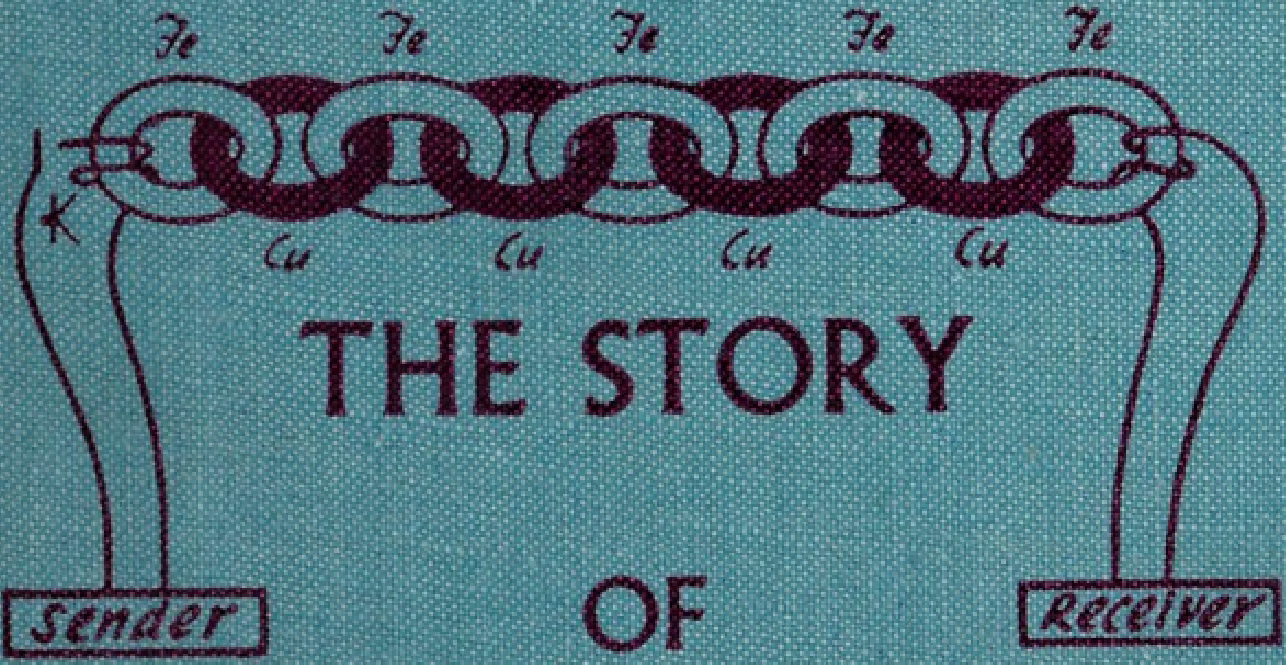

THE STORY OF ELECTROMAGNETISM

BY

SIR WILLIAM BRAGG

THE STORY OF ELECTROMAGNETISM

By the Same Author

THE UNIVERSE OF LIGHT

CONCERNING THE NATURE OF THINGS

THE WORLD OF SOUND

OLD TRADES AND NEW KNOWLEDGE

G. BELL & SONS, LTD

THE STORY OF ELECTROMAGNETISM

BY

SIR WILLIAM BRAGG

O.M., K.B.E., F.R.S.

LONDON

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PREFACE

EARLY in this year, 1941, it became obvious that there was urgent need for the supply of men in considerable numbers to operate the new technical devices of the war in the air. The men would have to be specially trained, because the principles of the apparatus could not be quickly apprehended, and it could not be handled efficiently without understanding and skill. It was desirable to shorten, if possible, the time spent on training after the men had joined up. For this purpose it was decided to form an Air Training Corps of youths who, while yet under military age, might receive some preliminary training for their subsequent service.

The new devices are mainly of electrical character, particularly those employed in transmission by radio. A large proportion of the fundamental principles on which the modern developments of electromagnetism are based were first investigated and explained in the laboratories and theatre of the Royal Institution. The managers resolved, therefore, to offer their help in the instruction of the new Corps, if it were found possible to contribute any service that might be of use. The offer was accepted, and it was arranged that a certain number of the cadets of the A.T.C. in the London district should attend at the Royal Institution where I should tell them something of the history of the electro-magnetic discoveries on which their future work was to be based. The lecture, which was given on three occasions, is here reproduced with the modifications appropriate to book form.

The lecture is meant to be a sketch of the gradual realisation of the fundamental principles of electro-magnetism, and the successive contributions of the principal discoverers are briefly described. Of course, the final structure is the work of many hands, and the full account would go into far more detail than can be covered in one lecture. Many more workers would be referred to than the few who are mentioned here. But my object is to show how one idea has led to another in a motion which has necessarily been slow because of the intangible character of electricity, and of magnetism. The mutual actions of two intangibles end in a tangible result. Neither electricity nor magnetism can be perceived directly by any human sense, but in combination they affect us in obvious ways every moment of the day. On this account there is a peculiar interest in the study of the methods by which our pioneers gradually unravelled those hidden actions and explained to us the rules on which we build so much.

The history of the discovery may be of no immediate benefit to the operator of radio and other devices, if his work and his thoughts are confined to the management of his instruments. Most operators do, however, find pleasure and help in learning about the evolution of the tools they are using. I hope that this small book may provide the necessary historical material. But I have further hopes. There will certainly be some among the youths now in training who will like to get down to fundamentals. If they do, they have the greater chance of understanding and even of suggesting new developments. This is important, because a combination of fundamental knowledge with immediate and continuous application in practice is the most fruitful source of new ideas, far more effective than either agent by itself. The present wide use of science in the war is enforcing the recognition of this major principle: it cannot be forgotten in the time to come.

As many as possible of the illustrations in the book are reproduced from drawings in the original papers. It seems to put the reader in touch with the discoverer if he sees before him the drawing which accompanied the first laboratory note or published paper. The little sketches that illustrate Faraday's work are copied from the originals in the margin of his Diary.

