discharge take a long circuit instead of a short one. Thus we may send it by a wire all round the room, or by a telegraph wire all round a town, and all the space inside it and some of that outside will be more or less magnetized. More or less, I say, and it is a case of less rather than more. Practically very little effect is felt except close to the conductor, and accordingly the self-induction increases very nearly proportionally to the length of the wire, and not in proportion to the area inclosed: provided also the going and return wires are kept a reasonable distance apart, so as not to encroach upon each other's appreciably magnetized regions. See Appendix (*e*).

But it is just as effective, and more compact, to intensify the magnetization of a given space by sending the current hundreds of times round it instead of only once; and this is done by inserting a coil of wire into the discharge circuit.

Yet a third way there is of increasing the magnetization of a given space, and that is to fill it with some very magnetizable substance, such as iron. This, indeed, is a most powerful method under many circumstances; for it is possible to increase the magnetization and therefore the self-induction or inertia of the current some 5000 times by the use of iron.

But in the case of the discharge of a Leyden jar iron is of no advantage. The current oscillates so quickly that any iron introduced into its circuit, however subdivided into thin wires it may be, is protected from magnetism by inverse currents induced in its outer skin, as Lord Rayleigh has shown, and accordingly it does not get simply magnetized; and so far from increasing the inductance of the discharge circuit it positively diminishes it by the reaction effect of these induced currents: it acts, in some respects, almost as a mass of copper might be expected to do.

The conditions determining rate of oscillation being understood, we have next to consider what regulates the damping out of the vibrations, *i.e.* the total duration of the discharge.

Resistance is one thing. To check the oscillations of a vibrating spring you apply to it friction, or make it move in a viscous medium ; and its vibrations are speedily damped out. The friction may be made so great that oscillations are entirely prevented, the motion being a mere dead-beat return to the position of equilibrium ; or, again, it may be greater still, and the motion may correspond to a mere leak or slow sliding back, taking hours or days for its accomplishment. With very large condensers, such as are used in telegraphy, this kind of discharge is frequent ; but in the case of a Leyden jar discharge it is entirely exceptional. It can be caused by including in the circuit a wet string, or a capillary tube full of distilled water, or a slab of wood, or other atrociously bad conductor of that sort ; but the conditions ordinarily associated with the discharge of a Leyden jar, whether it discharge through a long or a short wire, or simply through its tongs, or whether it overflow its edge or puncture its glass, are such as correspond to oscillations, and not to leak. The experimental discharge of a jar, first through wire, and next through wood, emphasizes the difference, by the very different sound and character of the spark.

When the jar is made to leak through wood or water the discharge is found to be still not steady : it is not oscillatory indeed, but it is intermittent. It occurs in a series of little jerks, as when a thing is made to slide over a resined surface. The reason of this is that the terminals discharge faster than the circuit can supply the electricity, and so the flow is continually stopped and begun again.

Such a discharge as this, consisting really of a succession of small sparks, may readily appeal to the eye as a single flash; but it lacks the noise and violence of the ordinary discharge, and any kind of moving mirror will easily analyze it into its constituents and show it to be intermittent. This can be done by shaking a mirror, or by waggling the head or an opera-glass.

It is pretty safe to say, then, that whenever a jar discharge is not oscillatory it is intermittent, and when not intermittent is oscillatory. There is an intermediate case, when it is really dead-beat, but it could only be hit upon with special care, while its occurrence by accident must be rare.

So far I have only mentioned resistance or friction as the cause of the dying out of the vibrations; but there is another cause, and that a most important one.

The vibrations of a reed are damped, partly indeed by friction and imperfect elasticity, but partly also by the energy transferred to the surrounding medium and consumed in the production of sound. It is the formation and propagation of sound-waves which chiefly damp out the vibrations of any musical instrument. So it is also in electricity. The oscillatory discharge of a Leyden jar disturbs the medium surrounding it, carves it into waves which travel away from it into space: travel with a velocity of 185,000 miles a second—travel precisely with the velocity of light. The phenomenon is roughly analogous to that of the Tuning-fork.

The second cause, then, which damps out the oscillations in a discharge circuit is *radiation: electrical* radiation if you like so to distinguish it, but it differs in no respect from ordinary radiation (or "radiant heat" as it was so constantly spoken of by Prof. Tyndall); it differs in no respect from Light except in the physiological fact that the retinal mechanism, whatever it may be, responds only to waves of a particular, and that a very small, size, while radiation in general may have waves which range from a million miles to a millionth of an inch in length.

The seeds of this great discovery of the nature of light were sown in the Royal Institution: it is the outcome of Faraday's magneto-electric and electrostatic induction: the development of them into a rich and full-blown theory was the greatest achievement of Clerk Maxwell; the harvest of experimental verification was reaped by a German physicist. The late Dr. Hertz, Professor in the University of Bonn, was a young investigator of the highest type. Trained in the school of Helmholtz, and endowed with both mathematical knowledge and great experimental skill, he has immortalized himself by a brilliant series of investigations which have cut right into the ripe corn of scientific opinion in these islands, and by the same strokes as have harvested the grain have opened up wide and many branching avenues to other investigators.

At one time I had thought of addressing you this evening on the subject of these researches of Hertz; but the experiments are not yet reproducible on a scale suited to a large audience, and I have been so closely occupied with some not wholly dissimilar, but independently conducted, researches of my own—researches led up to through the unlikely avenue of lightning-conductors—that I have had as yet no time to do more than verify some of the results of Hertz for my own edification (§ 189). The waves which I here refer to, parenthetically, as detected by myself, are those evidenced by electrical nodes and loops on long insulated wires attached to an oscillatory discharging source (§ 137). (See *The Electrician*, xxi., 607 and 623, Sept. 14 and 21, 1888.)

I have wandered a little from my Leyden jar, and I must return to it and its oscillations. Let me very briefly run over the history of our knowledge of the oscillatory character of a Leyden jar discharge. It was first clearly realized and distinctly stated by that excellent experimentalist, Joseph Henry, of Washington, a man not wholly unlike Faraday in his mode of work, though doubtless possessing to a less degree that astonishing insight into intricate and obscure phenomena ;—wanting also in Faraday's circumstantial advantages.

This great man arrived at a conviction that the Leyden jar discharge was oscillatory, by studying the singular phenomena attending the magnetization of steel needles by a Leyden jar discharge, first observed in 1824 by Savary. Fine needles, when taken out of the magnetizing helices, were found to be not always magnetized in the right direction, and the subject is referred to in German books as " anomalous magnetization." It is not the magnetization which is anomalous, but the currents which have no simple direction; and we find, in a memoir published by Henry in 1842, the following words:—

"This anomaly, which has remained so long unexplained, and which, at first sight, appears at variance with all our theoretical ideas of the connexion of electricity and magnetism, was, after considerable study, satisfactorily referred by the author to an action of the discharge of the Leyden jar which had never before been recognized. The discharge, whatever may be its nature, is not correctly represented (employing for simplicity the theory of Franklin) by the single transfer of an imponderable fluid from one side of the jar to the other; the phenomenon requires us to admit *the existence of a principal discharge in one direction and then several reflex actions backward and forward, each more feeble than the preceding, until the equilibrium is obtained.* All the facts are shown to be in accordance with this hypothesis, and a ready explanation is afforded by it of a number of phenomena, which are to be found in the older works on electricity, but which have until this time remained unexplained."[1]

The italics are Henry's. Now if this were an isolated passage it might be nothing more than a lucky guess. But it is not. The conclusion is one at which he arrives after a laborious repetition and serious study of the facts, and he keeps the idea constantly before him when once grasped, and uses it in

[1] *Scientific Writings of Joseph Henry*, vol. i. p. 201. Published by the Smithsonian Institution, Washington, 1886.

all the rest of his researches on the subject. The facts studied by Henry do in my opinion support his conclusion, and if I am right in this it follows that he is the original discoverer of the oscillatory character of a spark, although he does not attempt to state its theory. That was first done, and completely done, in 1853, by Lord Kelvin; and the progress of experiment by Feddersen, Helmholtz, Schiller, and others, has done nothing but substantiate it.

The writings of Henry have been only quite recently collected and published by the Smithsonian Institution of Washington in accessible form, and accordingly they have been far too much ignored. The two volumes contain a wealth of beautiful experiments clearly recorded, and well repay perusal.

The discovery of the oscillatory character of a Leyden jar discharge may seem a small matter, but it is not. We have only to recall the fact that the oscillators of Hertz are essentially Leyden jars—we have only to use the phrase "electro-magnetic theory of light"—to have some of the momentous issues of this discovery flash before us.

One more extract I must make from that same memoir by Henry,[1] and it is a most interesting one: it shows how near he was, or might have been, to obtaining some of the results of Hertz; though, if he had obtained them, neither he nor any other experimentalist could possibly have divined their real significance.

It is, after all, the genius of Maxwell and of a few other great theoretical physicists whose names are on

[1] *Loc. cit.* p. 204.

everyone's lips[1] which endows the simple induction experiments of Hertz and others with such stupendous importance.

Here is the quotation:—

"In extending the researches relative to this part of the investigations, a remarkable result was obtained in regard to the distance at which induction effects are produced by a very small quantity of electricity; a single spark from the prime conductor of a machine, of about an inch long, thrown on to the end of a circuit of wire in an upper room, produced an induction sufficiently powerful to magnetize needles in a parallel circuit of iron placed in the cellar beneath, at a perpendicular distance of 30 feet, with two floors and ceilings, each 14 inches thick, intervening. The author is disposed to adopt the hypothesis of an electrical *plenum*" [in other words, of an ether], "and from the foregoing experiment it would appear that a single spark is sufficient to disturb perceptibly the electricity of space throughout at least a cube of 400,000 feet of capacity; and when it is considered that the magnetism of the needle is the result of the difference of two actions, it may be further inferred that the diffusion of motion in this case is almost comparable with that of a spark from a flint and steel in the case of light."

Comparable it is, indeed, for we now know it to be the self-same process.

[1] And of one whose name is not on everybody's lips, but whose profound researches into electro-magnetic waves have penetrated further than is generally understood into the depths of the subject,—I mean that powerful mathematical physicist, Mr. Oliver Heaviside.

One immediate consequence and easy proof of the oscillatory character of a Leyden jar discharge is the occurrence of phenomena of sympathetic resonance.

Everyone knows that one tuning-fork can excite another at a reasonable distance if both are tuned to the same note. Every one knows, also, that a fork can throw a stretched string attached to it into sympathetic vibration if the two are tuned to unison or to some simple harmonic. Both these facts have their electrical analogue. I have not time to go fully into the matter to-night, but I may just mention the two cases which I have myself specially noticed.

A Leyden jar discharge can so excite a similarly-timed neighbouring Leyden jar circuit as to cause the latter to burst its dielectric if thin and weak enough. The well-timed impulses accumulate in the neighbouring circuit till they break through a quite perceptible thickness of air. Put the circuits out of unison, by varying the capacity or by including a longer wire in one of them; then, although the added wire be a coil of several turns, well adapted to assist mutual induction as ordinarily understood, the effect will no longer occur. It can be obtained again by diminishing either the static capacity or the self-induction.

That is one case, and it is the electrical analogue of one tuning-fork exciting another. It is too small at present to show here satisfactorily, for I only recently observed it, but it is exhibited in the library at the back. [A form of this experiment devised a few months later, page 291, is readily seen by an audience.]

The other case, analogous to the excitation of a stretched string of proper length by a tuning-fork, I published last year under the name of the experiment of the recoil kick; where a Leyden jar circuit sends waves along a wire connected by one end with it, which waves splash off at the far end with an electric brush or long spark. [Luminous nodes and loops on a very long wire were afterwards exhibited by me to the Physical Society.]

I will show merely one phase of it to-night, and that is the reaction of the impulse accumulated in the wire upon the jar itself, causing it either to overflow or burst. An ordinary gallon Leyden jar was here connected to a long wire round the room and then it was discharged ordinarily; the reaction of the pulses on the long wire caused it violently to overflow its lip in a cascade of sparks eight inches long.[1]

The early observations by Franklin on the bursting of Leyden jars, and the extraordinary complexity or multiplicity of the fracture that often results, are

[1] During the course of this experiment, the gilt paper on the wall was observed by the audience to be sparkling, every gilt patch over a certain area discharging into the next, after the manner of a spangled jar. It was probably due to some kind of sympathetic resonance. Electricity splashes about in conductors in a surprising way everywhere in the neighbourhood of a discharge. For instance, a telescope in the hand of one of the audience was reported afterwards to be giving off little sparks at every discharge of the jar. Everything which happens to have a period of electric oscillation corresponding to some harmonic of the main oscillation of a discharge is liable to behave in this way. When light falls on an opaque surface it is quenched; producing minute electric currents, which subside into heat. What the audience saw was probably the result of waves of electrical radiation being quenched or reflected by the walls of the room, and generating electrical currents in the act (§ 166). It is these electric surgings which render such severe caution necessary in the erection of lightning-conductors.

This explanation has since been entirely confirmed by similar occurrences in other places.

most interesting. (See *Electrician*, March 15 and 29, and April 5, 1889.) His electric experiments, as well as Henry's well repay perusal, though of course they belong to the infancy of the subject. He notes the striking fact that the bursting of a jar is an extra occurrence—it does not replace the ordinary discharge in the proper place, it accompanies it; and we now know that it is precipitated by it, that the spark occurring properly between the knobs sets up such violent surgings that the jar is far more violently strained than by the static charge or mere difference of potentials between its coatings; and if the surgings are at all even roughly properly timed, the jar is bound either to overflow or burst.

Hence the jar should always be made without a lid, and with a lip protruding a carefully considered distance above its coating: not so far as to fail to act as a safety valve, but far enough to prevent overflow under ordinary and easy circumstances.

And now we come to what is after all the main subject of my discourse this evening, viz. the optical and audible demonstration of the oscillations occurring in the Leyden jar spark. Such a demonstration has, so far as I know, never before been attempted, but if nothing goes wrong we shall easily accomplish it.

And first I will do it audibly. To this end the oscillations must be brought down from their extraordinary frequency of a million or hundred thousand a second to a rate within the limits of human audition. It can be done exactly as in the case of the spring—we first increase the flexibility and then we load it;

that is to say we employ considerable capacity, and great self-induction of a suitable kind, in large properly wound coils of well insulated wire without iron.

Using the largest battery of jars at our disposal, I take the spark between these two knobs—not a long spark, $\frac{1}{4}$ inch will be quite sufficient. Notwithstanding the great capacity, the rate of vibration is still far above the limit of audibility, and nothing but the customary crack is heard. I next add inertia to the circuit by including a great coil of wire, and at once the spark changes character, becoming a very shrill but an unmistakable whistle, of a quality approximating to the cry of a bat. Add another coil, and down comes the pace once more, to something like 5000 per second, or about the highest note of a piano. Again and again I load the circuit with magnetizability, and at last the spark has only 500 vibrations a second, giving the octave, or perhaps the double octave, above the middle C.

You see clearly why we get a musical note: the noise of the spark is due to a sudden heating of the air, so if the heat is oscillatory, the sound will be oscillatory too; but both will be an octave above the electric oscillation, if I may so express it, because two heat-pulses will accompany every complete electric vibration, the heat production being independent of direction of current.

Having thus got the frequency of oscillation down to so manageable a value, the optical analysis of it presents no difficulty: a simple looking-glass waggled in the hand will suffice to spread out the spark into a serrated band, just as can be done with a singing or a sensitive flame: a band too of somewhat the same appearance.

Using an ordinary four-square rotating mirror, driven electro-magnetically at the rate of some two or three revolutions per second, the band at the lowest pitch is seen to be quite coarsely serrated. At four revolutions per second, fine serrations can be seen even in the shrill whistling sparks.

The only difficulty in seeing these effects is to catch them at the right moment. They are only visible for a minute fraction of a revolution, though the band may appear drawn out to some length. The further away a spark is from the mirror, the more drawn out it is; but also the less chance there is of catching it.

With a single observer it is easy to arrange a contact maker on the axle of the mirror which shall bring on the discharge at the right place in the revolution, and the observer may then conveniently watch for the image in a telescope or opera-glass; though at the lower pitches nothing of the kind is necessary.

But to show it to a large audience various plans can be adopted. One is to arrange for several sparks instead of one; another is to multiply images of a single spark by suitably adjusted reflectors (which if they are concave will give magnified images); another is to use several rotating mirrors; and indeed I do use two, one adjusted so as to suit the spectators in the gallery.

But the best plan that has struck me is to combine an intermittent and an oscillatory discharge. Have the circuit in two branches, one of high resistance so as to give intermittences, the other of ordinary resistance so as to be oscillatory, and let the mirror analyze every constituent of the intermittent discharge into a serrated band. There will thus be not one spark, but a multitude of successive sparks, close enough together to sound almost like one, separate enough in the rotating mirror to be visible on all sides at once.

But to achieve it one must have great exciting power. In spite of the power of this magnificent Wimshurst machine, it takes some time to charge up our great Leyden battery, and it is tedious waiting for each spark. A Wimshurst does admirably for a single observer, but for a multitude we need an instrument which shall charge the battery not once only but many times over, with overflows between, and all in the twinkling of an eye.

To get this I must abandon my friend Mr. Wimshurst, and return to Michael Faraday. In front of the table is a great induction coil; its secondary has the resistance needed to give an intermittent discharge. The quantity it supplies at a single spark will fill our jars to overflowing several times over. The discharge circuit and all its circumstances shall remain unchanged. [Excite jars by coil, with slow hand-worked rod-and-mercury break.]