PREFACE

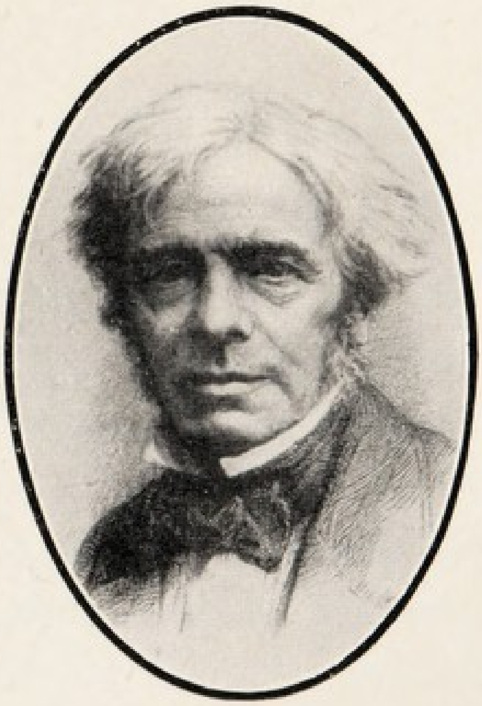
The chain of alternate links of copper and iron is an imaginary device which I have found useful when trying to explain the main principles of electromagnetism, since all those principles are separately and clearly in action when a pulse bearing energy travels along the chain. I hope it may be of service once again.

W. H. B.

VOLTA
AMPERE

OERSTED
OHM

The portraits of Oersted, Ampere and Ohm are reproduced from F. Grassi, *La Fisica e l'Elettrotecnica*, Milan, and that of Volta from *L'opera di Allessandro Volta*.



DAVY
CLERK-MAXWELL

FARADAY
HERTZ

The portraits of Davy and Faraday are reproduced by courtesy of the Managers of the Royal Institution, that of Clerk-Maxwell from *The Life of Clerk-Maxwell* by L. Campbell and W. Garnett (Macmillan), and that of Hertz from *The Work of Hertz* by Sir Oliver Lodge ("Electrician").

I

THE gradual unravelling of the laws of electromagnetism during the last hundred and fifty years has been one of the most wonderful scientific achievements of all time. In the pioneering discoveries of Volta and Oersted there was nothing to suggest the magnitude of their consequences. But Ampere, Arago, Ohm and Davy developed them ; Faraday followed with his epoch-making experiments : Clerk-Maxwell gave mathematical form to Faraday's discoveries and unfolded the theory of the electromagnetic wave of which light is an example. The distribution and use of power by electromagnetic machinery have been the work of many well-known men of recent years. And now electromagnetism is used in nearly all our enterprises small and great, from the ringing of a bell or the driving of a sewing-machine to the movements of ships and trains and the illumination of cities. One of the most strange of all its uses is that which we now speak of as radio or broadcasting : few developments have made such a stir, either in peace or in war. Many of those for whom this little book is especially intended will be engaged, when they enter on their war service, in operations which are based on the electromagnetic laws, the transmission of intelligence by wireless being one of the most important of them.

The transmission of power and signals through great distances either by wire and cable, or through open space never ceases to be a marvel. It is true that we have a precedent in the use that the natural world makes of light and heat which traverse space in the form of waves that are in fact electromagnetic as we shall see later. Our eyes are receivers fitted to detect and analyse the waves of light. Many of the processes of Nature depend on the transmission of energy in the form of heat. But the modern use of the electromagnetic wave finds no response in the human body: no sensory organ is fitted to detect the waves that we employ in broadcasting. Indeed, we cannot directly see or feel or hear either electricity or magnetism, nor any electromagnetic action. It is this which adds particular interest to the story of the gradual development of our understanding of the fundamental principles; we cannot but admire the patience and reasonings of those who explored the new country in which the usual means of the pioneer failed them and none of the discoveries could be expected nor even guessed at.

I propose in what follows to describe briefly the several steps in the advance towards the present understanding. Since the advance has been so long and difficult it might seem to be over-ambitious to attempt such a description. But the terms in which the fundamental principles can be expressed are not difficult in themselves: it was their discovery that was difficult because the way towards them was so blind. At every step the explorer had many ways along which he might make his next move, and the novelty was so great that forecasting was impossible. So a multitude of trials and much thought were required to keep on the right way. Now that the search—up to the present point—is over, it is comparatively simple to look back and observe the details of the road.

Before I begin the story let me describe the present position and set out the four fundamental principles on which electromagnetism is based. We can then look back and observe at which stage each of the principles came to be recognised. In this peculiar case it is justifiable to look at the end of the book before beginning to read it.

The statement of the four principles requires the use of terms which may not be familiar unless experiment has made them so. But for our present purpose they can be sufficiently explained in simple ways. I have found it convenient to use the description of a certain experiment which can readily be imagined, even if it is never put into practice. Let us imagine a chain made of successive links of copper and iron as in Fig. 1. By this device we can easily represent the four experimental results which are expressed in the four principles.

Let it be possible, by putting down the key at K, to send a current round the first copper link through the action of a battery. The next link, which is made of iron, becomes magnetised. While the magnetism in this link is growing—but not after it has reached

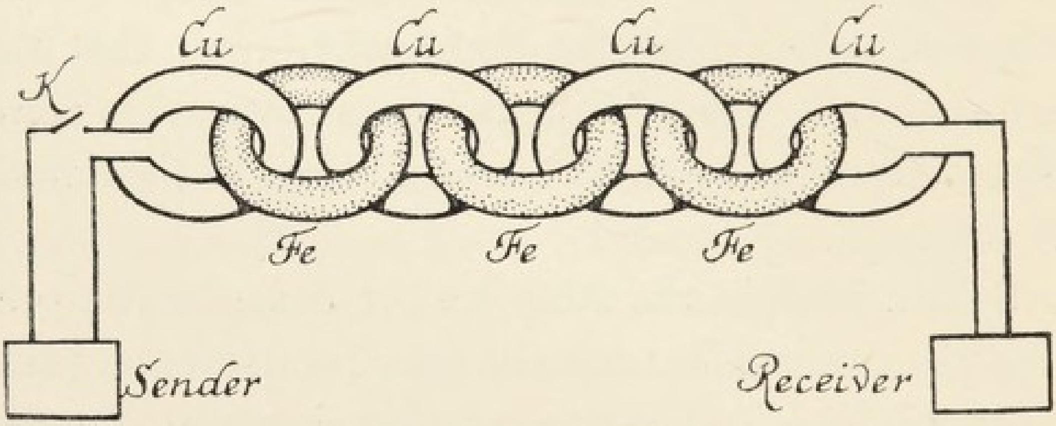


FIG. 1. When the key K is depressed, a source of electrical energy sends a current round the first copper link. This magnetises the first iron link, and the rise of this magnetisation initiates a current in the second copper link, and so on. Hence a pulse runs along the chain and in the end enters the receiver.

its maximum and become stationary—a current is generated in the third link, which is made of copper. Magnetism is then generated in the fourth link made of iron, then current in the fifth link made of copper, and so on to the end of the chain. Thus, however long the chain may be, a pulse travels to the far end of it. This is the prototype of all electromagnetic methods of distributing power, especially in alternating current form, and of wireless transmission.

Now let us look at these actions more closely.

1. The current in the copper link produces magnetism in the iron link next to it. That is the first of the four principles. But the amount of magnetism produced is not determined by the magnitude of the current alone. The amount depends on what the ring is made of: it depends on the nature of the iron or steel; it would be very much less—though not zero—if the ring were made of brass or wood. In fact there is an effort to produce magnetism and it is this effort which is proportional to the current, not the magnetism produced; the success of the effort depends on the material on which it acts. We call the effort "magnetomotive force." It is not a very apt term, but it serves its purpose. The first of the four principles is then :—

Moving electricity exerts magnetomotive force.

2. The magnetomotive force acts on the iron ring and produces an effect. We say that the iron ring is magnetised. If it were cut anywhere one of the two exposed ends would be a North pole and the other a South pole. This effect is measurable in amount and can be expressed in terms of a unit. If

the ring were made of wood or brass or even if there were no ring at all an effect would still be there : though much smaller in amount. Its presence in the latter case can be made evident in the usual way by the disposition of iron filings scattered in the space about the copper ring in which the current is running. We call the effect " magnetic induction ". Thus we have the second fundamental principle :—

Magnetomotive force tends to cause magnetic induction, the result depending on the opposition it encounters.

3. While the induction is growing in the iron ring under the influence of the magnetomotive force, a force is exerted in the third link made of copper, which tries to set electricity on the move through that link : it is described as electromotive force. It is only during the growth of the magnetic induction in the iron ring that the force is exerted : as soon as the induction has reached its maximum value the electromotive force ceases. The growth of the induction may be described as a movement of magnetism, which does not seem an appropriate term, but it is used because the same effect is produced if a magnet is actually moved about near the copper link and the same term serves to denote not only this motion but also the production of magnetic induc-

tion *in situ* as in the links of the chain. Thus we come to the third principle :—

Moving magnetism causes electromotive force.

4. The electromotive force produces a motion of electricity in the second copper ring. There will be a current the magnitude of which depends not only on the amount of electromotive force but also on the resistance which the material of the copper ring offers to the flow of the current. The fourth fundamental principle is :—

Electromotive force tends to cause electric current, the result depending on the opposition it encounters

Thus there is a complete cycle :—

Moving electricity causes magnetomotive force :
Magnetomotive force causes magnetic induction :
Changing or moving magnetic induction causes electromotive force :
Electromotive force sets electricity in motion :
And then begin again.

The symmetry of this statement is apparently disturbed by the use of the term " magnetic induction " in the second principle as against " electricity-in-motion " in the fourth, but, as we shall see later, the phrase " causes electric induction " could be used instead of " sets electricity in motion ", and would indeed be more accurate. We can conveniently leave this point for the present.

All the uses of electromagnetism are based on these four principles, which are continuously active in regular succession. Details vary greatly. For instance, in the transmission of power the copper link has become an electric cable of indefinite length, and the first movement of electricity may be caused by some other agency than a battery. In wireless transmission the metallic chain links may be replaced by what we call the immaterial ether ; at first sight a difficult conception ; but the way in which this happens will be clear, I hope, before we have done.

Let me repeat that as soon as the current in the first copper link has become established, and no longer varies in amount, as soon therefore as the magnetisation of the first iron link has become steady, there is no further transmission of a pulse along the chain. It is only when the magnetism in the iron link is altering that an electromotive force is excited in the next copper link. If the current once established is brought to zero, or is reversed, another pulse will be set off on its way along the chain : and so by continual reversals a series of pulses runs along like a set of waves.

Now let us go back to the beginning of the story and follow the course of discovery, observing so far as is possible the events which led up to the recognition of each of the four fundamental principles in turn.

II

THE first principle was established by Oersted the Dane; and he was able to make it because Galvani and Volta had already made observations from which it was possible to conceive the movement of electricity in the form of a current along a metal wire. No one, of course, had perceived electricity: it was known only that something was transmitted by the wire and it was natural to say that electricity moved, although the sense in which it moved was entirely arbitrary.