Running over the gamut with this coil now used as our exciter instead of the Wimshurst machine—everything else remaining exactly as it was—you hear the sparks give the same notes as before, but with a slight rattle in addition, indicating intermittence as well as alternation. Rotate the mirror, and everyone should see one or other of the serrated bands of light at nearly every break of the primary current of the coil. [Rotating mirror to analyze sparks.]

The musical sparks which I have now shown you were obtained by me during a special digression[1] which I made while examining the effect of discharging a Leyden jar round heavy glass or bisulphide of carbon. The rotation of the plane of polarization of light by a steady current, or by a magnetic field of any kind properly disposed with respect to the rays of light, is a very familiar one in this place. Perhaps it is known also that it can be done by a Leyden jar current. But I do not think it is; and the fact seems to me very interesting. It is not exactly new—in fact, as things go now it may be almost called old, for it was investigated six or seven years ago by two skilled French experimenters, Messrs. Bichat and Blondlot.

But it is exceedingly interesting as showing how short a time, how absolutely no time, is needed by heavy glass to throw itself into the suitable rotatory condition. Some observers have thought they had proved that heavy glass requires time to develop the effect, by spinning it between the poles of a magnet and seeing the effect decrease; but their conclusions cannot be right, for the polarized light follows every oscillation in a discharge, the plane of polarization being waved to and fro as often as 70,000 times a

[1] Most likely it was a conversation which I had with Lord Kelvin, at Christmas, which caused me to see the interest of getting slow oscillations. My attention had previously been mainly directed to getting them quick.

second in my own observations (See *Phil. Mag.* April 1889).

Very few persons in the world have seen the effect. In fact, I doubt if anyone had seen it a month ago except Messrs. Bichat and Blondlot. But I hope to make it visible to most persons here, though I hardly hope to make it visible to all.

Returning to the Wimshurst machine as exciter, I pass a discharge round the spiral of wire inclosing this long tube of CS_2; and, the analyzing Nicol being turned to darkness, there may be seen a faint—by those close to not so faint, but a very momentary—restoration of light on the screen at every spark.

Now I say that this light restoration is also oscillatory. One way of proving this fact is to insert a biquartz between the Nicols. With a steady current it constitutes a sensitive detector of rotation, its sensitive tint turning green on one side and red on the other. But with this oscillatory current a biquartz does absolutely nothing.

That is one proof. Another is that rotating the analyzer either way weakens the extra brightening of the field, and weakens it equally both ways.

But the most convincing proof is to reflect the light coming through the tube upon our rotating mirror, and to look now, not at the spark, or not only at the spark, but at the faint band into which the last residue of light coming through polarizer and tube and analyzer is drawn out. [Analyze the light in rotating mirror.]

At every discharge this faint streak brightens into a beaded band. If the analyzer is now rotated a little, alternate beads brighten, while the other alternate ones fade; by just extinguishing alternate beads, a measure of the rotation can be made, and it is considerable: these are the oscillations of the polarized light; and when examined side by side they are as absolutely synchronous with the oscillations of the spark itself as can be perceived.

Out of a multitude of phenomena connected with the Leyden jar discharge I have selected a few only to present to you here this evening. Many more might have been shown, and great numbers more are not at present adapted for presentation to an audience, being only visible with difficulty and close to.

An old and trite subject is seen to have, in the light of theory, an unexpected charm and brilliancy. So it is with a great number of other old familiar facts at the present time.

The present is an epoch of astounding activity in physical science. Progress is a thing of months and weeks—almost of days. The long line of isolated ripples of past discovery seem blending into a mighty wave, on the crest of which one begins to discern some oncoming magnificent generalization. The suspense is becoming feverish, at times almost painful. One feels like a boy who has been long strumming on the silent keyboard of a deserted organ, into the chest of which an unseen power begins to blow a vivifying breath. Astonished, he now finds that the touch of a finger elicits a responsive note; and he hesitates, half delighted, half affrighted, lest he be deafened by the chords which it would seem he can now summon forth almost at will.

LECTURE IV

MODERN VIEWS OF MATTER[1]

[*This article summarizes in popular form many of the most recent doctrines, and leads up to a more advanced treatise called* "*Electrons.*"]

A lump of matter is as surely composed of atoms as a house is built of bricks. That is to say, matter is not continuous and homogeneous, but is discontinuous; being composed of material particles, whatever they are, and non-material spaces. There is every reason to be certain that these spaces are full of a connecting medium—full of ether; there is no really void space. And the question may be asked, Is this ether not in a manner itself "substance"? Is it not matter in another form? To this I should reply, and I suppose all physicists would reply,—"substance" it may be, "matter" it is not. Not matter as we know it, not matter in the sense we use the term. That term is limited, I take it, to the material bodies which are built up of atoms; it does not extend to

[1] From an article contributed by the author to an American magazine called the *International Monthly*, in May 1900. For further developments see his Romanes Lecture of 1903 (Clarendon Press).

the substance, or medium, whatever it may be, occupying all the rest of space. This may be only a question of nomenclature, and therefore of no great importance, but that is the sense in which the terms are, here at any rate, employed. When I say that matter is certainly atomic, I do not mean that ether is atomic. I hold that ether is most certainly not atomic—not discontinuous; it is an absolutely continuous medium, without breaks or gaps or spaces of any kind in it,—the universal connector; permeating not only the rest of space, as I have just said, but permeating also the space occupied by the atoms themselves. The atom is a something superposed upon, not substituted for, the ether; it is most likely a definite modification of the ether, an individualization, with a permanent existence and a faculty of locomotion which the ether alone does not possess.

Matter is that which is susceptible of motion. Ether is that which is susceptible of stress. All energy appertains either to matter or to ether, and is continually passing from one to the other. When possessed by matter the energy is called kinetic; when possessed by ether the energy is called potential. All the activity of the material universe is due to, or represented by, or displayed in, the continual interchanges of energy from matter to ether and back again; accompanied by its transformation from the kinetic to the potential form and *vice versâ*.

And having asserted this, which I have said at greater length elsewhere,[1] and adding the proviso that not by all physicists is it as yet, so far as I know,

[1] *Phil. Mag.* June 1885, also June 1881, and Oct. 1879.

universally accepted; I shall henceforward discard further reference to the ether, in this chapter, and shall deal with matter alone.

Matter consists of atoms, or molecules; for present purposes there is no need to discriminate. Chemically it is convenient to attribute slightly different meanings to the two terms, but the distinction is of the easiest and most elementary character. A molecule is the smallest complete and normal unit of any substance; it consists usually of two or more atoms, though it may consist of one; and what we have to say here relates essentially to the atom.

Is the atom an ultimate atom? Is it really and truly indivisible; is it an ultimate element or unit which cannot be split up into parts; or does the customary postulate of its indivisibility mean no more than that we have not yet succeeded in discovering a way of decomposing it; or again, does it mean that if we did by any means break it up into fragments it would no longer be an atom of matter, but something else? Suppose for a moment that the atom was a vortex ring in ether, for instance, which could not be split up without destruction; the splitting up would not destroy the substance of which the ring is composed, but it would destroy the motion which constituted it a ring, which gave it individuality; it would destroy everything which entitled it to the term "matter." If broken up it would be resolved into ordinary ether, as a dispersed smoke ring loses its individuality in common air.

A common vortex ring of air or water contains within itself the seeds of its own decease; it is composed of an imperfect fluid—possessing, that is to say, viscosity—and accordingly its life is short; its peculiar energy being dissipated, its vortex motion declines, and as a ring it perishes. But imagine a ring built of some perfect fluid, of some medium devoid of viscosity, as the ether is; then it may be immortal; it can neither be produced nor annihilated by known means; and it is just this property, combined with other properties of elasticity, rigidity, and the like, that led Lord Kelvin originally to his brilliant and well-known hypothesis.

In the crude form here suggested, the hypothesis has not turned out exactly true; that is to say, no one believes now that an atom is simply a vortex ring of ether, and that the rest of the ether is stagnant fluid in which the vortex rings sail about. Any number of difficulties surround such an hypothesis as that. Its apparently attractive simplicity is superficial. Nevertheless, it is not to be supposed that every hydro-dynamical theory of the universe is thereby denied. It is quite conceivable that a single fluid in different kinds of motion—some kinds of motion not yet imagined perhaps—may possibly be found capable of explaining all the facts of physics and chemistry. Whether of biology, too, is a much larger question.

But these hydro-dynamic explanations are a step beyond anything that I propose to discuss now. I have only said as much as this in order to make it clear that what now follows, even if it be completely true, must not be held to replace and negative all the attempts that have been made, and that still will be made, to account for material phenomena by the motions or strains of a perfect fluid. I may as well say, however, that the motions that must be postulated will have to be of a far finer grain,—the individualization on a far smaller scale—than the original vortex-atom view: *viz.* the idea of one vortex ring for each atom, and differently shaped or tangled rings for the different elemental atoms. If there is to be vorticity at all, it would appear that the whole ether must be full of it; it cannot be a simple, stagnant, structureless, homogeneous fluid; for that would not transmit light—would not account even for optical phenomena, still less for those of static electricity and magnetism.

Unintentionally we have drifted back to the ether again, whereas I want to concentrate attention on the atom of matter. Is it indivisible, or does it consist of parts? If so, how many, and what are they? Can one of them be detached from the rest of the atom and observed? Can the motion of a fraction of the atom be detected and measured? Can the atom be broken up, and its constituent parts dealt with? If different kinds of atoms are broken up will they yield fragments of different kinds, or will they all yield fragments of the same kind? Can the fragments move at a measurable speed, and can the effect of bombardment be observed, when they are stopped? Are the fragments all alike, and can they be weighed? Are they, or can they be, charged with electricity; and if so, what properties do they possess when so charged? Can an atom be charged, and if so, how? When a current of electricity is conveyed, by what mechanism is it transmitted? Can its phenomena be always accounted for by the transport of an electrostatic charge? What is meant by the inertia of matter? Has electricity an existence apart from matter? What is the relation, if any, between a unit of electricity and an atom of matter?

All these questions appear to be capable of receiving an answer; they also appear to me to be in process of being answered. And I would not say too much about the impossibility of an answer being given to some further questions before long; but they are in a different category from these, and involve a higher order of difficulty. The question, what is the nature of an electric charge, for instance, is not among the questions which are in process of being answered with any certainty or with any simplicity just yet; it will probably remain for some years yet a question and a challenge. Nor is the answer, when it comes, likely for a long time to be an easy one, such as it is possible to state in general terms and ordinary language.

The existence of an electrical charge we must assume: a charged body is a fact; whether a charge can exist without a body may be doubtful, but it is safe to assume that the properties of an electric charge are those which we know and are familiar with, by experiment upon ordinary large pieces of matter positively and negatively electrified. What are these properties? They are best expressed, in Faraday's language, as a "field of force," a region full of lines of force, every line necessarily starting from a positive charge and ending in a negative one; no line closed upon itself, every line two-ended, every positive charge being connected with an equal negative one; no possibility of having *plus* electricity without *minus* electricity, any more than it is possible for one end of a piece of string to exist without the other end. This fact, the existence of positive and negative charges, we must assume too: they exist, they have opposite properties, they are like opposite aspects of the same thing, or opposite elements of one compound; or opposite strains (as Prof. J. Larmor puts it)—a right-handed and a left-handed strain in the ether. Whatever they are, they exist, and their explanation must be waited for.

The charges themselves are after all only the terminals or boundaries of the field: the whole field of force itself is the most real thing; one cannot say that the charges are the cause of the lines of force, or the lines of force the cause of the charges: they simply co-exist. The lines of force represent a structure of some kind in the ether, they need no "matter" for their existence, they can penetrate what we call absolute vacuum, they are clearly an ethereal phenomenon. But what about their ends? Can they terminate except on an atom of matter? The answer is uncertain, but at any rate we can say this, that never experimentally have we *known* them to terminate except on a material body, or something equivalent to a material body. From body to body they reach; and one of the bodies is positively charged, while the other is negatively charged. That is what, at least to begin with, we must assume as universally true.

The manner of starting such lines into existence is familiar. Any two different bodies put into contact and separated will usually be found joined by such a field of force, provided precautions are taken that the ends shall not slip or leak away, back to each other, during the separation process.

Once the field is established, it may be carried about; but it has gradually become clear that the field is carried *through* the ether and not *with* it. In other words the field is not really moved—it is truer to say that it ceases in one place and starts in another; that as a charged body moves about, its lines of force are perpetually decaying on the side of recession, and being generated on the side of approach: continuing constant in number, so long as there is no leakage, but not possessing individuality of existence. The abandoned region of ether is relieved from strain, and the encroached-upon region sustains the strain.

This transfer of the lines of force has a singular result; a result unguessed by Faraday—a result barely explained even by Maxwell; it interposes a certain obstacle to change of motion. It does not simulate a resistance, or friction, or force of any kind that would tend to bring a body to rest; but it simulates an inertia, the precise opposite of force,—a power of moving when no force acts—a property requiring an unbalanced force to change the motion, or even to stop it.

But matter alone, uncharged, possesses this inertia; the effect of any charge on it is merely to increase the ordinary material inertia or massiveness,—necessarily to *increase* it, whether the charge be positive or negative, showing that it is proportional to the square of the charge, or to the charge and the potential conjointly;—and the precise value of the increase has been calculated both by Professor J. J. Thomson and by Mr. Oliver Heaviside.

Hence there is discovered a new kind of inertia, an inertia-reaction to mechanical force, obedient to Newton's second law, but not a measure of quantity of matter as we have hitherto known it. It may perhaps have nothing to do with weight: that is to say, it need not be connected with the force of gravitation; and yet it simulates one, and that the most fundamental, of the properties of matter,—the property of inertia,—the property which is measured precisely by the ratio of any unbalanced force acting, to the acceleration which it is able to produce.

Are there then two kinds of inertia: one material, the other electrical? What do we know about the material kind? Very little. It has been accepted as a property which it was vain to attempt to explain,—a property whose presence is inextricably bound up with the existence of matter, and believed to be more essential to it than gravitation. What do we know about the electrical kind? Not much, but *more*. In a sense it is intelligible, we can realize how it depends on the field of force surrounding the charge, how it is a property not located in the charge or the charged body, but depends on a modification of the ether extending all through space external to the charged body, though concentrated chiefly in its immediate neighbourhood, and especially concentrated in the space between two charged bodies close together when these are opposite in sign.

That as a fact an electric current, in virtue of its magnetic properties, possesses something akin to, or which simulated, momentum, has been known to science ever since Lord Kelvin wrote that wonderful paper on "Transient Currents" in 1853; or even since Helmholtz wrote his memoir "die Erhaltung der Kraft" in 1847. But that this electro-kinetic momentum was due to a real inertia, and that the apparent inertia would not cease with the current, but would remain as a property of an electrostatic charge,—a constant property, whether the charge was in rest or in motion, just as it is a constant property of matter, —all this was not at that time, nor long afterwards, known; probably it was not even suspected.

To-day the question to be asked is, whether there is any other inertia at all? There is certainly the electrical kind,—its mechanism is fairly and to some extent intelligible,—is there any of the material kind? The possibility of the question represents a curious inversion of the ancient order of ideas, but the question is most seriously asked; though its answer is uncertain. To Dr. Johnstone Stoney it has appeared likely that a charge can exist without the necessary presence of a material atom as a nucleus or resting place. Matter can exist without a charge, why not a charge without matter? A cat without a smile, as Lewis Carroll says, why not a smile without a cat? At any rate he has given such an isolated charge of electricity a name—"electron": that means a unit of electric charge, positive or negative, disconnected from any material body, and of which no fractions are possible, —the hypothetical ultimate "atom," so to speak, of electricity.

But we must not be too sure that such detached charges can exist without matter. As electrical units they are known and measured in electrolysis,—*i.e.*, in liquid conduction of electricity; and there they are certainly associated, and inseparably associated while in the liquid, with material atoms. The whole conveyance of electricity through a liquid consists in the convection of the atomic charge by a travelling atom, or, it may be, the convection of an atom by its travelling charge. Atoms thus charged and travelling are called "ions": some of them are positive and some negative, and they travel of course in opposite directions along a potential gradient.

All this is familiar, and the magnitude of the ionic charge has long been known. Known it is also that hydrogen atoms have one such charge, oxygen atoms two, gold atoms three, and so on. As many as six such unit charges, all of one sign, may, it is supposed, be possessed by some kinds of atoms;—or as few as none,—but never a fraction. An ionic charge is the irreducible minimum, as it would appear, and was styled by Maxwell "One molecule of electricity." Every actual or possible charge is an exact multiple of this unit. Small of course it is, but not small compared with the mass of an atom; its ratio to the atomic mass is accurately known; this ratio, the ratio of the quantity of matter to the quantity of electricity, is called 'the electro-chemical equivalent of the substance,' and was measured first by Faraday,—afterward with greatest accuracy by Lord Rayleigh.

Nowadays, through Dr. Johnstone Stoney, Professor Loschmidt, and Lord Kelvin, we know approximately the absolute mass of an atom; hence we know, with equal approximation, the value of the atomic or ionic charge, in terms of what we call an electrostatic unit; and it comes out about 10^{-10} of such a unit per monad atom. All this is the a, b, c, of electro-chemistry. Why then introduce it here? For the sake of completeness, and as a reminder to those whose physics may be a trifle rusty.