Galvani observed that the muscles of a frog's leg were set into action by the discharge of electricity generated by the frictional machine. The muscles were also affected when the body of the frog lay on a metal plate and the scalpel, penetrating the nerve, touched the plate. This was in 1780. Volta supposed that in the latter experiment the fact that there were two metals involved in it was somehow important. He knew also that when two metal plates such as copper and zinc were placed one above the tongue and the other below it and were made to touch each other, there was a sharp taste in the mouth. Following up this idea he made a pile consisting of plates of zinc, silver and wads of cloth dipped in brine, arranged in regular order—zinc, silver, wad, zinc, silver, wad, and so on. By attaching wires to a zinc plate at one end of the pile and a silver plate at the other he could repeat Galvani's observations with much greater effect. Fig. 2 shows the arrangement. A pile constructed

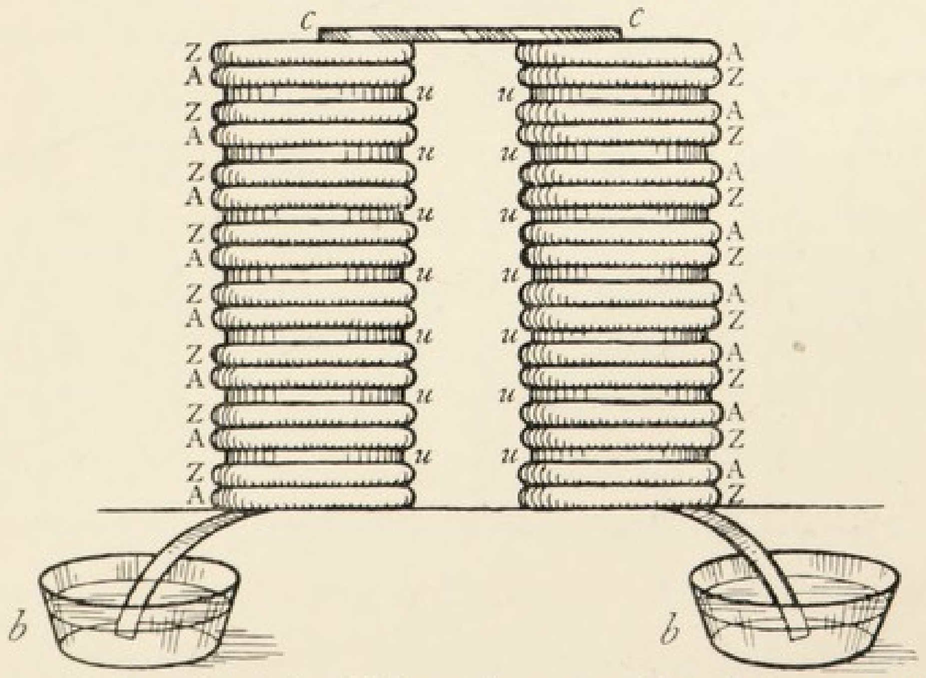


FIG. 2. A drawing of a Volta pile, reproduced from an illustration on p. 262 of the collection of Volta's papers published by the Italian Electrotechnical Association under the title "L'opera di Alessandro Volta." (Z=zinc; A=silver; *u*=umida (damp)).

by Volta and presented by him to Faraday is still preserved at the Royal Institution. Volta varied the construction by substituting glass cups containing brine or weak acid for the wads of damp cloth; the copper and zinc plates remained as before, but were now dipped into the cups. This was Volta's

" Crown of cups ", the obvious precursor of the electric battery. See Fig. 3. Copper could take the place of silver.

Volta's experiment roused great interest. Napoleon heard of it and invited him to Paris in 1801. Volta gave an account of it in a letter which he wrote

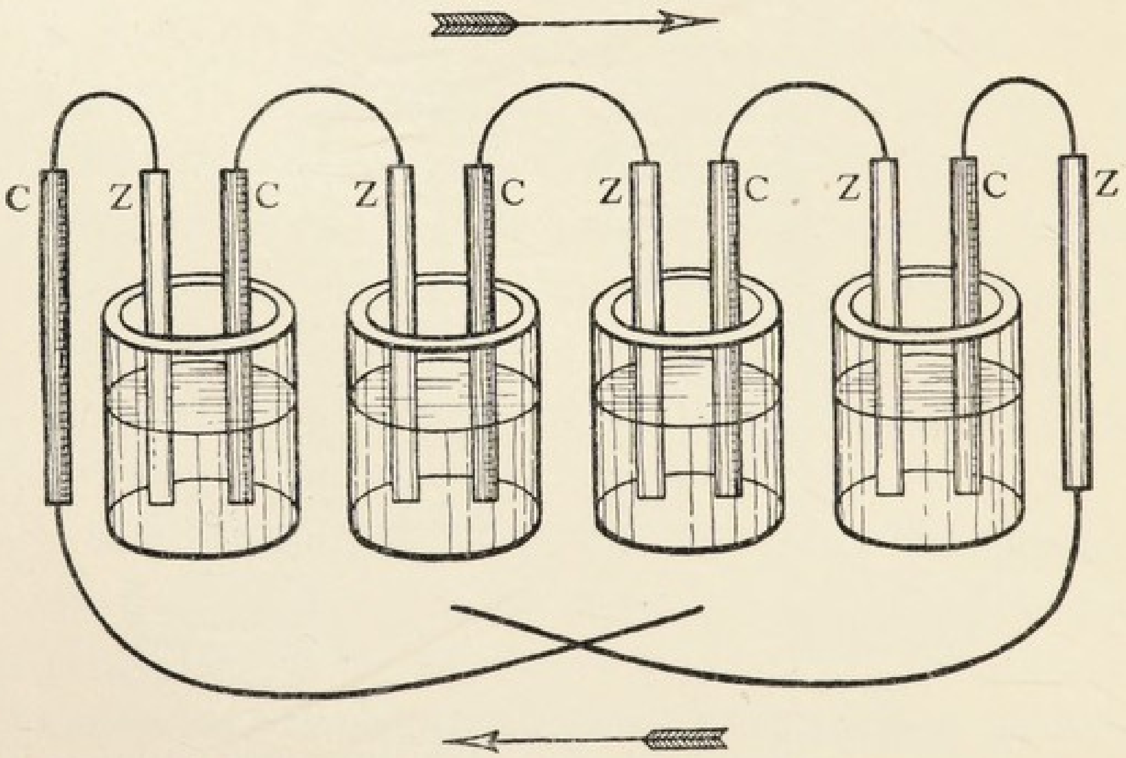


FIG. 3. The arrangement of Volta's electric battery; sometimes called Volta's " Crown of cups." The drawing is taken from Noad's Electricity (1843).

in 1800 to Sir Joseph Banks, then President of the Royal Society of London, who caused it to be published in the Royal Society's Transactions. The contents of the letter were communicated to other London scientists and philosophers, as they were then called, who eagerly constructed Volta's piles and batteries and tried new experiments for themselves. In particular Nicholson and Sir Anthony Carlisle showed that when the ends of the two wires were both immersed in a vessel containing a weak solution of an acid, but without touching one another, hydrogen bubbles appeared on one of the wires and oxygen on the other. Nicholson was the editor of a scientific magazine and published in it the account of these experiments (*Nicholson's Journal*, July, 1800).

It is to be remembered that at this time and for twenty years afterwards there was no such thing as a galvanometer. Such effects as I have just described were the only indication of the so-called " electric current ". At the Royal Institution frogs for experimental purposes are said to have been kept in a basement room, known for long afterwards as the Froggery. When it became necessary to reconstruct parts of the Institution buildings the place of the Froggery and the memory of its use were preserved by letting into the floor a small brassplate shaped to the outline of a frog.

Electromagnetism had not yet appeared in any form, but these experiments paved the way for it. Before we follow up the main story it is interesting to turn aside for a moment in order to consider one other notable experiment of that time. Sir Humphry Davy was then the Director of the Royal

Institution. In 1807 he repeated in effect the Nicholson and Carlisle experiment, but he substituted moistened potash for the water. With this he filled a small glass cup, through the bottom of which a wire was inserted making contact with the potash inside. The latter was moistened with water

Oct. 19, 1807

When Potash was introduced into a tube having a platina wire attached to it so and fused into the tube so as to be a conductor, i.e. so as to contain just water enough though solid and inverted over mercury, when ye Platina was made neg—no gas was formed and the mercury became oxydated.

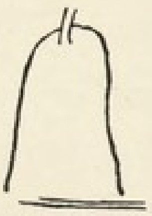


FIG. 4. A few lines, with a copy of the original sketch, from the diary of Sir Humphry Davy: part of his description of his great experiment of the separation of potassium from potash by electrolysis.

and the whole was inverted over mercury as in Fig. 4. When the connections were made so that current from the battery ran through the mercury to the potash and then out by the wire, a glow was observed on the wire. Davy rightly interpreted this as being due to the combination of potassium—which the current had separated from the other constituents of potash—with the oxygen in the water. The potash molecule had been broken, which was indeed a " capital experiment ", as Davy proudly described it in his diary. It will be remembered that the idea of atomic combinations, then being taught by John Dalton, was the subject of eager discussion, and the separation of the potassium metal from a compound called potash was a most important event. This experiment and others of like kind were the beginnings of electrochemistry which is therefore older than electromagnetism.

III

THE experiment which led to the establishment of the first of the four electromagnetic principles was made in 1819. Professor Oersted of the University of Copenhagen was lecturing on the discoveries of

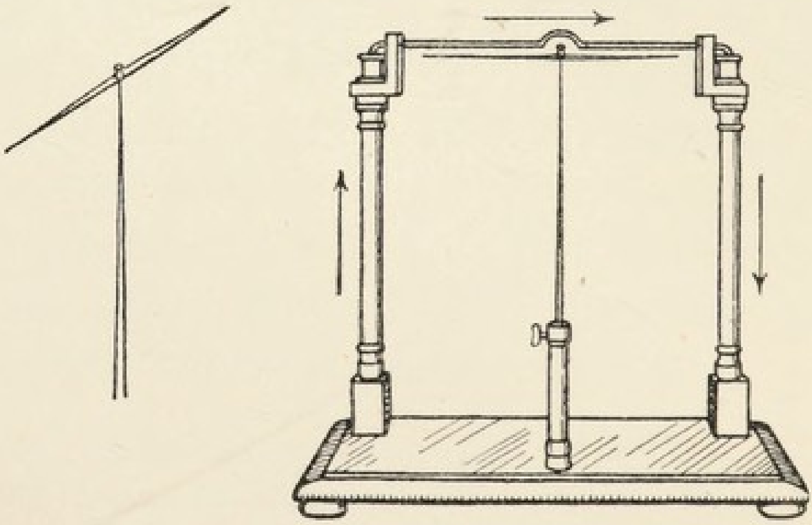


FIG. 5. A drawing from Noad's Electricity, illustrating Oersted's experiment. The elaborate form of the apparatus represents the attention given to what was at one time a new and surprising effect.

Galvani and Volta and had on his lecture table a battery such as Volta had described. He had also by him a magnet swinging on a pivot. What he had been doing with it during the main part of the lecture we do not seem to know, but at the end, one of his colleagues tells us, he said that as there was a battery in action he would try whether anything happened if he put the current-carrying wire close to the needle and *parallel* to it. To his surprise and that of his audience the needle moved in the way that is familiar to us all. It moved away from the parallelism with the wire and set itself more or less across it. This was the first demonstration of the action of a current on a magnet.

It may seem very surprising that this action had not been discovered long before 1819. For twenty years batteries had been made and used in such experiments as those of Nicholson and Davy. Wires carrying electric currents were familiar to many experimenters: so were magnets. Why was this apparently obvious connection so long unknown?

There were perhaps two reasons. In the first place the experience of the time did not suggest any such action, rather the contrary. In those days when electrostatic machines were so well known and the effects of electric charges so much studied, it can hardly have escaped notice that a charged body had no effect on a magnet and that a piece of steel charged up in the same way whether it was magnetised or not. There is in fact no relation between magnetism at rest and electricity at rest. The electricity must be set in motion if it is to exercise magnetomotive force: and that is what Oersted at last discovered.