Now comes the first question:—is the atomic charge fixed to the individual atom, or can it be passed on to other atoms? Answer:—in the liquid state the charge is certainly fixed to the atom; there is no trace of physical or metallic conductivity in a chemically conducting liquid; true liquid conduction is wholly convective; the atom travels with its charge, and at the same rate; the two are inseparable in the body of the liquid always,—whether the current pass from one liquid to another of different composition, or not,—provided always that no part of the liquid becomes solid, forming an insoluble precipitate. This answer is rendered possible by the careful quantitative experiments of Faraday. It was and has been several times doubted, —for good reasons, but for reasons whose other meaning is now understood.

But the case s quite otherwise when the current leaves the solution, as it must when a solid electrode is reached. Then the charge and the atom separate; the electricity goes one way,—into the electrode and on through a wire; its quondam carrier or atom goes another way, into the liquid perhaps, or else stops behind on the electrode, and ultimately, it may be, escapes as gas, or otherwise undergoes customary chemical accidents. It is not difficult to picture two or more such atoms, thus planted side by side or superposed in close contact, relieved from the similar charges which kept them asunder, combining, possibly by ordinary cohesion, either with each other or else with the electrodes to which they cling.

It is more interesting to follow the freed charge in its progress through the metal. How does it travel now? There is no convection or conveyance *per ion* here, it must either make its way between the atoms, or it must be handed on from one to another. The method of transmission is not that of a seed carried by a bird, but that of a fire-bucket passed from hand to hand. And yet not quite or not necessarily like that,—for we have no certain means of individualizing the charge, as we have the bucket: all we know is that the same amount is passed on; but an atom may conceivably receive one charge and pass on another of equal quantity,—provided there is any meaning in this attempt at individualization of electricity.

There is plainly a temptation to attempt such individualization, when it is realized how like an "atom," in some respects, this unit of charge is. It can be had in multiples but not in fractions, there is a sort of "law of combining proportion;"—most of the arguments of Dalton for the atomic theory of matter now apply to electricity. Is electricity then atomic too? Does it also consist of indivisible portions each of definite quantity and all exactly alike? It is not wise to assert such things too hastily, but that is the appearance which facts present. Dr. Johnstone Stoney, among others, has definitely faced some of the consequences of this view of electricity and has supposed that these apparently indivisible units can separately exist as "electrons"; and Dr. J. Larmor has attempted a comprehensive mathematical theory of the whole material universe, on the basis of these electrons as strain centres in an otherwise homogeneous ether.

Anyway we must admit that such electrons, whether they have a separate existence or not,—that is, whether they can exist apart from matter or whether they only represent a charge existing on a material particle of some kind,—are themselves a great deal more like matter than we might have expected. Considered by themselves they possess inertia, as we have seen, and are capable of acceleration under mechanical force, in accordance with Newton's Laws of Motion.

At the same time an electron is certainly not an atom, for it is capable of being separated from an atom and conveyed one way while the rest of the atom goes the other way. It appears in fact, so far, as only another name for an ionic charge, plus the postulate of individuality and identity. For when masked or neutralized, the electron is not destroyed, but is merely brought face to face with an equal electron of opposite sign; the distant effects of each are then neutralized until they are once more separated.

Electrolytic conduction certainly consists in the travelling together of an atom and its charge; but metallic conduction may be either the travelling of an identical electron from atom to atom, or it may be the reception of one electron and the passing on of another; and this latter view is on the whole the more probable. If each atom receives a charge from an adjacent one, and passes an equal charge on to the one adjacent on the other side, this process may readily be accompanied by a slight molecular motion exhibiting itself as a rise of temperature. And if, having the process of interchange of constituents in view, we contemplate what must happen at a junction of two different metals across which a current is flowing, we shall witness a curious interchange or transfusion of substance, but without change of identity—without real transmutation, and without combination or alloy. This is not the place to dwell on that aspect further: suffice it to say that the modern doctrine of the nature of the atom must have an influence on a vast number of physical phenomena, whether they occur in wires or whether they occur in nerves.

But a consideration of metallic conduction would never have given us the conception of an electron. Nor would a study of electrolytic conduction. The latter gives us the notion of an ionic charge, an indivisible electrical unit; but we find it there always associated with an atom of matter. How then have we gained the idea that it may be possibly associated with masses of matter less than the atom, or possibly with no mass of matter at all; how have we got the notion of an electron as a separate entity? The idea has come to different men in different ways, and we are not now concerned with any historic order; I will take the facts in any order convenient for exposition.

A few years ago Professor Zeeman, of Amsterdam, discovered that the lines in the spectrum of incandescent sodium vapour were slightly broadened by the influence of a strong magnetic field applied to the flame, when examined in a spectroscope of adequate power. It was an effect that Faraday had looked for, and failed to find; because it is very minute, and the optical resources of his day were quite inadequate to show it. Nowadays the splendid diffraction-gratings of Professor Rowland of Baltimore make the demonstration (though not the discovery) comparatively easy: and the lines of the spectrum of all sorts of metals are found to be doubled or tripled or quadrupled, or even hextupled, according to the nature of the metal and the individual character of each line. Well, what of that? The bare fact is not illuminating. No; but no fact is really bare, except in the subjective sense that we have not yet clothed it in theory. In this case the theory was ready, it was provided by Larmor and by Professor H. A. Lorentz of Leyden, another brilliant mathematical physicist. By these men and by Fitzgerald of Dublin the bearing of the new fact was quickly grasped, as well as by Zeeman also, as shown in his correspondence with Lorentz. At once the measured amount of the broadening, the distance apart of the components of the doubling, became the means of ascertaining the electro-chemical equivalent of the radiating matter.

Electro-chemical equivalent is a term in electrolysis; what has that to do with radiation? It signifies the mass of matter associated with a unit charge of electricity. Precisely,—but considered from the point of view of Clerk Maxwell's theory of light it applies to a radiating body also. In order to emit waves into the ether an electric oscillation is necessary, a mechanical oscillation will not do. A radiating atom *must* contain some sort of vibrating electric charge. It may be that the whole atom, with its ionic charge, is vibrating; and it may be that an electric charge is surging to and fro on an atom, as it surges on a Hertz-conductor; or it may be that some fraction of the atom possesses the charge, and that this fraction only is set vibrating, while the remainder is inert.

This electric view of radiation, which ever since the time of Maxwell and Hertz has been in everybody's mind, is proved to be the true one by Zeeman's phenomena—*i.e.*, by the fact that a magnet influences the vibration, either accelerating or retarding or otherwise complicating it; for a magnet only so acts on an electric current—that is on an electric charge (or charged body) in motion.

Moreover it furnishes us with a means of determining how much matter, or rather how much inertia, is associated with the vibrating electric charge; for on this depends the effective result of the magnetic influence. How the measurements are made would lead us too far into detail: suffice it to say that the change in the frequency of vibration, caused by the application of a magnetic field of measured intensity, can be quite accurately determined from the changed appearance of a spectral line when examined micrometically; and that when this measurement is made, in the light of Lorentz's theory, the value of $^{m}/_{e}$, the ratio of the mass carried to the charge which carries it—to invert the usual order of expression,—can be reckoned.

It could also be reckoned in electrolysis; and it would be natural to expect that the two determinations should agree. But they do not agree. For some reason or other the electro-chemical equivalent concerned in electrolysis is something like a thousand times larger than the electro-chemical equivalent concerned in radiation. What does this mean?

It must mean either that the electric charge, whose vibrations start the series of ether waves that we call "light," is a thousand times bigger than the electrical unit or ionic charge associated with an atom in electrolysis; or it must mean that the mass of matter associated with the vibrating electric charge is but a small fraction of the total mass of an atom. Or, of course, though that may be thought unlikely, a certain proportion of both these divergences from the expected state of things might have to be admitted.

There is nothing for it but to examine and decide between these hypotheses by quantitative experiment. But it is not an easy matter to think of an experiment that will discriminate. It is not difficult to measure the ratio $^m/_e$, but to measure separately either the quantity m or the quantity e is a puzzle. Can it be possible that the atom itself is stationary, and that the electric charge is oscillating to and fro over its surface by simple conduction, as if it were a Hertz-vibrator? The Zeeman effect points to something more than that, it points to a real orbital motion, a motion like that of a planet or a satellite, a motion of something with inertia, subject to the mechanical laws of motion, and perturbed in a recognized manner by mechanical force—by the force exerted on its electrical charge by a magnetic field.

Can it be possible that the ionic charge, in the concentrated and individual shape of an electron, is sufficiently individual and detached to be performing a vibratory excursion on its own account? Are we to think of the atom as having a vibrating charged tongue,—not exactly like the clapper of a bell, because it does not strike anything, but like a bead on the end of the spring of a Wheatstone's Kaleidophone,—a vibrating portion performing a definite orbit, which is perturbed by a magnetic field?

There is this much further information to be obtained from the Zeeman effect; the sign of the effect is such as to indicate that the moving electric charge is negative—that radiation is due to the vibration of negative electricity; and that the corresponding quantity of positive electricity, which must be present somewhere in the molecule, is comparatively or practically stationary.

It is no new thing for negative electricity thus to show itself more mobile than positive. Such special mobility is very familiar in the high vacuum tubes introduced and studied with such admirable results by Sir William Crookes, by Professor Hittorf, and others. In a highly exhausted tube negatively charged particles are flung off the cathode at high speed, travelling in straight lines, travelling that is to say without striking each other for a considerable distance, but ready to bombard anything introduced into their path, and either to propel it forward like the vanes of a mill, or to heat it to incandescence, or both.

Such charged and flying particles, for so Sir

William Crookes conceived them to be, have attracted, under the name cathode rays, considerable attention. They are decidedly energetic and are extraordinarily penetrative. Hertz found that they could go through a metallic partition. A sheet of solid aluminium interposed as a shutter between two halves of the vacuum tube, did not act as a shutter, but as a semi-transparent window: a decided proportion of these cathode rays went right through it,—or, if they did not go through, they appeared to. At any rate a considerable number were shot off the hinder face of the shutter by reason of the impact of cathode rays on its front face, and these fresh cathode rays continued and preserved the properties of the old. By means of such a metallic partition Lenard became able to study these rays after they had gone through into other media: into gases at different pressure for instance; and ultimately out into ordinary atmospheric air. Across the crowded obstruction of ordinary high pressure air it was not likely that these emerging rays, the Lenard rays as they are called, could travel far; they go a few inches but they soon have to stop. Nevertheless they too are penetrative: they can go through metal sheets, and can affect photographic plates, or the eye, on the other side, and give many surprising results of a kind of shadow photography. And then the next step:—the discovery by Röntgen that the impact of the cathode rays, or the Lenard rays either for that matter, especially if they struck a dense substance that they could not well penetrate, excited shivers of another kind altogether,—a kind of vibration or shock or quiver, much higher in pitch than a source of light, a vibration which starts those hyper-rapid ethereal waves known as Röntgen or X radiation.

That is what these cathode rays can do, but what are they in themselves? They are certainly electrically charged, for if caught in a hollow vessel connected with an electroscope, its leaves will diverge with negative electricity. Are they then a flight of negatively charged atoms? That is what most of us thought they were; but Sir William Crookes, by an effort of predictive genius, described them as consisting of matter in a "fourth state": neither solid nor liquid nor gaseous, but,—in some other state.

Why are they not atoms? We can answer clearly now,—for several reasons, but chiefly for these two:—they move too far, and they move too fast.

First they move too far. Atoms are truly excessively minute, but from our point of view they must be considered as comparatively big things, the thousand millionth of an inch in diameter; and they cannot travel far without mutual collisions. They are constantly colliding, even in a very good vacuum. In ordinary air every atom strikes another about six thousand million times a second, and it cannot travel even a microscopic distance without collision; its free path is microscopic, or on the average ultra-microscopic. In a vacuum of course it is much freer, but still it is difficult to get a vacuum good enough for atoms on the average to travel a whole inch unmolested; but, in such a vacuum as that, the cathode rays would experience no difficulty in travelling without a collision a foot, or even a yard, if the tube were long enough. How then can they be material atoms? Well, it may be said, perhaps they have a long free path because their motion is organized,—they are all moving one way, they are not a mob but an army, and random collisions are not to be expected. A good answer, and one which may very likely have been responsible for our persistent idea that the cathode rays must be charged atoms. Still, however, there were some who urged,—no, they are not atoms, they are either something etherial and not material at all, a genuinely new kind of radiation,—or else they are electrons, isolated electric charges, flying off the cathode and flying along without any body to them, disembodied electricity, the pure spirit of electric charge.

The bare possibility made them worthy of careful study. How fast are they travelling; what is their velocity?

The experimental answer to this question is not hard. Whatever they are, they represent to some extent an electric current; whether they contain matter or not, they contain electricity, and they are in rapid movement; hence a magnet will deflect them. Everyone knew that a magnet would deflect them; it was only required to measure the amount of the curvature of path caused by a given magnetic field in order to be able to calculate,—what? the velocity? Well, not exactly the velocity, but the product of the velocity and the electric charge of each. Assume that the electric charge was known; assume that it was the ionic charge observed in electrolysis; assume that it was a kind of visible electrolytic procession of extraordinary rapidity that was going on in the vacuum tube before our eyes,—and the calculation of their velocity was only a matter of arithmetic.

The assumption and the measurement of curvature by a magnet were both made; and the result came out gigantic,—the particles were moving with a speed unknown in matter before; a speed twenty thousand times quicker than bullets; a speed becoming almost comparable—still far short of that but almost comparable—with the speed of light: about one twentieth of it or thereabouts. How could matter move at such a speed as that? Doubtless they were under the action of violent forces in the immediate neighbourhood of the electrodes, but their motion did not appear to depend on the persistence of a violent accelerating force; they appeared to move readily after the force had ceased, by reason of their own momentum. After all, they might still be material atoms, flung off by electrical forces at this gigantic speed. The potential gradient divided by the acceleration would furnish a means of determining the value of their electro-chemical equivalent,—the ratio of mass to charge. Is there any way of determining this?

Perhaps it may be possible to measure their energy, or their momentum, and thus in some way to gain an estimate of the mass of all the moving particles. It is not difficult to make a rough estimate of their aggregate energy, by letting them impinge, say, on the suitably coated bulb of a thermometer,—a thermometer acting as a calorimeter, after the fashion of Favre and Silbermann on a minute scale,—or, say, on the junction of a thermo-electric pile. The heat generated per minute by their impact can be determined; but that only gives their aggregate energy and gives no information about the energy of each, until they can be counted.

Similarly it is not very difficult to make a measurement of their aggregate electric charge. Catch them in a vessel of known electrostatic capacity, and measure the rise of potential caused by them in a minute. The measurement is delicate and requires skill, but it can be done, and the idea of doing it is natural enough. But again what is the result? Only the aggregate charge; only a number which, in combination with the aggregate energy or aggregate momentum, and the estimate of velocity on a certain hypothesis, will give the electro-chemical equivalent; that is to say, will give the ratio of the inertia to the charge of each particle.

But that is no small thing to determine; it is of great interest. Especially in the light of the phenomenon of Zeeman it is most interesting to see whether the resulting value of this ratio will come out in agreement with that obtained in liquid electrolysis, or whether it will agree with that much smaller value concerned in luminous radiation.

The measurements have been made, not only by Professor Schuster, but also in the Cavendish Laboratory, Cambridge, by Professor J. J. Thomson; and the result is of surpassing interest. The electro-chemical equivalent, or ratio of m to e, comes out, not in accordance with the electrolytic value, but in almost exact accordance with the value obtained by Zeeman.

The vibrating beads to which incandescent radiation is due, on the one hand, and the rushing particles which constitute the cathode rays in a vacuum tube, on the other, appear to be identical. The relationship is so close it can hardly be accidental. It can hardly be that it is only the *ratio* that is the same. In all probability both their masses and their charges are equal, each to each.

If it is an electron whose motions generate ordinary light, then it is a flight of isolated electrons that constitutes the cathode rays.

On the other hand, if it is a vibrating fragment of the atom whose motions generate luminous waves, then it is a flying isolated fragment of an atom which is flung off a cathode, travels in a straight line through many obstacles, at high speed and with a long free path, and ultimately, when stopped suddenly enough, generates the rays of Röntgen.

Either of these hypotheses is sensational. It were hard to say which is the more sensational. One involves a disembodied electric ghost; the other demands the splitting up of atoms into thousands of fragments, each with an electric charge of its own.

But there is one avenue still open to the commonplace. Perhaps after all the cathode rays are entire atoms,—perhaps the atom is vibrating as a whole, inside its molecule, in the Zeeman flame;—perhaps it is only the electric charge on each that is a thousand times too big, not the inertia that is a thousand times too small. This assumption would reconcile all the measurements, so far; if the difficulties of the high speed, and the long free path, the extraordinary high charge, and many other difficulties—more instinctively felt than possible to express briefly—could be met and overcome by special pleading.

There are thus three hypotheses to be decided between, not two; and the third or last mentioned is in deadly hostility to the other two,—the other two between which there is no known means of discriminating up to the present date (1900).[1]

Nevertheless a decision can be come to in respect to the third and commonplace hypothesis. But some further measurement is necessary. The particles must be *counted*. It is not enough to determine their aggregate energy, or their aggregate charge; we must determine either their individual energy or their individual charge—and the easiest way of doing this is to count them.

Easy to say; but how to do it?

So far I have mentioned some measurements made by Professor J. J. Thomson and his co-workers, as measurements natural to be made in a laboratory; not easy measurements,—in fact very ingenious measurements, requiring novel designs and skilled construction, and accurate thought; but in these things the Cavendish Laboratory, its professors and assistants, have never been lacking.

To devise a means of counting the particles associated with a given aggregate charge, and to execute the measurements successfully, seems to me a decidedly high flight of genius. We in England have not been lacking in veneration for Clerk Maxwell nor

[1] For the more recent discrimination, my 1906 book on "Electrons" can be referred to.

in admiration for Lord Rayleigh, but I think we may say that we feel that the mantle of those extraordinarily brilliant predecessors has descended worthily on their successor; and that his researches, —those conducted by him personally, with Mr. Everett's experimental assistance, as well as those supervised by him in the hands of exceptionally able disciples and students,—have brought lustre not only upon the Cavendish Laboratory, but upon the general pursuit of physical science in these islands.

I must explain how the counting is done; and for that purpose must refer to a totally different and apparently quite disconnected chapter of physical science, viz., the formation of clouds and mist. It was shown some twenty years ago, by Mr. John Aitken of Edinburgh, that every drop of water in a cloud or mist was condensed around a nucleus, usually a dust particle. I suppose I may take it as known that a mist consists of water globules—raindrops in fact, only of smaller size—and that these drops represent condensed water vapour. Well, Mr. Aitken showed that vapour could only condense in presence of a nucleus, that is to say, usually upon a solid surface,—either the wall of a vessel or of some solid or liquid body. Once started into existence, a drop could readily increase in size by fresh condensation; but there was a difficulty in starting it into existence. In other words an infinitesimal rain-drop could not exist. Such a raindrop, we know by Lord Kelvin's theory of vapour tension, would instantly evaporate, no matter how moist the air around it was. How then can *any* rain-drop exist—since, it would be thought, it must be infinitesimal to start with, and must gradually grow? The same kind of difficulty has been felt in Darwinian evolution concerning any finished organ whose early stages must have been useless, and therefore unconducive to the survival of its possessor. There is no such difficulty about an eye, because the merest glimmerings of light must have been useful; but the difficulty is, or was, felt about the electric organ of some fishes, which could hardly be usefully destructive until well developed. The initiation of the ordinary rain-drop is now explained: it never *was* infinitesimal, it started condensing upon some finite foreign surface or nucleus; for, as Mr. Aitken shows, if the damp air is carefully filtered through cotton wool so as to exclude all foreign particles, then no mist can form, the vapour can be saturated and super-saturated; the walls of the vessel may run down with condensed moisture, but the inside dust-free space remains perfectly clear and transparent.

The nuclei in this, the ordinary, case consisted of dust particles. But now what is the result of charging the dust with electricity what will be the effect of an electric charge upon an infinitesimal rain-drop, if such a thing for a moment existed? The result is to check its evaporation. The rapid evaporation of a small drop is due to the curvature of its surface and its surface tension; an electric charge tends virtually to diminish this, it tends to cause a slight surface *pressure* or distending force. A charged soap-bubble, for instance, is a trifle bigger than an uncharged one, the two effects of surface tension and electric tension are opposite. Not exactly opposite, for one is tangential and the other is radial; but whereas the tangential tension, on a convex surface like that of a liquid drop, has a resultant inwards—the electric ($2\pi\sigma^2$) acts wholly outwards. The surface or cohesive tension of a liquid is an intense force, and even its radial component is moderately big, especially for small drops. The tension caused by a given electric charge is usually a small force, but it increases very rapidly as the body possessing the charge gets smaller. The effect of the cohesive tension varies inversely as the simple diameter of the drop. The effect of the electric tension varies inversely as the fourth power of the diameter of the drop. Hence as the drop shrinks the two opposing tendencies necessarily become equal when it reaches a certain minute size; and then the effect of its curvature is obliterated—it behaves as if flat. Such a drop can as easily exist as any liquid with a flat surface can; and any drop smaller than that would rapidly or even suddenly grow to this equilibrium size.

The moral of all this is that no solid nucleus is after all *essential*; an electric charge will do as well. No matter how small such a charge may be, it will do something; even the charge on a single atom will suffice. Hence it follows that charged atoms or ions will serve as nuclei for the condensation of vapour and the formation of mist.

It is not the atom itself that acts as a nucleus, but its charge; the atom, for such a purpose, can be regarded as almost infinitesimal; any perceptible, or barely perceptible, dust particle must consist of billions of atoms. A single grain of lycopodium dust contains just about a trillion (that is a million million million). A charged atom or ion, therefore, acts as a nucleus, and if the cathode or Lenard rays are directed on an atmosphere containing water-vapour nearly saturated, some of it at once condenses, and you get a fog.

Myriads of mist-globules, too small to be individually seen, are the result of supplying electric charges to some of the atoms in clear, moist, perfectly dust-free air.

If dust is present too, so that there is already some ordinary condensation, then the addition of the charged ions adds to it greatly and makes the mist much thicker. Instead of a white or light grey colour it takes on a deep brown or slaty appearance, —it puts on the aspect of a thunder cloud. The experiment is easily shown by taking sparks in or near a steam jet, and looking either at the jet or at its shadow. Undoubtedly this electric condensation, superposed upon ordinary dust-nucleus condensation, is the cause of the dense and angry looking appearance of a thunder cloud.

Thus, then, we see that if we introduce cathode rays, of known aggregate energy or known aggregate electric charge, into a vessel containing dust-free damp air, a precipitation of myriads of mist-globules instantly occurs. How many mist-globules? Just as many as there are nuclei; one mist-globule for every corpuscle, and no more. Hence, count the mist-globules and you count the corpuscles. This was the method devised by Mr. C. T. R. Wilson.

Many years ago, in a lecture on "Dust" to the

British Association at Montreal, 1884 ("Nature," vol. xxxi. p. 265), I suggested that this formation of mist might furnish Lord Kelvin with another mode of measuring the divisibility of matter, another estimate of the size of the atom; the idea being to weigh the total amount of solid evaporated from a bit of platinum wire, and to count the mist-globules thereby permitted to exist.

But how are we to count the mist-globules? It is hopeless to try to see them individually and count them that way. It must be done indirectly. J. J. Thomson proceeded first to weigh the cloud, and then to estimate the size of its constituent spherules. Given the individual size of the liquid spheres, and given the aggregate weight of the water contained in them, the calculation of their number is only a question of simple arithmetic. Weigh the cloud! It is a delicate operation, but it is a straightforward laboratory operation: it can be done indirectly by inference from the expansion which precipitated it, or it can be directly performed with a balance.

Estimate the size of each globule,—they are all practically the same size,—how is that to be done? Here we invoke the aid of some hydrodynamical mathematical researches of Sir George Stokes, half a century or so ago, concerning the motion of spheres through a resisting fluid. Consider a mist-drop or rain-drop falling through air; it is obeying the first law of motion; it is moving with steady speed under the action of no force,—just like a railway train or a ship after it has got well started. No force, that is no unbalanced force, is acting upon it. The earth is pulling it down, and air-friction is retarding its fall; the weight and the resistance balance; and the conditions of balance determine its speed,—determine the rate at which it drops. But plainly its rate of fall depends on its size. If it gets bigger it weighs a good deal more, and it is resisted only a little more; hence, in order again to attain equilibrium, it must move faster: because the resistance, in fluid motion, increases with the speed. On the other hand, if it gets smaller it may, and indeed must—if left to itself—go slower, so that still the diminished weight and the diminished resistance may balance each other. All this is obvious. What Stokes calculated, among many other things, was the exact dependence of speed on size, for a water-sphere falling through air. Given its size he could reckon its speed. Given its speed he could reckon its size. All that Wilson had to do then, after he had his cloud formed in dust-free air and weighed it, was to watch its rate of sinking. Such a mist, indeed any mist, formed in a bell-jar, is soon observed to be sinking or settling down; a clear space appears at the top, and if it is left quiet for half an hour or so, the whole upper region or even the whole vessel may become clear, by reason of the gravitative subsidence of the drops. It is just like the case of powder, or fine sand, shaken up in water and left to settle. If the particles are of different sizes, the coarser ones will settle first; and we have the sorting process known as levigation. If they are all the same size, a clear space will appear at the top, and the rate of settling can be observed by watching the movement of the boundary of this clear space,—

i.e. by timing the rate of subsidence of the top of the cloud.

By this plan the total weight of the cloud, and the size and therefore the weight of each globule in the cloud, are separately determined; and so the number of globules in the cloud is determined. Each globule represents one corpuscle. Thus, then, the corpuscles are also counted. Their aggregate mass and aggregate charge were already determined; and so their individual mass and their individual charge become known.

And now what is the net result and outcome of all these measurements? The result is that the charge belonging to each corpuscle is the usual ionic charge, familiar in electrolysis; but the mass of each is not the mass of an atom at all, it is a much smaller mass, —about the seven-hundredth part of an atom of hydrogen.[1] The corpuscles are not atoms, they seem more like fragments of atoms; or else isolated electric charges and not (in any other sense) 'material' at all. They appear to have just the mass and charge of those things whose vibrations are observed in the radiation phenomenon of Zeeman; the things whose orbital motions and vibrations emit light. Moreover the same corpuscles are obtained, whatever may be the composition of the residual gas in the vacuum tube.

All this applies to the case of the *negatively* charged bodies which constitute the cathode rays; it is not

[1] Recent measurements seem likely to change the above "seven" to seventeen.

so easy to isolate and examine a body charged with the unit of positive ionic charge; in the positive case it is found that though the charge is the same, the mass is very much greater, being in fact approximately equal to the whole atom.

We will return to the result of the vacuum tube investigations. Clerk Maxwell gave it as his opinion that a fruitful avenue to discovery lay in a study of the phenomena accompanying electric discharge in gases; and since that *dictum* a splendid series of investigations, by Crookes and Schuster and J. J. Thomson in this country, not to mention others,[1] have culminated in the present surprising discovery. The discovery is that the atom is not simple but compound; that it is composed of a great number of similar parts; that these parts can be isolated and dealt with, if not individually, yet separately from the rest of the atom; that each fragment or corpuscle is electrically charged, charged with the ionic charge, charged with Maxwell's indivisible unit or atom of electricity, the very same charge that we have so long been familiar with in electrolysis;—the very same charge, but by no means the same quantity of matter. The matter associated with it and carrying it, or

(1) But there are a great number of others that *ought* to be mentioned: Righi of Bologna, and Elster and Geitel of Wolfenbüttel (helped in their researches by American funds); and Becquerel and Curie of Paris, and Michelson of Chicago, and many others;—and a quantity of work on an entirely cognate and confirmatory subject,—the discharge of negative electricity from surfaces by means of ultra-violet light,—a subject which space alone forbids my dealing with as its importance deserves. This article does not aim at being encyclopædic.

carried by it, is not an atom but a corpuscle, a fragment, one of the foundation stones of which the atoms are built up; the same identical fragment experimented upon by Zeeman, whose vibrations cause the emission of light.

Foundation stones of which the atoms are built up; does that mean all atoms, atoms of every kind? Are they the *same* corpuscles that go to the making of every kind of atom? are all the chemical elements built of the same identical corpuscles; only the grouping, the arrangement, and the number of them being different? Why not? So points the evidence. The very same cathode rays are found, whatever be the nature of the gaseous residue left in the vacuum tube. The fragments or corpuscles do not differ.

Here is Prout's hypothesis come to life again with a vengeance! All atomic weights multiples of hydrogen? Not necessarily so,—but multiples of something; multiples of the weight of a corpuscle.

Given the corpuscles, some charged positively and some negatively, all otherwise exactly alike, and all with precisely the same numerical amount of charge,—and you can build up the elements. Take seven hundred of them, let us say, three hundred and fifty from each set, arrange them in some unknown grouping—and, on one hypothesis, they will form an atom of hydrogen. Take sixteen times, or rather fifteen and eight-tenths times as many, and you may arrange an atom of oxygen; possibly they will themselves naturally fall into the correct grouping if you provide the right number of them. Probably the groupings of numbers slightly different from these are not so stable,—not so likely to be permanent.

We are now too much in the region of hypothesis, but when in sight of a unification of matter such as this, a unification that has always dangled itself before the eyes of philosophers, a trifle of hypothesis beyond the bounds of experiment and calculation may for a moment be pardoned.

But we will leave this region now, and return to our atom of hydrogen with its seven hundred [or possibly 1700] similar corpuscles. Remove one of them, remove one of the negative variety; what have we left? We have left a positively charged monad atom of hydrogen; a hydrogen ion; an atom charged with the ionic charge, and amenable to electrolysis.

What shall we do with the removed corpuscle? It can be given up to another atom, which will then become negatively charged, unless it promptly hands on another or the same corpuscle to a neighbouring atom, which it may or may not be able to do. If it is able to effect that transfer, then the body to which it belongs is a metallic conductor.

For some reason, unknown at present, it is the negative corpuscles which are the mobile ingredient, the mounted infantry as it were of the corps; a positively charged atom appears to be charged, not positively by accretion of positive corpuscles, but by difference, by loss of negative corpuscles. It has then at least one unbalanced positive corpuscle to the good, and by means of its electrical attractions the whole atom can be sluggishly dragged about; but it does not show the mobility of the equally charged but far less encumbered, free, negative corpuscle. Not likely to, when it has several hundred times the mass, and only experiences the same force. Isolated *positive* corpuscles are not yet known; positive charges appear always associated with atoms of matter, but most of the activity and the excessive rapidity of electrical actions appears due to the high charge and small inertia of the negative corpuscle.

But why do these corpuscles, at least when free, possess an electric charge, and always the same electric charge? Can they be *dis*charged? Have they anything to leave behind if they were discharged? How much of them is electric charge and how much material substance? Is there any material substance at all? Are they anything at all but electric charges?

An electric charge, we saw near the beginning of this article, possesses inertia; a corpuscle too possesses inertia; is its inertia partly electric and partly material; part due to its substance and part due to its charge? Electrical inertia we understand; in the light of electro-magnetic law it is inevitable; but what is material inertia? Is there such a thing? Are the corpuscles after all nothing but electrons? Have they any material body or substratum at all? These are questions which have not yet (1900) received an answer. The inertia of an electron, that is of (say a spherical) electric charge, depends upon its size,—its geometrical size,—the diameter of the sphere, so to speak. The smaller its size, the more concentrated will be the electric field near it, and the greater will be its inertia for a given quantity of charge. Make it small enough, and it may have any inertia you like. Group such electrons into an atom, and the atom will have the inertia appropriate to their number. Now the inertia of an atom is known, and the inertia of a corpuscle is known; but the size of a corpuscle is not known. It is certainly small; but is it small enough to account for the whole of its inertia, or must a residue of material substratum be permitted?

Is all matter resolvable into an aggregate of electric charges of opposite sign? And does the explanation of the material universe consist in finding an answer to the question, what is an electric charge? There is more than one physicist who would answer, "probably yes."

Near the beginning of this paper I set down some questions which I said were capable, or were becoming capable, of being answered; and now near the end I have set down some more questions which are in process of being answered. There are a few men now living who are capable of answering them.

In conclusion, it is not to be supposed that I have here presented an epitome of all the evidence that can be adduced in favour of a certain view of the constitution of matter. The ideas have not come upon physicists suddenly; the ground has been prepared by many indirect hints and suggestions,—the discharge of negative electricity by light being among them. And there is other evidence not mentioned here. The facts that originally suggested the idea of an electron, for instance, have hardly been referred to; the evidence derived from spectroscopy, and a study of stellar spectra, has not been so much as hinted at; only the most salient and strongest features of the edifice have been represented. It must suffice to say that there is other evidence,—some appealing more to chemists, some to astronomers, some to mathematicians,—evidence in favour of, and evidence against, such theses as the composite structure of the atom, the building up of the elements, the unification of matter, and the possible unification of matter and electricity.

For a continuation of this subject the reader is referred to my treatise on "Electrons."

Since the appearance of this article it has been proved, by Rutherford and others, not only that an atom can fling away a corpuscle, but that it can break up and detach bits of itself,—flinging them forcibly away.

In the normal or undisturbed atom—in which condition, for years together, 999 out of every thousand atoms, even of radium, would be found—the positive electricity must be equal in quantity to the negative.

When several corpuscles have escaped, the residual mass of the atom will be strongly positively charged, will become self-repellent, and may split into two portions, like a loaf; and when the portions are of very unequal size, 100 to 1, comparable to a cannon and a shot, the small portion is propelled away with great velocity, and constitutes an α ray; both it and the residue are found to be positively charged.

The breaking up of an atom of matter is by some thought to be of the nature of an explosion, the pieces being expelled with deflagrating violence; by others it is thought to be the tangential flying off of a part whenever it attains a certain critical velocity.

In any case there appears to be an enormous store of energy, both potential and kinetic, inside an atom; and when for any reason either of these energies rises above a certain value, disruption results. Explosion might be brought about by an accidental configuration in which the repulsive forces came prominently into play. Instability of motion would result if any charged particle attained to the speed of light; for in that case there are good theoretical and some experimental reasons for asserting that its momentum would disproportionately increase, without any counterbalancing increase in the retaining force. The mass of matter is *usually* assumed constant; and so it is at all ordinary speeds; but, according to the electrical theory of matter, the mass is not quite constant at high velocities, but increases slightly with the speed, until at the speed of light itself it becomes suddenly infinite.