In the second place the character of the action must have been a complete surprise. Philosophers were familiar with the idea of action across space, as when the sun attracts the earth, or a magnet attracts or repels another magnet, or an electric charge attracts or repels another charge. But in all these cases the force that attracts or repels acts along the line joining the two sources of the force. Here was something quite new: the current moved the magnetic pole—not in a line joining the pole to any point on the wire but *sideways*. To us the action is so familar that it is difficult for us to realise how startling and unbelievable it must have been when it was first observed. It is possible to recapture the sensation when we observe, especially for the first time,

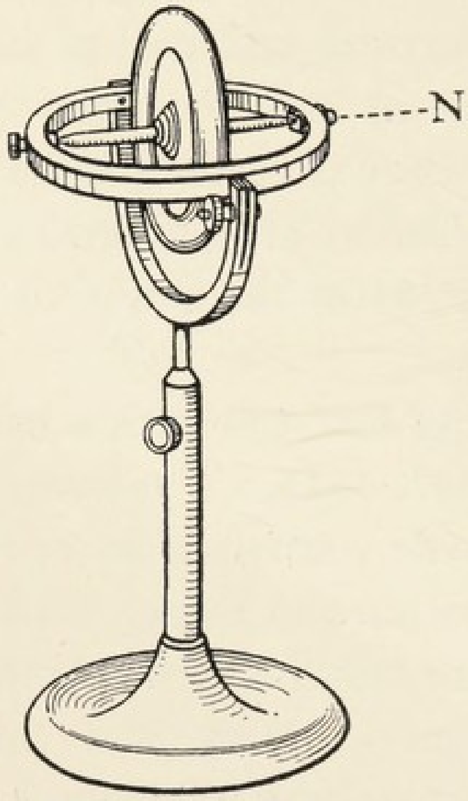


FIG. 6. A gyrostat. The wheel in the centre is made to spin rapidly. The mounting is such that the axis of the wheel can take up any direction. If force is applied at N in a direction which is horizontal and at the same time perpendicular to the axis, the point N does not so much yield in the direction of the force as rise or fall vertically, that is to say at right angles to the applied force.

the so-called gyroscopic action. A heavy wheel is set spinning on a horizontal axis, and the whole—wheel, axle and bearings—is mounted in gimbals on a stand so that it can be turned round a vertical axis. If now one applies a force to one end of the axis of spin, it tends to move sideways, rather at right angles to the direction in which the force is applied than along that line. To anyone who tries this for the first time the effect is a great surprise. It can, of course, be explained on dynamical principles. If anyone at that time did try whether a wire carrying a current acted on a magnet he would look for an attraction between the wire and the magnet as a whole, drawing the two together or pushing them apart. There is actually a relatively small indirect effect of this kind as we shall see in a moment, but it could easily be missed.

Oersted's discovery set many enquiries on foot. In France Ampere made a considerable advance when he showed that a wire carrying a current had all the properties of a magnet. It could attract or repel another current-carrying wire. When some objected that this effect of current on current could have been at once deduced from Oersted's experiment without further trials, he drew—it is said—two keys from his pocket. Each could move a magnet mounted on a pivot but they had no action on each other. Ampere investigated the whole subject of the mutual action of two wires carrying current. It was right to recognise the fundamental importance of his work by using his name to denote the unit of current.

The French philosopher Arago showed that a wire

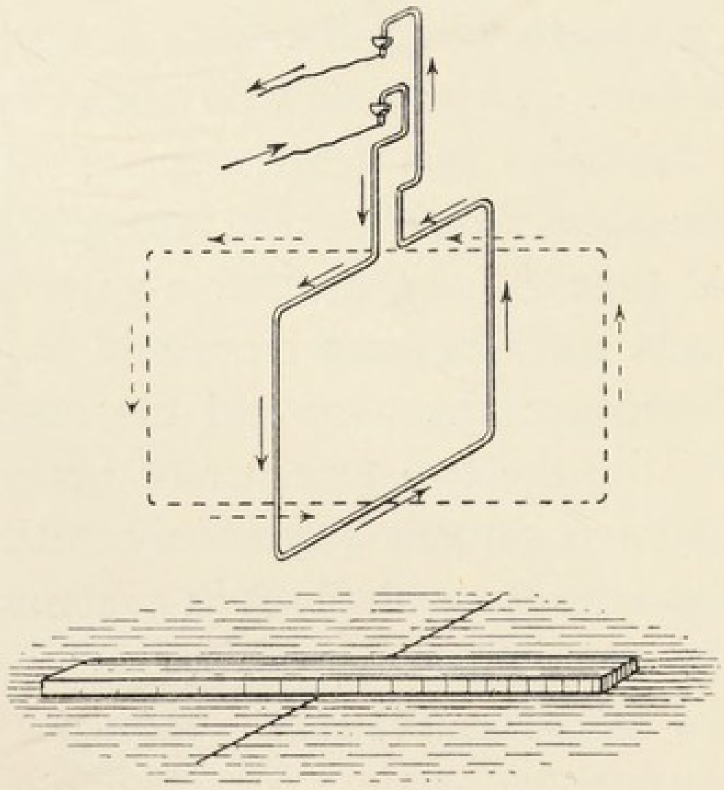


FIG. 7. The figure shows a form of Ampère's experiment, which is the converse of Oersted's. It is reproduced from Guillemin's Forces of Nature. The magnet is at rest on the table. The loop carrying the current sets itself at right angles to the magnet.

carrying a current could not only move a magnet, but could also magnetise a piece of iron. In England, Sir Humphry Davy pointed out that this explained the behaviour of iron filings scattered on a piece of paper pierced by a wire carrying a current; the wire being perpendicular to the paper. The filings arranged themselves in roughly formed circles round the wire. As Davy said, the filings became small magnets under the influence of the current, and fitted themselves together head to tail. The