From every point of view the instability of an atom must be regarded as a natural consequence of the electrical theory of matter, and of the fact that an accelerated electric charge radiates its energy away. Consequently Professor Larmor some years ago expected radio-activity, and saw no reason why it should not occur in every form of matter; and recently the researches of the Hon. R. J. Strutt seem to make it probable that nearly all ordinary materials actually have some extremely slight radio-active power. It is a power which must be regarded, not as the property of any fixed and permanent substance, but as the concomitant and advertisement of catastrophic change from one form of matter into another.

The phenomenon bears a sort of crude resemblance to an astronomical case: namely, the contraction and gradual collapsing of a nebula, with occasional shrinking off of peripheral material, as an unstable stage is periodically reached, in accordance with the rough approximation known as Bode's law; together with a strong radio-activity of the central mass, and the conversion of constitutional potential energy into heat.

The actual appearance of Helium, as a disintegration product from Radium emanation—first suspected by Rutherford, on the basis of physical measurement of the *a* rays or positively charged projectiles—has been confirmed spectroscopically by Ramsay and Soddy; and Ramsay in pursuing this atomic degradation and transmutation branch of the subject into remarkable experimental developments. See, for instance, *Nature*, July 18, 1907.

LECTURE V

THE INTERSTELLAR ETHER [1]

THERE is, I believe, a general tendency to underrate the certainty of some of the convictions to which natural philosophers have gradually, in the course of their study of nature, been impelled; more especially when those convictions have reference to something intangible and occult. The existence of a continuous space-filling medium, for instance, is probably regarded by most educated people as a more or less fanciful hypothesis, a figment of the scientific imagination, a mode of collating and welding together a certain number of observed facts, but not as in any physical sense a reality, as water and air are realities.

I am speaking purely physically. There may be another point of view from which all material reality can be denied, but with these questions physics proper has nothing to do; it accepts the evidence of the senses, regarding them as the tools or instruments wherewith man may hope to understand one definite aspect of the universe; and it leaves to philosophers,

[1] Contributed as an article to the *Fortnightly Review* for June 1893, and now reprinted by permission.

equipped from a different armoury, the other aspects which the material universe may—nay, must—possess.

By a physical "explanation" is meant a clear statement of a fact or law in terms of something with which daily life has made us familiar. We are all chiefly familiar, from our youth up, with two apparently simple things, motion and force. We have a direct sense for both these things. We do not understand them in any deep way, probably we do not understand them at all, but we are accustomed to them. Motion and force are our primary objects of experience and consciousness, and in terms of them all other less familiar occurrences may conceivably be stated and grasped; and whenever a thing can be so clearly and definitely stated, it is said to be "explained" or understood; we are said to have "a dynamical theory" of it. Anything short of this may be a provisional or partial theory, an explanation of the less known in terms of the more known; but motion and force are postulated in physics as the completely known, and no attempt is made to press the terms of an explanation further than that: a dynamical theory is recognized as being at once necessary and sufficient.

Now, it must be admitted at once that of very few things have we at present such a dynamical explanation. We have no such explanation of matter, for instance, or of gravitation, or of electricity, or ether, or light. It is always conceivable that of some things no purely dynamical explanation will ever be forthcoming, because something more than motion and force may perhaps be essentially involved. Still, physics is bound to push the search for such an explanation to its furthest limits; and so long as it does not hoodwink itself by vagueness and mere phrases—a feebleness against which its leaders are mightily and sometimes cruelly on their guard, preferring to risk the rejection of worthy ideas rather than permit a semi-acceptance of anything fanciful and obscure—so long as it vigorously probes all phenomena within its reach, seeking to reduce the physical aspect of them to terms of motion and force, so long it must be upon a safe track; and, by its failure to deal with certain phenomena, it will learn—it already begins to suspect, its leaders must have long surmised—the existence of some third, as yet unknown, category, by incorporating which the physics of the future may rise to higher flights and an enlarged scope.

I have said that the things of which we are permanently conscious are motion and force, but there is a third thing which we have likewise been all our lives in contact with, and which we know even more primarily, though perhaps we are so immersed in it that our knowledge realises itself later—viz., life and mind. I do not pretend to define these terms, or to speculate as to whether the things they connote are essentially one and not two. They exist, in the sense in which we permit ourselves to use that word, and they are not yet incorporated into physics. Till they are, they must remain more or less vague; but how or when they can be incorporated is not for me even to conjecture.

Still, it is open to a physicist to state how the universe appears to him, in its broad character and physical aspect. If I were to make the attempt I should find it necessary, for the sake of clearness, to begin with the simplest and most fundamental ideas; in order to illustrate, by facts and notions in universal knowledge, the kind of process which essentially occurs in connexion with the formation of higher and less familiar conceptions, in regions where the common information of the race is so slight as to be useless. Beginning with our most fundamental sense I should sketch the matter thus:—

We have muscles and we can move. I cannot analyze motion, I doubt if the attempt is wise, it is a simple immediate act of perception, a direct sense of free unresisted motion. We may indeed move without feeling it, and that teaches us nothing, but we may move so as to feel it, and this teaches us much, and leads to our first scientific inference, viz., "space"; that is, simply, room to move about. We might have had a sense of being jammed into a full or tight-packed universe; but we have not: we feel it to be a spacious one.

Of course we do not stop at this baldness of inference: our educated faculty leads us to realise the existence of space far beyond the possibility of direct sensation; and, further, by means of the appreciation of *speed* in connexion with motion, of uniform and variable speed, we become able to formulate the idea of "time," or uniformity of sequence, and other more complex notions—acceleration and the like—upon a consideration of which we need not now enter.

But our muscular sense is not limited to the perception of free motion: we constantly find it restricted or forcibly resisted. This muscular action impeded is another direct sense, that of "force," and attempts to analyze it into anything simpler than itself have hitherto only resulted in confusion. By "force" is meant primarily muscular action not accompanied by motion. Our sense of this teaches us that space, though roomy, is not empty: it gives us our second scientific inference—what we call "matter."

Again we do not stop at this bare inference. By another sense, that of pain, or mere sensation, we discriminate between masses of matter in apparently intimate relation with ourselves, and other or foreign lumps of matter; and we use the first portion as a measure of the extent of the second. We proceed also to subdivide our idea of matter, according to the varieties of resistance with which it appeals to our muscular sense, into four different states, or "elements" as the ancients called them; viz., the solid, the liquid, the gaseous, and the ethereal. The resistance experienced when we encounter one or other of these forms of material existence varies from something very impressive—the solid, through something nearly impalpable—the gaseous, up to something entirely imaginative, fanciful, or inferential, viz. the ether. The ether does not in any way affect our sense of touch (*i.e.* of force); it does not resist motion in the slightest degree. Not only can our bodies move through it, but much larger bodies, planets and comets, can rush through it at what we are pleased to call a prodigious speed (being far greater than that of an athlete) without showing the least sign of friction. I myself, indeed, have lately been trying delicate experiments to see whether a whirling mass of iron could to the smallest extent grip the ether and carry it round, with so much as a thousandth part of its own velocity. The answer is, no; I cannot find a trace of mechanical connexion between matter and ether, of the kind known as viscosity or friction.

Why, then, if it is so impalpable, should we assert its existence? May it not be a mere fanciful speculation, to be extruded from physics as soon as possible? If we were limited for our knowledge of matter to our sense of touch, the question would never even have presented itself; we should have been simply ignorant of the ether, as ignorant as we are of any life or mind in the universe not associated with some kind of material carcass. But our senses have attained a higher stage of development than that. We are conscious of matter by means other than its resisting force. Matter acts on one small portion of our body in a totally different way, and we are said to "taste" it. Even from a distance it is able to fling off small particles of itself sufficient to affect another delicate sense. Or again, if it is vibrating with an appropriate frequency, another part of our body responds; and the universe is discovered to be not silent, but eloquent, to those who have ears to hear.

Are there any more discoveries to be made? Yes; and already some have been made. All the senses hitherto mentioned speak to us of the presence of ordinary matter—gross matter, as it is sometimes called—though when appealing to our sense of smell, and more especially to a dog's sense of smell, it is not very gross; still, with the senses hitherto enumerated, we should never have become aware of the ether. A stroke of lightning might have smitten our bodies back into their inorganic constituents, or a torpedo-fish might have inflicted on us a strange kind of torment; but from these violent tutors we should have learnt little more than a schoolboy learns from the once ever-ready cane.

But it so happens that the whole surface of our skin is sensitive in yet another way, and a small portion of it is astoundingly and beautifully sensitive, to an impression of an altogether different character—one not necessarily associated with any form of ordinary matter—one that will occur equally well through space from which all solid liquid or gaseous matter has been removed. Hold your hand near a fire, put your face in the sunshine, and what is it you feel? You are now conscious of something not arriving by ordinary matter at all. You are now as directly conscious as you can be of the ethereal medium. True the process is not very direct. You cannot apprehend the ether as you can matter, by touching or tasting or even smelling it, but the process is analogous to the kind of perception we might get of ordinary matter if we had the sense of hearing alone. It is something akin to vibrations in the ether that our skin and our eyes feel.

It may be rightly asserted that it is not the ethereal disturbances themselves, but other disturbances excited by them in our tissues, that our heat nerves feel; and the same assertion can be made for our more highly-developed and specialized sight nerves. All nerves must feel what is occurring next door to them, and can directly feel nothing else; but the "radiation," the cause which excited these disturbances, travelled through the ether, not through any otherwise known material substance.

It should be a commonplace to rehearse how we know this. Briefly, thus: Radiation conspicuously comes to us from the sun. Now, in the intervening space, if any free or ordinary matter exists, it must be an exceedingly rare gas—in other words, a few scattered particles of matter, some big enough to be called lumps, some so small as to be merely atoms, but each with a considerable gap between it and its neighbour. Such isolated particles are absolutely incompetent to transmit light. And, parenthetically, I may say that no form of ordinary matter, solid, liquid, or gaseous, is competent to transmit a thing travelling with the speed and subject to the known laws of light. For the conveyance of radiation, or light, all ordinary matter is not only incompetent, but hopelessly and absurdly incompetent. If this radiation is a thing transmitted by anything at all it must be by something *sui generis*. But it *is* transmitted, for it takes time on the journey, travelling at a well-known and definite speed, and it is a quivering or periodic disturbance, falling under the general category of wave motion. Nothing is more certain than that. No physicist disputes it. Newton himself, who is commonly asserted to have promulgated a rival theory, felt the necessity of an ethereal medium, and knew that light consisted essentially of waves. (See Appendix *q*.)

A small digression here, to avoid any possible confusion due to the fact that I have purposely associated together temperature nerves and sight nerves. They are admittedly not the same, but they are alike in this, that they both afford evidence of radiation; and, were we blind, we might still know a good deal about the sun. If our temperature nerves were immensely increased in delicacy (not all over, for that would be merely painful, but in some protected region), we might even learn about the moon, planets, and stars. In fact, an eye, consisting of a pupil (preferably a lens) and a sunken cavity lined with a surface sensitive to heat, could readily be imagined, and might be somewhat singularly effective. It would be more than a light recorder, it could detect all the ethereal quiverings caused by surrounding objects, and hence would see perfectly well in what we call "the dark." But it would probably see far too much for convenience, since it would necessarily be affected by every kind of radiation in simple proportion to its energy; unless, indeed, it were provided with a supply of screens with suitably selected absorbing powers. But whatever the advantage or disadvantage of such a sense-organ might be, we as yet do not possess one. Our eye does not act by detecting heat; in other words, it is not affected by the whole range of ethereal quiverings, but only by a very minute and apparently insignificant portion. It wholly ignores the ether waves whose frequency is comparable with that of sound; and for thirty or forty octaves above this nothing about us responds; but high up, in a range of vibration of the inconceivably high pitch of four to seven hundred million million per second—a range which extremely few accessible bodies are able to emit, and which it requires some knowledge and skill artificially to produce—to those waves the eye is acutely, surpassingly, and most intelligently sensitive.

This little fragment of total radiation is in itself trivial and negligible. Were it not for men, and glow-worms, and a few other forms of life, hardly any of it would ever occur, on such a moderate-sized lump of matter as the earth. Except for an occasional volcano, or a flash of lightning, only gigantic bodies like the sun and stars have energy enough to produce these higher flute-like notes, and they do it by sheer main force and violence—the violence of their gravitative energy—producing not only these, but every other kind of radiation also. Glow-worms, so far as I know, alone have learnt the secret of emitting the physiologically useful waves, and none others.

Why these waves are physiologically useful, why they are what is called "light," while other kinds of radiation are "dark," are questions to be asked, but, at present, only tentatively answered. The answer must ultimately be given by the Physiologist, for the distinction between light and non-light can only be stated in terms of the eye, and its peculiar specialized sensitiveness; but a hint may be given him by the Physicist. The ethereal waves which affect the eye and the photographic plate are of a size not wholly incomparable with that of the atoms of matter. When a physical phenomenon is concerned with the molecular groupings of matter, it is relegated at present to the vaguer group of knowledge summarized under the head of Chemistry. Sight is probably a chemical sense. In the retina may be complex aggregations of atoms, shaken asunder by the incident light vibrations, and rapidly built up again by the living tissues in which they live; the nerve-endings meanwhile appreciating them in their temporarily dissociated condition. A vague speculation, not to be further countenanced except as a working hypothesis leading to examination of fact, but, nevertheless, the direction in which the thoughts of some physicists are tending—a direction towards which many recently discovered experimental facts point.[1]

It would take too long to do more than suggest some other functions for which a continuous medium of communication is necessary. Nothing is becoming more certain than that action at a distance is impossible. A body can only act immediately on what it is in contact with; it must be by the action of contiguous particles, that is, practically, of a continuous medium, that force can be transmitted across space. Radiation is not the only thing the earth feels from the sun: there is in addition its gigantic gravitative pull, *a force or tension more than a million million steel rods, each seventeen feet in diameter, could stand.* What mechanism transmits this gigantic force? Again, take a steel bar itself: when violently stretched with how great tenacity its parts cling together; yet its particles are not in absolute contact, they are only virtually attached to each other by means of the universal connecting medium, the ether, —a medium that must be competent to transmit the

[1] Cf. sections 157A, 143, 187, 200, and 195, of the present book. On the subject of universal contact action, also, as opposed to action at a distance, the reader is referred to Lecture II on "The Ether and its Functions," reprinted above.

greatest stresses which our knowledge of gravitation and of cohesion shows us to exist (See Appendix *r*).

Hitherto I have mainly confined myself to the perception of the ether by our ancient sense of radiation, whereby we detect its subtle and delicate quiverings. But we are growing a new sense; not indeed an actual sense-organ, but not so very unlike a new sense-organ, though the portions of matter which go to make the organ are not associated with our bodies by the usual links of pain and disease; they are more analogous to artificial teeth or mechanical limbs, and can be bought at an instrument-maker's.

Electroscopes, galvanometers, telephones—delicate instruments these; not yet eclipsing our sense-organs of flesh, but in a few cases coming within measurable distance of their surprising sensitiveness. And with these what do we do? Can we smell the ether, or touch it, or what is the closest analogy? Perhaps there is no useful analogy; but nevertheless we deal with it, and that closely. Not yet do we fully realize what we are doing. Not yet have we any dynamical theory of electric currents, of static charges, and of magnetism. Not yet, indeed, have we any dynamical theory of light. In fact, the ether has not yet been brought under the domain of simple mechanics—it has not yet been reduced to motion and force: and that probably because the force aspect of it has been so singularly elusive that it is a question whether we ought to think of it as "material" at all. No, it is apart from mechanics at present. Conceivably it may remain apart; and our first additional category, wherewith the foundations of physics must some day be enlarged, may turn out to be an ethereal one; and this inclusion may have to be made before we can attempt to annex vital or mental processes. Perhaps they will all come in together.

Howsoever these things be, this is the kind of meaning lurking in the phrase that we do not yet know what electricity or what the ether is: we have as yet no dynamical explanation of either of them. But the present century has taught us what seems to their student an overwhelming quantity of facts about them; and when next century, or the century after, lets us deeper into their secrets, and into the secrets of some other phenomena now for the first time being rationally investigated, I feel as if it would be no merely material prospect that will be opening on our view, but that we shall get a glimpse into a region of the universe, as yet unexplored by Science, which has been sought from far, and perhaps blindly apprehended, by painter and poet, by philosopher and saint.

LECTURE VI

THE LESSONS OF RADIUM [1]

IN 1903 the Royal Society awarded its Davy Medal to M. Pierre Curie, and to Madame Curie, Docteur ès Sciences, for their researches on Radium; and Professor Curie lectured on the subject at the Royal Institution. The visit to London of these two physicists, who, in the intervals of teaching at Paris, enriched the world with brilliant chemical discoveries, had the effect of locally accentuating the interest felt throughout the scientific world in the new element and its extraordinary properties.

Briefly these properties, as investigated by several physicists, are that radium, like the other far less active substances previously discovered, is constantly emitting, without apparent diminution, three kinds of rays: rays called γ which appear to be chiefly of the same nature as the x rays of Röntgen; rays called β, or cathodic, which are similar to the cathode rays in a Crookes tube and to the Lenard rays outside such a tube, and are found to consist of extremely minute

[1] An article which appeared in *The Nineteenth Century and After* for July 1903; now reprinted by permission.

flying corpuscles or electrons negatively charged; and rays called α, which appear to be composed of projected and positively charged atoms of matter flying away at an immense speed measured by Professor Rutherford, of Montreal. The whole power of emission is designated radio-activity, or spontaneous radio-activity to distinguish it from the variety which can be artificially excited in several ways, and was discovered in the first instance as an experimental fact by M. Becquerel. The most prominent, the most usually and easily demonstrated kind, are the β rays; for these possess remarkable penetrating power and can excite phosphorescent substances or affect photographic plates and electroscopes after passing through a great length of air or even through an inch of solid iron. But although these are the most conspicuous, they are not the most important. The most important by far are the α rays, the flinging off of atoms of matter. It is probable that everything else is subordinate to this effect, and can be regarded as a secondary and natural consequence of it.

For instance, undoubtedly radium or any salt of radium has the power of constantly generating heat: M. Curie has now satisfactorily demonstrated this important fact. Not that it is to be supposed that a piece of radium is perceptibly warm, if exposed so that the heat can escape as fast as generated—it can then only be a trifle warmer than its surroundings; but when properly packed in a heat-insulating enclosure it can keep itself five degrees Fahrenheit above the temperature of any other substance enclosed in a similar manner; or when submerged in liquid air it can boil away that liquid faster than can a similar weight of anything else. Everything else, indeed, would rapidly get cooled down to the liquid-air temperature, and then cease to have any further effect; but radium, by reason of its heat-generating power, will go on evaporating the liquid continually, in spite of its surface having been reduced to the liquid-air temperature. But it is clear that this emission of heat is a necessary and quantitative consequence of the vigorous atomic bombardment —always provided that the emission is due to some process occurring inside the atom itself, and not to any subsidiary or surrounding influences. Now that is just one of the features which is most conspicuous. Tested by any of the methods known, the radio-activity of radium appears to be constant and inalienable. Its power never deserts it. Whichever of its known chemical compounds be employed, the element itself in each is equally effective. At a red heat, or at the fearfully low temperature of liquid hydrogen, its activity continues; nothing that can be done to it destroys its radio-activity, nor even appears to diminish or increase it. It is a property of the atoms themselves, without regard, or without much regard, to their physical surroundings or to their chemical combination with the atoms of other substances. And this is one of the facts which elevate the whole phenomenon into a position of first-class importance.

The most striking test for radio-activity is the power of exciting phosphorescence in suitable substances: as, for instance, in diamond. Sir Wm. Crookes has shown that by bringing a scrap of radium, wrapped in any convenient opaque envelope, near a diamond in the dark, it glows brilliantly; whereas the "paste" variety remains dull. A number of other substances emit light also when submitted to the emission (in this case usually the β emission) from radium; and Crookes has also shown that the substance known as zinc-blende if submitted to the α rays of radium (which can be done by bringing a scrap of it sufficiently near a zinc-blende screen with no interposed obstacle or impediment), the bombardment, when looked at in the dark, becomes visible not as a mere generally diffused glow, as in ordinary cases of phosphorescence, but as a multitude of luminous specks, darting or flashing hither and thither to all appearance, but really occurring first in one place and then in another, each flash or light-speck representing the impact of the atomic projectile upon a target. To see them individually some moderate magnifying power must be employed, and it then constitutes a simple and beautiful experiment, for which the merest trace of radium is sufficient.

But although the excitation of phosphorescence is the most striking test and proof of the power of radio-activity, because it appeals so directly to the eye, it is by no means the most delicate test; and if that had been our only means of observation, the property would be still a long way from being discovered. It was the far weaker power of a few substances—substances found in Nature and not requiring special extraction and concentration, such as Madame Curie applied to tons of the oxide-of-uranium-mineral called "pitch-blende" in order to extract a minute amount of its concentrated active element—it was the far weaker power of naturally existing substances such as that of pitch-blende itself, of thorium, and originally of uranium, which led to the discovery of radio-activity. And none of these substances is strong enough to excite visible phosphorescence. Their influence can be accumulated on a photographic plate for minutes, or hours, or days together, and then on developing the plate their radio-active record can be seen; but it is insufficient to appeal direct to the eye. In this photographic way the power of a number of minerals has been tested.

But even this is far from being the most sensitive test. The most sensitive test that can be applied is the power which any radio-active substance possesses of rendering atmospheric air conductive, and so discharging any electrified body in its neighbourhood. The most minute trace of radio-activity can be detected in this way; and by this means R. J. Strutt has found that the property is widely diffused—that most metals and many other substances possess it to some small degree; many mineral waters distinctly possess it, and traces of the power have been detected in common water from deep wells.

The emission of atoms does not seem, at first hearing, a very singular procedure on the part of matter; many forms of matter can evaporate, and many others emit scent. Wherein, then, lies the peculiarity of radio-active substances, if the power of flinging away of atoms at tremendous speed is their central feature? It all depends on what sort of atoms they are. If they are particles of the substance itself, there is nothing novel in it except the high speed: but if it should turn out that the atoms flung off belong to quite a different substance—if one elementary body can be proved to throw off another elementary body—then clearly there is something worthy of stringent inquiry. Now, Rutherford has measured the atomic weight of the atoms thrown off, and has shown that they constitute less than 1 per cent. of the atoms whence they are projected; though whether the matter flung off corresponds to any known material is at present quite uncertain. It has been suggested that it may perhaps be helium, but that was at first little better than a guess. The guess is being confirmed, however, by later researches: each projectile appears as if it were half an atom of helium—if such a thing is temporarily possible.

But the radio-activity of the substance itself—a substance like radium or thorium—is by no means the whole of what has to be described. When the emission has occurred, when the light atoms have been thrown off, it is clear that something must be left behind; and the properties of that substance must be examined too. It appears to be a kind of heavy gas, which remains in the pores of the radium salt and slowly diffuses away. It can be drawn off more rapidly by a wind or current of air, and when passed over suitable phosphorescent substances it causes them to glow. It is, in fact, itself radio-active, as the radium was; but its chemical nature is at present quite unknown. Its activity soon ceases, however, gradually fading away, so that in a few days or weeks it is practically gone. It leaves a radio-active deposit on surfaces over which it has passed; a deposit which is a different substance again, and whose chemical nature is likewise different and unknown. The amount of substance in these emanations and deposits is incredibly small, and yet by reason of their radio-activity, and the sensitiveness of our tests for that emission, they can be detected, and their properties to some extent examined. Thus, for instance, the solid deposit left behind by the emanation can be dissolved off by suitable reagents, and can then be precipitated or evaporated to dryness and treated in other chemical ways, although nothing is visible or weighable or detectable by any known means except the means of radio-activity. So that directly one of the chain of substances which emanate from a radio-active substance ceases to possess that particular kind of activity, it is liable to pass out of recognition; and does so pass, unless another active change speedily supervenes. What happens to one of these products after it has ceased to be radio-active, or what further changes take place in it, remains at present absolutely unknown: (unless it should turn out to be some substance with which we are otherwise familiar—for instance lead in the case of radium, or perchance copper in some other case). So it is quite possible that these emanations and deposits and other products of spontaneous change may be emitted by many, perhaps all, kinds of matter, without our knowing anything whatever about them.

The emanations from radium and thorium, however are recognisable enough, by reason of their remarkably active properties; they can be passed along tubes and otherwise dealt with: and not only do they behave as a gas in ordinary ways, but their liquefying-point has likewise been approximately determined and found to be something like 250 degrees below the Fahrenheit zero. At this temperature, at any rate, they condense and decline to pass on; perhaps because they are entangled with the liquefying air or some of its constituents, possibly because they really liquefy themselves; but whether they really condense or not, they by no means lose their radio-active property, but like every kind of substance which is known to possess this property, they continue it unchanged and undiminished through whatever vicissitudes they pass.

That being so, what is the meaning of the series of facts which have been here hastily summarised; and how are they to be accounted for? Here we come to the hypothetic and at present incompletely verified speculations and surmises, the possible truth of which is arousing the keenest interest. There are people who wish to warm their houses and cook their food and drive their engines and make some money by means of radium; it is possible that these are doomed to disappointment. But it is always rash to predict anything whatever in the negative direction, and I would not be understood as making any prediction, or indicating any kind of opinion, on the subject of possible practical applications of the substance: except, as we may hope, to medicine, where radium, applied periodically, has been found effective in the treatment of superficial but malignant growths like rodent ulcer.

Applications have their place, and in due time may come within the range of practicability, though there is no appearance of them at present. Meanwhile the real points of interest are none of these, but of a quite other order. The easiest way to make them plain is to state them as if they were certain, and not confuse the statement by constant reference to hypothesis: guarding myself from the beginning by what I have already said as to the speculative character of some of the assertions now going to be made.

Atoms of matter are not simple, but complex; each is composed of an aggregate of smaller bodies in a state of rapid interlocked motion, restrained and coerced into orbits by electrical forces. An atom so constituted is fairly stable and perennial, but not infinitely stable or eternal. Every now and then one atom in a million, or rather in a million millions, gets into an unstable state, and is then liable to break up. A very minute fraction of the whole number of the atoms of a substance do thus actually break up, probably by reason of an excessive velocity in some of their moving parts: an approach to the speed of light in some of their internal motions—perhaps the maximum speed which matter can ever attain—being presumably the cause of the instability. When the break-up occurs, the rapidly moving fragment flies away tangentially, with enormous speed—twenty thousand miles a second—and constitutes the α ray or main emission.

If the flying fragment strikes a phosphorescent obstacle, it makes a flash of light; if it strikes (as many must) other atoms of the substance itself, it gets stopped likewise, and its energy subsides into the familiar molecular motion we call 'heat'; so the substance becomes slightly warmed. Energy has been transmuted from the unknown internal atomic kind to the known thermal kind: it has been degraded, from regular orbital astronomical motion of parts of an atom, into the irregular quivering of molecules; and the form of energy which we call heat has therefore been generated,—making its appearance, as usual, by the disappearance of some other form of energy, but, in this particular instance, of a form previously unrecognized.

Hitherto a classification of the various forms of energy[1] has been complete when we enumerate rotation, translation, vibration, and strain, of matter in the form of planetary masses, ordinary masses, molecules, and atoms, and of the universal omnipresent medium 'ether,' which is to 'matter' as the ocean is to the shells and other conglomerates built out of its dissolved contents. But now we must add another category, and take into consideration the parts or electrons of which the atoms of matter are themselves hypothetically composed.

The emission of the fragment is accompanied by a convulsion of the atom, minuter portions or electrons being pitched off too; and these, being so extraordinarily small, can proceed a long way through the interstices of ordinary obstacles,—seeing, as it were, a clear passage every now and then even through an inch of solid lead, and constituting the β rays; while

[1] See a paper by the author in the *Philosophical Magazine* for October 1879.

the atoms themselves are easily stopped, even by paper. But the recoil of the main residue is accompanied by a kind of shiver or rearrangement of the particles, with a suddenness which results in an x-ray emission such as always accompanies anything in the nature of a shock or collison among minute charged bodies; and this true ethereal radiation is the third or γ ray of the whole process. Like the heat-production, it is a simple consequence of the main phenomenon, which is a partial break-up—a sort of convulsion or volcanic eruption—of the atom.

The emission over, and the fragment of the atom gone, the residue is no longer radium, but is something else. What it is we do not yet know; but since it is produced in isolated atoms here and there, with crowds of foreign substance between, there is no cohesion or any continuity between its particles; they are separated like the atoms of a gas, or like the molecules of a salt in a very dilute solution in which there are millions or billions of times as many atoms of the solvent as there are of the dissolved salt. So they are easily carried away by any motion of the medium in which they are mechanically embedded; but they retain their individuality, and their radio-active power persists, because the breaking-up process is by no means finished, stability is far from attained. Indeed, the instability is more marked than it was in the original substance; for whereas in the original substance only one single atom here and there out of a million of millions was affected by it, here in the diffusing emanation, or first product of incipient atomic dissociation, every atom seems unstable, or at least to be in a very critical condition. So that in a time to be reckoned in minutes or days or months (according to the nature of the emanation, whether it be from thorium or radium or uranium) a further breakdown has occurred in every atom; and so its accompaniment of radio-activity ceases. The radio-active power has disappeared from the emanation, but it has not wholly ceased: it has been transferred, this time, to a solid deposit which has been the residual outcome of the second break-up. For the atoms of this deposit also are unstable, and break up, in a time which can be reckoned in months, days, or minutes apparently in roughly inverse order to the duration of the parent emanation. Another and another substance has also been suspected, by Rutherford and Soddy, as the outcome of this third break-up; while gradually the radio-active power of the resulting emanations becomes imperceptible, and further investigation by present methods becomes impossible, for lack of means of detection of sufficient delicacy.

Here, then, we appear to have, in embryo, a transmutation of the elements, the possibility of which has for so long been the guess and the desire of alchemists. Whether the progress of research will confirm this hypothesis, and whether any of the series of substances so produced are already familiarly known to us in ordinary chemistry, remains to be seen. It is not in the least likely that any one radio-active substance can furnish in its stages of collapse the whole series of elements; most likely one substance will give one series, and another substance will give another; and it may be that these emanations are new and unstable elements or compounds such as are not already known, or it may be that they approximate in properties to some of the known elements, without any exact coincidence. The recognized elements which we know so well must clearly be comparatively stable and persistent forms ; but it does not follow that they are infinitely stable and perpetual. The probability is that every now and then, whether by the shock of collision or otherwise, the configuration necessary for instability will be attained by some one atom, and then that particular atom will fling off the fragment and emit the rays of which we have spoken, and begin a series of evolutionary changes of which the details may have to be worked out separately for each chemical element.

If there be any truth in this speculation, matter is an evanescent and transient phenomenon, subject to gradual decay and decomposition by the action of its own internal forces and motions, somewhat as has been suspected and to some extent ascertained to be the case for energy. But, we must ask, "How comes it, then, that matter is still in existence? Why has it not already all broken down, especially in these very radioactive and therefore presumably rapidly decadent forms of radium and the like?" The question naturally directs us to seek some mode of *origin* for atoms, to conjecture some falling together of their pristine material, some agglomeration of the separate electrons of which they are hypothetically composed, such as is a familiar idea when applied to the gravitational aggregates of astronomy which we call nebulæ and suns and planets.

We may also ask whether many other phenomena, known but not understood, are not now going to receive their explanation. The light of the glowworm and firefly and other forms of life is one thing which deserves study; the Brownian movements of microscopic particles is another. Are we witnessing in the Brownian movement any external evidence, exhibited by a small aggregate of an immense number of atoms, of the effects of internal rearrangement and emission of the parts of the atoms, going on from the free surface of the particle?

Many more questions may be asked; and if the conjectures now rife are to any great extent confirmed, it is clear that many important avenues for fruitful experimental inquiry will be opened up. Among them an easy and hopeful line of investigation, lying in the path of persons favourably situated for physically examining the luminous emission of live animals, may perhaps usefully be here suggested:—

Can it be that the light emitted by the glowworm —which is true light and not technical radio-activity, and yet which is accompanied by a trace of something which can penetrate black paper and affect a light-screened photographic plate—is emitted because the insect has learned how to control the breaking-down of atoms, so as to enable their internal energy in the act of transmutation to take the form of useful light instead of the useless form of an insignificant amount of heat or other kind of radiation effect; the faint residual penetrating emission being a secondary but elucidatory and instructive appendage to the main luminosity?

Objections to any particular interpretation of radio-activity—such an interpretation as has here been suggested—have been adduced from time to time by conservative chemists and by a few physicists; and all such objections must be duly considered and weighed. The testing of rival hypotheses can only result in further elucidation of the truth, whatever it may be. But let me conclude by asking readers to give no ear to the absurd claim of paradoxers, and others ignorant of the principles of physics, who, with misplaced ingenuity, will be sure to urge that the foundations of science are being uprooted and long-cherished laws shaken. Nothing of the kind is happening. The new information now being gained in so many laboratories is supplementary and stimulating, not really revolutionary, nor in the least perturbing to mathematical physicists; for on the electric theory of matter it is the kind of thing that ought to occur. And one outstanding difficulty which till lately obstructed or incommoded this theory, a difficulty felt and expressed by Professor Larmor—viz. that matter *ought* to be radio-active and unstable if the electric theory of its constitution were true—this theoretical obstacle is being removed in the most brilliant possible way.

APPENDIX

APPENDIX.

Students may find this brief summary of quantitative facts useful, although they are now most of them to be found in text-books. Appendix *p* is specially worthy of attention.

Electro-magnetism.

(*a*) The fundamental fact of electro-magnetism, ascertained by direct experiment, is that a circuit conveying a current exactly imitates a magnet of definite moment, the equivalent moment being

$$ml = \mu n \mathrm{AC}$$

where A is the mean area of the coil, n the number of turns of wire, C the current, and μ a constant characteristic of the medium inside the coil, whose absolute value till lately we have had no means of ascertaining (§§ 68, 69, 127, and Chap. 17).

Magnetic Induction, Reluctance, and Permeability.

(*b*) The intensity of magnetic field at a distance r from a pole of strength m is $\frac{m}{r^2}$, and this may be called the number of lines of force (or tubes if the idea be preferred) per unit area. The total number of lines of force through a spherical surface of this radius is $\frac{m}{r^2} \times 4\pi r^2$, or $4\pi m$.

This number, $4\pi m$, must likewise thread any closed surface whatever, inclosing the pole; and in fact it is the number the pole possesses. It may be called the total magnetic flux or displacement, or the total induction, due to the pole; the name "induction," first used vaguely in the sense of *influence* by Faraday, having been given this definite connotation by Maxwell. The same expression likewise gives the number of lines of force due to a complete magnet; for the superposition of lines, due to an equal opposite pole, curves the original lines but alters not their number. With two detached poles the lines simply go from one to the other: with a complete magnet the lines all form closed loops extending from north to south through air, and back through steel. In the case of a coil they likewise are closed loops, all threading the coil and then spreading out through the surrounding medium. In all real cases, therefore, the lines of force form close curves. Magnetic circuits are always closed, just as electric circuits are.