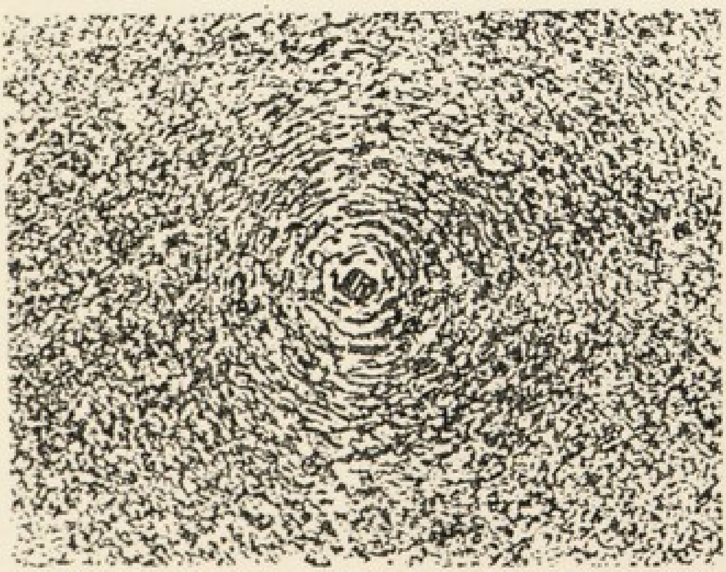


FIG 8. Iron filings arranged round a wire carrying a current. From an entry in the later pages of Faraday's diary. (Vol. VI, Plate II.)

arrangement is illustrated in Fig. 8, which is a copy of a record made by Michael Faraday, who was then Davy's assistant.

Faraday was himself deeply interested in the curious relation between electric current and magnet: his notebook contains a detailed account of all the experiments he made. He arranged a vertical wire to carry a current, and placed nearby a small magnet needle. It was not mounted on a pivot as a magnet is ordinarily mounted, because that mounting would have prevented any movement of the magnet as a whole. It was suspended by a long thread. He placed the magnet in all sorts of positions with relation to the wire and observed the effects. Some of these were merely repetitions of Oersted's original experiment in different forms. He found that if the centre of the magnet was close to the wire and east or west of it the needle as a whole was attracted or repelled. If the direction of the current was reversed so also were the effects. In the end he saw that no other explanation was wanted than that with which we are now familiar, viz. that the current tries to move the magnet pole at right angles both to itself and to the shortest distance from itself to the pole. The force falls away as the distance increases.

It followed from this that it might be possible to make one pole revolve continuously round a current, if it need not drag the other pole after it: for, of course, the effects on the two poles are equal and opposite. This Faraday achieved by the method shown in Figs. 9*a*, *b*, *c*. The current in Fig. 9*a* runs up through the vertical wire after entering by way of the mercury without passing close to the lower pole of the magnet which is submerged and loosely tethered at the bottom of the cup. The