Take the simplest case of an anchor-ring coil, or helix, bent into a closed circuit (like Fig. 47 or 29): all its lines are then inside it, and their total number, being $4\pi m$, is $\frac{4\pi\mu n A C}{l}$; where l is the mean circumference of the anchor-ring, or length of the magnetic circuit. This is called the total flux of magnetic induction, or briefly the total induction, and we will denote it by N.

Now, in the analogous case of a voltaic circuit, the current is ratio of electromotive force to resistance, and the resistance may be written $\frac{l}{\kappa A}$; κ being specific conductivity, and A sectional area of conductor of length l.

To bring out the analogy, we shall write the magnetic flux—

$$N = \frac{4\pi n C}{\dfrac{l}{\mu A}},$$

where the numerator is sometimes called magneto-motive force, and the denominator magnetic resistance, or preferably, as suggested by Mr. Heaviside, magnetic *reluctance*. Obviously μ takes the place of electric conductivity and is a sort of magnetic conductivity: it was from that point of view that Lord Kelvin long ago christened it "permeability" (see § 82).

If the magnetic circuit is not so simply constituted, but is composed of portions of different areas, length, and material, in series—as the magnetic circuit of a dynamo is, for instance—

the magnetic reluctance can be written (still pursuing the analogy)—

$$R = \frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2} + \dots,$$

and $N = \frac{4\pi n C}{R}$ as before.

Mutual Induction

(*c*) If a single turn of a secondary wire surround this closed magnetic circuit, as in Fig. 47, the total induction through it, whatever its shape or size, is just N : and if it surround the ring n' times, the effective total induction is $n'N$. This is the induction of the primary through the secondary, which, written out in full is—

$$\frac{4\pi\mu n n' AC}{l}.$$

The relation is a mutual one; and if the same current were to flow in secondary, the same number of lines would thread effectively the primary. Hence we call it *mutual* induction, and write it MC ; where M, the coefficient of mutual induction between the two coils, is—

$$M = \frac{4\pi\mu n n' A}{l};$$

the A and the l referring most easily to a simply and obviously closed magnetic circuit. Two detached coils situated anyhow with respect to each other, will have a specifiable value of M, but it is not so easy to write it down.

Self-Induction.

(d) Instead of using a secondary coil to surround the induction caused by the primary, we may consider the primary as surrounding the induction caused by itself, and so speak of its "self-induction" as—

$$\frac{4\pi\mu n^2 AC}{l},$$

which, written LC, gives us the coefficient of self-induction, called the "inductance,"—

$$L = \frac{4\pi\mu n^2 A}{l},$$

or,

$$= 4\pi\mu n n_1 A,$$

where n_1=number of turns per unit length. (§§ 115 and 98.)

Here, again, every coil has a specifiable self-induction, but in most cases it is not so easy to write down. It always means, however, the ratio of the self-produced magnetic induction to the current which has produced it—

$$L = \frac{N}{C}.$$

Value of Inductance in a few other simple Cases.

(*e*) The magnetic field produced by a straight wire varies inversely with the distance; being, at a distance r from a straight wire of sectional radius a, conveying a current C—

$$\frac{2\mu C}{r}.$$

and this therefore specifies the number of lines through unit area, taken in the plane of the wire.

So the whole number of circular lines of force included between the wire and any distance b, in a drum of thickness l, is—

$$\int_a^b \frac{2\mu C l}{r} dr = 2\mu C l \cdot \log \frac{b}{a}.$$

Now, if at the distance b there is a parallel wire conveying the return current, it, too, will have the same number of lines of force; so the whole number involved in a length, l, of a pair of parallel wires is—

$$4\mu l \log \frac{b}{a} \times C;$$

and as all the lines of force that exist pass between the wires, this expression sums up the whole magnetic flux produced by the going and return parallel currents; and the coefficient of C in the last expression is therefore the coefficient of self-induction for the case of two thin parallel wires at a distance b.

For a circular loop of radius r, radius of section of wire being a, this modifies itself to—

$$L = 4\pi\mu r\left(\log\frac{8r}{a} - 1\tfrac{3}{4}\right)$$

(see § 140). In every case μ refers to the space near the wire, not to the substance of the wire itself.

In both these cases, the magnetization of the substance of the wires themselves is treated as *nil*. In the case of extremely rapidly alternating currents, this is correct (§ 47). In the case of copper wires not too close together, it is never *very* incorrect.

Energy of a Current.

(*f*) A magnet of moment ml, in a magnetic field of intensity H, experiences a couple mlH sin θ: and therefore a simple stiff coil of wire, conveying a current, experiences a couple μnACH sin θ. If it turns a small angle, $d\theta$, the work done, or the change of potential energy, is μnACH sin $\theta d\theta$; and therefore the potential energy of the circuit in any position is $-\mu n$ACH cos θ: which may be written NC, because nA cos θ is the effective area of the coil resolved perpendicularly to the lines of force which thread it, to the number μH per unit area.

This result may be generalized; a current in a magnetic field always possesses energy NC. If the field is due to external causes, *i.e.* having an existence independent of the current, the energy is potential energy of strain, and tends to cause the circuit to rotate. This is the principle of electric motors. But if the field is due to nothing but the current itself—if it is a self-produced and self-maintained field—the value of N is LC, and the energy is now more conveniently called kinetic energy. To obtain its value, we must remember that the induction and the current die out together, it is not as if they had an independent existence; and so the energy is—

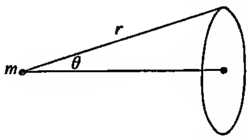
$$\int_0^C N\,dC = \tfrac{1}{2}LC^2.$$

This is the work which must be done at starting and a stopping a current (Chap. V.).

Pole near a Circuit.

(*g*) If a single pole find itself on the axis of a circle, the number of its lines of force which penetrate the circle is $\frac{m}{r^2} \times 2\pi r^2 (1 - \cos\theta)$, the latter factor being the area of the portion of a sphere with centre at m, cut off by the said circle. The expression $2\pi(1-\cos\theta)$, since it measures the ratio of the area subtended by a conical angle to the square of the radius, is, in analogy with the circular measure of a plane angle, called a solid angle. It is the solid angle of the cone with vertex m and base the circle, or the angle subtended by the circle to an eye placed at m. Call this angle ω; then the number of lines of force, or the magnetic induction through the circle, is $m\omega$.

If the circle becomes now a circuit conveying a current C, the system has energy $m\omega C$, and accordingly there will be a tendency to relative motion; the force in any direction being equal to the rate of change of $m\omega C$ per unit distance in that direction.



The potential of the pole on the circuit is $m\omega$: the potential of the circuit on the pole is $C\omega$. If the pole is situated anywhere, and the coil is of any shape, ω can still be specified, but not so easily. If there is a collection of magnets, their potential on a circuit, or induction through it, can be written $\Sigma(m\omega)$.

Magneto-electricity.

(*h*) The fundamental fact of magneto-electricity is that if the induction through a circuit change, from any cause whatever, an E.M.F. is set up in the circuit equal to the rate of change of the magnetic nduction—

$$e = \frac{dN}{dt}$$

This is not strictly a relation independent of the fundamental fact of electro-magnetism : the two are connected by the law of the conservation of energy. I may indicate this important fact sufficiently for our present purpose, by quoting the conservation of energy, in a form applicable to the case of a circuit conveying a steady current, as—

$$\mathrm{EC}dt = \mathrm{RC}^2dt + \mathrm{C}d\mathrm{N}\,;$$

whence

$$\mathrm{RC} = \mathrm{E} - \frac{d\mathrm{N}}{dt},$$

or the resultant E.M.F. consists not only of the E.M.F. applied, but contains also an intrinsic or induced E.M.F. magnetically excited in the circuit ; this being what Faraday discovered as magneto-electricity.

Various Modes of exciting Induction Currents.

(*i*) Now N may be made up in a multitude of ways. It may be a component of terrestrial magnetic field, say, $n\mathrm{AH}\cos\theta$. It may be caused by magnets in the neighbourhood, $\Sigma(m\omega)$. It may be due to induction from some other coil, MC′. It may be due to the current passing in the coil itself, say LC. The total induced E.M.F. is the rate of change of the sum of all these, or—

$$e = \frac{d}{dt}\{n\mathrm{AH}\cos\theta + \Sigma(m\omega) + \mathrm{MC}' + \mathrm{LC}\}\,;$$

and accordingly it may be excited in many ways :—by changes in size or shape of coil ; by changing its aspect to the field (as in a dynamo) ; by moving magnets in its neighbourhood (as in an alternating-current machine) ; by varying the current in or shifting the position of other circuits (as in a Ruhmkorff coil) ; or lastly, by changing its own current, or its own coefficient of self-induction. Changes in the last term, $\frac{d}{dt}$(LC), are especially called E.M.F. of self-induction, and used to be called extra-currents.

Primary current alone: and Coil with revolving Commutator.

(j) The equation to a current of varying strength, in the simplest case of a lone circuit, is—

$$\mathrm{E} - \mathrm{RC} = \frac{d}{dt}(\mathrm{LC}),$$

where E is the applied E.M.F.; and this may be written out more fully—

$$\mathrm{L}\frac{d\mathrm{C}}{dt} + \left(\mathrm{R} + \frac{d\mathrm{L}}{dt}\right)\mathrm{C} = \mathrm{E},$$

which shows that in the case of circuits of variable self-induction the resistance has not its most simple value, but has an extra term in it, a spurious or imitative resistance, $\frac{d\mathrm{L}}{dt}$.

An example of a circuit of variable self-induction is one which is continually having wire withdrawn from or added to it, so that a current has to be stopped in portions where it was already established, and started in hitherto stagnant portions: a case quite analogous to the viscosity of gases, and commonly illustrated by passengers of appreciable inertia getting in and out of a moving train. An instance of the case occurs in every Gramme ring, or indeed every dynamo armature when spinning with a commutator, quite independently of the magnetic field in which it may happen to be spinning. In all such cases the effective resistance is rather greater than R, being $\mathrm{R} + \frac{d\mathrm{L}}{dt}$, or $\mathrm{R} + n\,\mathrm{L}$; where the self-induction virtually added to the circuit n times a second is L.

Leyden Jar.

(k) In the case of a discharging condenser, of capacity S, the quantity stored in it at any instant is such that $\mathrm{C} = -\frac{d\mathrm{Q}}{dt}$, or that $\mathrm{Q} = \mathrm{Q}_0 - \int_0^t \mathrm{C}dt$; and the difference of potential between its terminals is $\frac{Q}{S}$, which is the E.M.F. applied to the circuit. So the equation to the discharge current is—

$$L\frac{dC}{dt} + RC = \frac{Q}{S}.$$

The solution of the equation in this case is—

$$C = \frac{E}{pL}e^{-mt} \sin pt,$$

where $m = \frac{R}{2L}$, and regulates the total duration of the discharge,

$$\text{and where } p = \frac{1}{\sqrt{(LS)}} \text{ approximately}$$

$$\left\{\text{more accurately } \sqrt{\left(\frac{1}{LS} - m^2\right)}\right\},$$

and regulates the rapidity of alternation, which is $\frac{p}{2\pi}$.

The wave-length of the emitted radiation (Chapter XIV.) is

$$\lambda = \frac{2\pi}{p} . v = 2\pi\sqrt{\left(\frac{L}{\mu} . \frac{S}{K}\right)}$$

With these quick oscillations, R is nothing at all like its ordinary value for steady currents ; because the outside of the wire only is used (§§ 45 and 102) ; but, calling the ordinary value R_0, R is very approximately, for high rates of alternation,—[1]

$$R = \sqrt{(\tfrac{1}{2}p\mu_0 l . R_0)},$$

l being the length of the wire, and μ_0 the magnetic permeability of its *substance* (§ 46).

The emission of radiation by such a circuit goes to increase R still more (§ 142 and p. 370). See also (m).

Alternating Current.

(l) In case of any coil or armature spinning in a magnetic field, the equation to the current is—

$$- RC = \frac{d}{dt}\left(nAH \sin\theta + LC\right),$$

$$\text{or } L\frac{dC}{dt} + \left(R + \frac{dL}{dt}\right)C = nAH \sin\theta\frac{d\theta}{dt};$$

[1] Rayleigh, *Phil. Mag.*, May 1886.

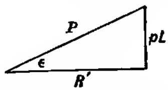
taking the E.M.F. as alternating according to a sine function. Writing this equation—

$$L\frac{dC}{dt} + R'C = E_0 \sin pt,$$

the solution is—

$$C = \frac{E_0 \sin (pt - \epsilon)}{\sqrt{\{R'^2 + (pL)^2\}}},$$

where $\tan \epsilon = \frac{pL}{R'}$. The R′ differs from simple R, as already explained in (*j*), only when a commutator is employed : which it often is not. The denominator of the above expression



may be called impedance, and denoted by P (see next section), the quantities being related as in this little diagram. The quantity ϵ is the lag of the current behind the applied E.M.F.

The hypothenuse may be called the applied E.M.F., the vertical side the counter or induced E.M.F., and the base the effective E.M.F., when an alternating current is being by any means generated in a coil.

Two Definitions of Electric Resistance, and Distinction between the two.

(*m*) The oldest definition of the term "resistance of a conductor" is that given by Ohm, viz. the ratio—

$$\frac{\text{E.M.F. applied to the conductor}}{\text{Current excited in it}}.$$

But another is contained in the law of Joule, viz. the ratio—

$$\frac{\text{Energy dissipated per second by the conductor}}{\text{Current squared which it transmits}}.$$

In cases of no reversible obstruction the two definitions agree; but in cases of chemical action, of reversible heat effects, and of varying magnetic induction, some of the energy may be stored—

all is not dissipated,—and under these circumstances the two definitions do not agree. A distinction must be drawn between them: the term resistance cannot properly be applied to both quantities.

Now it is found convenient to retain the name resistance for the *second* definition—the dissipation of energy coefficient; and to realize that in the total obstruction specified by the first definition there is included "back E.M.F.," "polarization," or other reversible obstruction, in addition to resistance proper; while in the very important case of the total obstruction met with by an alternating current, it has become convenient to call the quantity defined by the first of the two equations "impēdance."

The two definitions of resistance may indeed be always made to agree, if, in the Ohm's law definition, instead of *applied* E.M.F., we reckon *resultant* E.M.F. And this is the neatest and simplest mode of taking into account such things as chemical or thermal polarization, and also a magnetic back E.M.F., so long as it is steady and external, as in the case of electric motors. But, when dealing with alternating generators, some understanding has to be come to as to how the value of their E.M.F. is to be reckoned, and no simple subtraction of a back E.M.F. is convenient. Referring to last section, we see that the expression for current contains as numerator a lessened or lagging E.M.F., and as denominator an obstruction or impēdance containing a term in addition to what is usually called resistance.

It is from this point of view that the idea and term "impēdance" have become so useful.

The value of this quantity is, in general, as has been shown,

$$\sqrt{\{(p\mathrm{L})^2 + \mathrm{R}^2\}};$$

and its two portions may be styled respectively the inertia, or conservative portion, and the frictional or dissipative portion (§ 38).

Part of the energy dissipated appears as heat in the conductor, and this is the only portion on which Joule experimented; but another portion we now know is propagated out as radiation into space (§ 142): both portions together are included in the numerator proper in the above second definition of R.

Induced Current in Secondary Circuit. Transformers.

(*n*) The E.M.F. induced in a secondary circuit surrounding a ring like Fig. 47, whose primary coil has an alternating or intermittent current, C, sent round it, is, referring back to (*h*) and (*c*)—

$$M\frac{dC}{dt}, \quad \text{or } 4\pi nn'\frac{\mu A}{l}.\frac{dC}{dt};$$

and depends, therefore, directly on the number of turns of wire in the secondary coil, and on the rate of variation of the primary current. This is the principle of induction-coils and of "secondary generators" or transformers (§ 115). The E.M.F. thus obtained is completely under control by choosing a suitable value for n', according as high E.M.F. (in Ruhmkorff coils) or a powerful current (for electric welding) is required. They are called transformers, because, of the two electrical factors in mechanical "power," EC, they can change the ratio, leaving the product nearly constant: just as ordinary machines do with the force and velocity factors of the same product "power." So, in precise analogy with gaining in force what you lose in speed, you gain in E.M.F. what you lose in current; or *vice versâ*.

The equations to primary and secondary currents, C and C′ are—

$$E - RC = \frac{d}{dt}\left(LC + MC'\right),$$

$$0 - R'C' = \frac{d}{dt}\left(L'C' + MC\right);$$

and from the solution of these, the effective or apparent self-induction of primary, when its secondary is short-circuited and when all resistances are kept small, comes out equal to $L - \frac{M^2}{L'}$. Now since, for a simply closed magnetic circuit,

$$L : L' : M = n^2 : n'^2 : nn',$$

the effective self-induction (and therefore the impēdance) of the primary is approximately zero when its secondary is short-circuited—a fact which is the Magna Charta of commercia transformers.

Rate of Transmission of Telegraphic Signals, in the Simplest Case.

(*o*) Consider a unit length of a pair of parallel thin copper wires not too close together, a going and return wire, at a distance b apart, the sectional radius of each wire being a. The self-induction of this portion, see (*e*), is—

$$L_1 = 4\mu \log\frac{b}{a} = 1480 \log_{10}\left(\frac{b}{a}\right) \text{micro-secohms per mile,}$$

and the static capacity of the same portion is (by somewhat similar reasoning)—

$$S_1 = \frac{K}{4 \log\frac{b}{a}} = \frac{1}{52 \log_{10}\left(\frac{b}{a}\right)} \text{ micro-farads per mile.}$$

Hence

$$L_1 S_1 = \mu K.$$

The resistance of unit length of the pair may be called R_1.

Now consider an element of the pair of wires, of length dx, and write down the slope of potential between its ends when a current, C, flows along it, and also their rise of potential with time; we get—

$$\left.\begin{aligned} L_1\frac{dC}{dt} + R_1 C + \frac{dV}{dx} &= 0, \\ \text{and} \quad S_1\frac{dV}{dt} + \frac{dC}{dx} &= 0. \end{aligned}\right\}$$

The solution of these equations, for the case of an applied rapidly alternating E.M.F., $V_0 \sin pt$, at the origin, may be written—

$$V = V_0 e^{-\frac{m_1}{p_1}x} \sin p\left(t - \frac{x}{p_1}\right),$$

where $m_1 = \frac{R_1}{2L_1}$ and $p_1 = \frac{1}{\sqrt{(L_1 S_1)}}$.

Now, a "wave" being any disturbance periodic both in space and time, its simplest general equation is—

$$y = a \sin (pt - nx),$$

where y is the extent of this disturbance, at any place distant x from the origin, and at any time, t, from the era of reckoning.

The coefficient a is the amplitude of the vibration ; n is the space-period-constant, or $\frac{2\pi}{\lambda}$; p is the time-period-constant, or $\frac{2\pi}{T}$; the velocity of advance of the waves is one space-period in onetime-period, viz. $\frac{\lambda}{T}$ or $\frac{p}{n}$.

Hence the above bracketed pair of equations give waves travelling along the wires with the speed $\frac{1}{\sqrt{(L_1 S_1)}}$, which we have seen equals $\frac{1}{\sqrt{(\mu K)}}$, and with an amplitude dying out along the length of the wires according to a logarithmic decrement $\frac{1}{2} R_1 \sqrt{\left(\frac{S_1}{L_1}\right)}$. [*Electrician*, xxi, 607, Sept. 14, 1888].

The speed of propagation of pulses along wires is therefore precisely the same, in this simple case, as the propagation of waves out through free space, viz. the velocity $\frac{1}{\sqrt{(\mu K)}}$ (§§ 128, 132, 137). All complications go to decrease, not to increase, the speed (§ 135).

Dimensions of Electrical Quantities.

(p) Writing L, M, T, F, v, for units of length, mass, time, force, velocity, as usual, and A for area ; the fundamental and definite experimental relations, independent of all considerations about units and systems of measurements, are—

Of electrostatics,	$Q = L\sqrt{(KF)}$	(1)
Of magnetism,	$m = L\sqrt{(\mu F)}$	(2)
Of electro-magnetism,	$mL = \mu AC$	(3)

The last may also be written—

$$m = \mu v Q \quad . . . . (3')$$

in which form it suggests the magnetic action of a moving charge, which Rowland's experiment has established.

Combining the three equations, we deduce—

$$\sqrt{\left(\frac{\mu}{K}\right)} = \frac{m}{Q} = \mu v;$$

whence
$$\mu K = \frac{1}{v^2} = \frac{\text{density}}{\text{elasticity}},$$

the well-known relation connecting the two ethereal constants.

Comparing many electrical equations with corresponding mechanical ones, we find that the product LC takes the place of momentum (mv), and that $\frac{1}{2}LC^2$ takes the place of kinetic energy ($\frac{1}{2}mv^2$), and indeed *is* the energy of a current, see (*f*). Hence it is natural to think of L as involving inertia, and of μ or $4\pi\mu$ as a kind of density of the medium concerned.

Assuming this, $\frac{4\pi}{K}$ at once becomes an elasticity coefficient (as indeed electrostatics itself suggests), because $\mu K v^2 \equiv 1$; and the dimensions of all electrical units can be specified as follows without any arbitrary convention or distinction between electrostatic and electro-magnetic units :—

Sp. ind. cap., K $= \frac{\text{strain}}{\text{stress}} = \frac{\text{area}}{\text{force}} = \frac{LT^2}{M} =$ shearability.

Permeability, $\mu = \frac{\text{inertia}}{\text{volume}} = \frac{M}{L^3} =$ density.

Electric charge, Q $= L^2 = \frac{\text{volume}}{\text{displacement}}$.

Magnetic pole, $m = \frac{M}{T} =$ momentum per unit length.

Electric current, C $= \frac{L^2}{T} =$ displacement × velocity.

Magnetic moment, $ml = \frac{ML}{T} =$ momentum.

E.M.F., E $= \frac{\text{work}}{Q} = \frac{M}{T^2} =$ pressure × displacement, or work per unit area.

Intensity of magnetic field, H $= \frac{F}{m} = \frac{L}{T} =$ velocity.

Intensity of electrostatic field, $\frac{F}{Q} = \frac{M}{LT^2} =$ energy per unit volume.

Surface density, $\sigma = \frac{Q}{A}$ = a pure number.

Electric tension, $\frac{2\pi\sigma^2}{K} = \frac{M}{LT^2}$ = a pressure or tension.

Capacity, $S = \frac{Q}{E} = \frac{L^2T^2}{M}$ = displacement per unit pressure.

Coefficient of resistance, $\frac{E}{C} = \frac{M}{L^2T}$ = impulse or momentum per unit volume.

Magneto-motive force, $4\pi nC = \frac{L^2}{T}$ = current.

Reluctance, $\frac{l}{\mu A} = \frac{L^2}{M} = \frac{\text{area}}{\text{inertia}}$.

Magnetic induction, $N = \frac{M}{T}$ = moment of momentum per unit area

Coefficient of induction (self or mutual), $\frac{N}{C} = \frac{M}{L^2}$ inertia per unit area.

This is an improvement on the rough practical system which assumes as of no dimensions sometimes K, and sometimes μ, according as one is dealing with electrostatics or with magnetism; but very likely it is only a stepping-stone. Prof. Fitzgerald suggested that, regarding everything from the strictly kinematic and ethereal point of view, both K and μ may be a *slowness* of the vorticity; and by that assumption also everything becomes simple and of unique dimensions. Whatever of this turns out true, it is not to be supposed that we can long go on with two distinct systems of units, the electrostatic and the electro-magnetic, and two distinct sets of dimensions for the same quantities; knowing as we do that neither set can by any reasonable chance turn out to be the right one.

[*Added later.*] It must be admitted that in 1900 a different conclusion as regards the dimensions of μ and κ was arrived at by R. A. Fessenden (*Phys. Rev.* 10, Jan. and Feb. 1900). His conclusion was in favour of the other possible alternative—shown by W. Williams to be the only other—namely, the inverse of the above; with κ a density and μ the reciprocal of an elasticity. Such an opinion is subversive of all ideas on the subject advocated in this book; but it is not on that account to be discarded without examination.

Professor Fessenden's argument, however, appears to be based on the fact that the permeability of substances begins to decrease under great magnetic intensity, while the capacity of a condenser does not perceptibly decrease when subjected to great electric force.

I find myself wholly unable to admit the force of this argument. Such change as occurs, occurs only in the presence of *matter*, and can be explained by a simple molecular hypothesis; no change in the value of the ethereal constants themselves has ever yet been proved or even suspected, nor is a variation at all likely to occur under any practicable values of either applied force. The influence of matter is a mere superposition of something imperfect and complicated upon the simple and fundamental properties of the pristine ether; and any deviations from constancy are clearly the effect of matter alone. So I strongly adhere to the "dimensions" recorded in this appendix, as given in 1889.

NEWTON'S GUESSES CONCERNING THE ETHER.

(*q*) Newton's queries at the end of his "Opticks" finish in the early editions with Query 16, and I have found it difficult to come across the later queries except in Latin. I therefore here copy such portions of these queries as have an obvious bearing on our present subject; in order to make them more easy of reference.

"*Qu.* 17. If a Stone be thrown into stagnating Water, the Waves excited thereby continue some time to arise in the place where the Stone fell into the Water, and are propagated from thence in concentrick Circles upon the Surface of the Water to great distances. And the Vibrations or Tremors excited in the Air by percussion continue a little time to move from the place of percussion in concentrick Spheres to great distances. And in like manner, when a Ray of Light falls upon the Surface of any pellucid Body, and is there refracted or reflected, may not Waves of Vibrations or Tremors be thereby excited in the refracting or reflecting Medium at the point of Incidence . . . ?"

"*Qu.* 18. If in two large tall cylindrical Vessels of Glass inverted, two little Thermometers be suspended so as not to touch the Vessels, and the Air be drawn out of one of these Vessels, and these Vessels thus prepared be carried out of a cold place into a warm one; the Thermometer *in vacuo* will grow warm as much and almost as soon as the Thermometer which is not *in vacuo*. And when the vessels are carried back into the cold place, the Thermometer *in vacuo* will grow cold almost as soon as the other Thermometer. Is not the Heat of the warm Room conveyed through the Vacuum by the Vibrations of a much subtiler Medium than Air, which after the Air was drawn out remained in the Vacuum? And is not this Medium the same with that Medium by which Light is refracted and reflected, and by whose Vibrations Light communicates Heat to Bodies,[1] and is put into Fits of easy reflexion and easy Transmission? And do not the Vibrations of this Medium in hot Bodies contribute to the intenseness and duration of their Heat? And do not hot Bodies communicate their Heat to contiguous cold ones, by the Vibrations of this Medium propagated from them into the cold ones? And is not this Medium exceedingly more rare and subtile than the Air, and exceedingly more elastick and active? And doth it not readily pervade all bodies? And is it not (by its elastic force) expanded through all the Heavens?"

"*Qu.* 19. Doth not the Refraction of Light proceed from the different density of this Ætherial Medium in different places, the Light receding always from the denser parts of the Medium? And is not the density thereof greater in free and open Space void of Air and other grosser Bodies, than within

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[1] Note the precision and propriety of this phrase: far superior to most of the writing on the subject of absorption of radiation during the present century. It could only be improved by substituting *generates in* for "communicates to," in accordance with the modern kinetic theory of heat.

the Pores of Water, Glass, Crystal, Gems, and other compact Bodies?"[1]

"*Qu.* 21. Is not this Medium much rarer in the denser Bodies of the Sun, Stars, Planets, and Comets, than in the empty celestial Spaces between them? And in passing from them to great distances, doth it not grow denser and denser perpetually, and thereby cause the gravity of those great Bodies towards one another, and of their parts towards the Bodies; every body endeavouring to go from the denser parts of the Medium towards the rarer? For if this Medium be rarer within the Sun's Body than at its surface, and rarer there than at the hundredth part of an Inch from its Body, and rarer there than at the fiftieth of an Inch from its Body,[2] and rarer there than at the orb of *Saturn*; I see no reason why the Increase of density should stop anywhere, and not rather be continued through all distances from the Sun to *Saturn*, and beyond. And though this Increase of density may at great distances be exceeding slow, yet if the elastic force[3] of the medium be exceeding great, it may suffice to impel Bodies from the denser parts of the Medium towards the rarer, with all that power which we call Gravity. And that the elastick force of the Medium is exceeding great, may be gathered from the swiftness of its Vibrations. Sounds move above 1140 English Feet in a second Minute of Time, and in seven or eight Minutes of Time they move about one hundred English Miles. Light moves from the sun to us in about seven or eight Minutes of Time, which distance is about 70,000,000 English Miles, supposing the horizontal Parallax of the Sun to be about 12″. And the Vibrations or Pulses of this Medium, that they may cause the alternate Fits of easy Transmission and easy Reflexion, must be swifter than Light, and by consequence above 700,000 times

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[1] In Newton's opinion light travelled quicker in gross matter than in space, and thence it is that he inverts our Fresnel-derived views. He continues the same inversion in his query concerning gravitation, here next following.

[2] It was his experiments in diffraction which made him think of this gradual change in the properties of ether as one recedes from a body.

[3] Meaning what we call the pressure. Maxwell has estimated that a distortional pressure of 37,000 tons to the square inch is needed to account for terrestrial gravity. See (*r*) below.

swifter than Sounds. And therefore the elastick force of this Medium, in proportion to its density, must be above 700,000 × 700,000 (that is, above 490,000,000,000) times greater than this elastick force of Air is in proportion to its density. For the Velocities of the Pulses of Elastick Mediums are in a subduplicate Ratio of the Elasticities and the Rarities of the Mediums taken together." . . .

"*Qu.* 22. May not Planets and Comets, and all gross Bodies, perform their motions more freely, and with less resistance in this Æthereal Medium than in any Fluid, which fills all Space adequately without leaving any Pores, and by consequence is much denser than Quick-silver and Gold? And may not its resistance be so small as to be inconsiderable? For instance; if this Æther (for so I will call it [1]) should be supposed 700,000 times more elastick than our Air, and above 700,000 times more rare; its resistance would be above 600,000,000 times less than that of Water. And so small a resistance would scarce make a sensible alteration in the Motions of the Planets in ten thousand Years. If any one would ask me how a Medium can be so rare, let him tell me how the Air in the upper part of the Atmosphere can be above an hundred thousand times rarer than Gold. Let him also tell me how an electrick body can by Friction emit an Exhalation so rare and subtile, and yet so potent, as by its Emission to cause no sensible Diminution of the weight of the electrick Body, and to be expanded through a Sphere whose Diameter is above two Feet, and yet to be able to agitate and carry up Leaf Copper, or Leaf Gold, at the istance of above a Foot from the electrick Body?

"*Qu.* 23. Is not Vision performed chiefly by the vibrations of this Medium?" . . .

THE ETHER AND GRAVITATION.

(*r*) To illustrate what has been said in Chapter XVII, Lecture 2, Lecture 5, and elsewhere, concerning a probable explanation of gravitation by a stress in the Ether, the following quotation

[1] The interest of these extracts lies largely in their belonging to the very early days of the conception of an ether, and in their remarkable insight into many things, though in detail they often do not completely accord with present knowledge.

from Clerk Maxwell's article "Attraction" in the *Encyclopædia Britannica* may be useful:—

"To account for such a force by means of stress in an intervening medium, on the plan adopted for electric and magnetic forces, we must assume a stress of an opposite kind from that already mentioned [cf. § 92 above]. We must suppose that there is a pressure in the direction of the lines of force, combined with a tension in all directions at right angles to the lines of force. Such a state of stress would, no doubt, account for the observed effects of gravitation. We have not, however, been able hitherto to imagine any physical cause for such a state of stress. It is easy to calculate the amount of this stress which would be required to account for the actual effects of gravity at the surface of the earth. It would require a pressure of 37,000 tons' weight on the square inch in a vertical direction, combined with a tension of the same numerical value in all horizontal directions. The state of stress, therefore, which we must suppose to exist in the invisible medium, is 3000 times greater than that which the strongest steel could support."

Other Possible Functions of the Ether.

(*s*) Several physicists have held that the ether probably has some psychological significance; and now that it is turning out to be so extraordinarily massive and substantial a reality, it is unlikely that its psychical significance should be in any way inferior to the admitted psychical significance of the infinitesimal fraction of it which appeals to our present senses as "matter."

I shall therefore quote from Clerk Maxwell and from G. F. FitzGerald: premising that the ideas involved or wrapped up in these quotations should be understood in the largest and most serious sense possible.

From Clerk Maxwell's *article "Ether" in the* Ency. Brit.

"Whether this vast homogeneous expanse of isotropic matter is fitted not only to be a medium of physical interaction between distant bodies, and to fulfil other physical functions of which, perhaps, we have as yet no conception, but also, as the authors of '*the Unseen Universe*' seem to suggest, to constitute the material organism of beings exercising functions of life and mind as high or higher than ours are at present, is a question far transcending the limits of physical speculation."

From G. F. FitzGerald's "*Helmholtz Memorial Lecture.*"

"As we then follow out the directions pointed out by Helmholtz's work, we cannot help being impressed with how far ultimate explanations of nature lead us closer and closer to the conclusion that these phenomena of our consciousness are all explicable as differences of motion. It is the motion which is imposed upon us. Is there not, then, reason in the suggestion that colour and sound, nay, space, time, and substance are functions of our consciousness, produced by it under the action of what may be called an external stimulus, and that the only part of the phenomenon which essentially corresponds to that stimulus is the always pervading motion? And what is the inner aspect of motion? In the only place where we can hope to answer this question, in our brains, the internal aspect of motion is *thought.* Is it not reasonable to hold, with the great and good Bishop Berkeley, that thought underlies all motion? A purely rational machine might get on very well through the world without believing that other brains than his own had underlying thoughts. It is the position of the consistent Positivist. To him nature is what others would call a consistent dream. Such a position posits nothing that is not positively felt. It is consistent, but inhuman. For human life we require sympathy and affection. For the highest life we require the highest ideal of the Universe to work in. Can any higher exist than that, as language is a motion expressing to others our thoughts, so Nature is a language expressing thoughts, if we learn but to read them? May we not hope that studies of physiological actions, of chemical constitution and change, of vortex motion, of the laws of matter and ether, may some day enable us to discover the motions in our brains underlying sound and light, and smell and touch, and pain and pleasure, hate and love? And may we not hope, then, to be able to form some dim analogies by which we may divine what underlies the much more complex motions of organic nature as a whole, and have a scientific basis for investigating what underlies the whole sequence of organic evolution?"

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