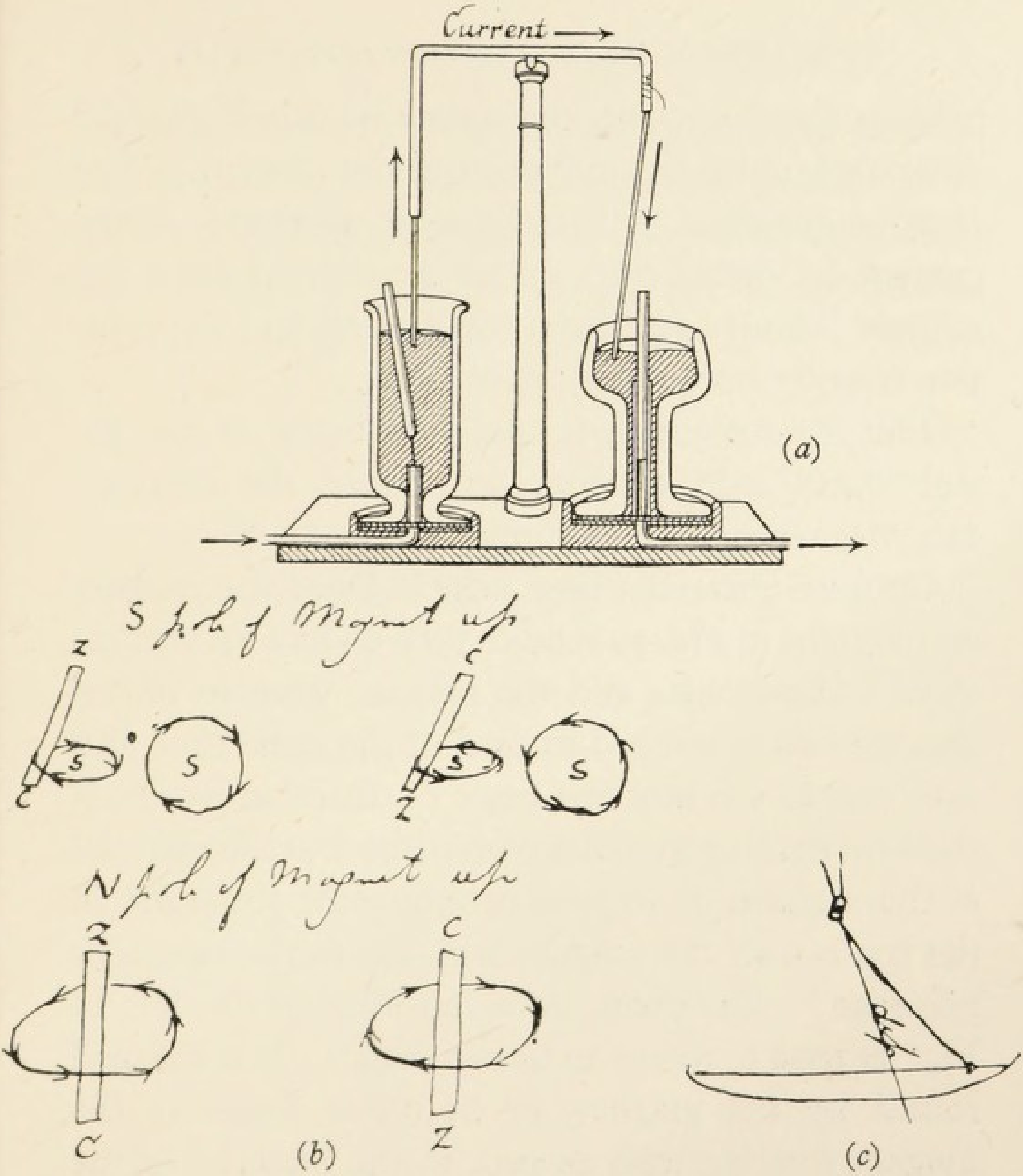


FIG. 9. (*a*) A drawing of apparatus showing a magnetic pole revolving about a current, and a current about a pole. (*b*) One of the sketches in Faraday's diary (Vol. I, p. 51) showing the directions of the rotations of the magnet pole round the wire, and vice versa. (*c*) Rotation of a wire in the earth's magnetic field. A wire carrying a current is suspended by a loose linkage at its upper end; the lower end dips into mercury and is buoyed up by a fragment of cork to prevent it sinking too far. The wire revolves round the line of magnetic dip. (Vol. I, p. 63.)

magnet floats upright, the upper pole being in the open and under the influence of the current. The rotation imagined by Faraday is set up as soon as the current is turned on : under centrifugal force the magnet swings away from the vertical and the rotation thereby becomes more obvious.

The reverse action is easily arranged as on the right-hand side of Fig. 9*a*. Here the current-carrying wire revolves round the magnet.

Curious questions now arise. Does the magnet on the right in Fig. 9*a* tend to turn on its own vertical axis ? If the wire and the magnet were so linked that they were obliged to turn at the same time and rate, would the motions cease ? In other words, is the wire tending to rotate with respect to the material of the magnet, or with respect to some condition in the space near the magnet and due to the magnet's presence ? Or, again, does the wire on the left in Fig. 9*a* tend to rotate on its own axis ? Is it dragged round by the magnet, or in other words is the magnet rotating with respect to the material of the wire or with respect to the current inside the wire and the conditions which it creates in surrounding space ?

All these matters had to be investigated by experiment : we know the answers now and the questions do not trouble us. But it took a long time for Faraday to work his way through all the possibilities.

We know now that the primary actions are electric and magnetic, and that the material bodies which carry the electric and magnetic inductions move only when their motion gives opportunity for the inductions to act and react on each other.

IV

In the period from 1819 to 1831, the latter being the date of Faraday's great experiment which established the third of the four laws stated above, Faraday tried more than once to discover a certain parallelism between electricity and magnetism, the existence of which seemed to be likely. It can be put very simply. A piece of iron placed alongside a magnet becomes magnetised. Will a wire capable of carrying a current be made to do so by placing it alongside another wire carrying a current? Twice he tried this and similar experiments: he describes the results in his diary. They were decidedly negative. Yet he might have discovered then the effect that he found later. His two wires lay side by side, not touching. One was connected to a battery, the other to a galvanometer. When he completed the circuit containing the battery there would actually be a momentary electromotive force in the wire connected to the galvanometer, and if the latter connections were complete there would be a momentary indication of current by the galvanometer. He noticed nothing of this kind: it may well have been too weak to see, or he may not have been looking at the right moment, or he did not join up the galvanometer circuit until after he had completed the other and the current had reached its full value, which it would do in a very short moment. Anyhow, he failed at that time to find the analogy he sought.

On August 29, 1831, he was successful. He used

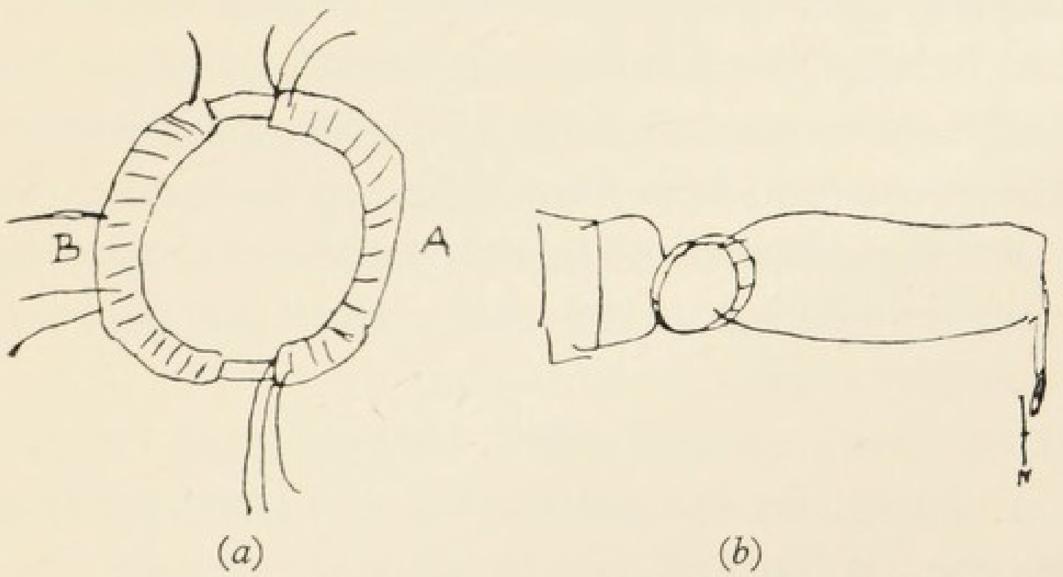


FIG. 10. Sketches from the Diary (Vol. I, p. 367), showing (*a*) the ring used on Aug. 29, 1831, (*b*) the effect on a magnet of a helix through which the current from the B side of the ring is made to run, when the A side is alternately connected with the battery and disconnected. The battery is on the left: the ring next and the small helix roughly drawn is close to the needle marked N.

an arrangement which would certainly give a very much larger effect than any that the two parallel wires could have given. He took a soft iron ring and wound various coils of copper wire on it: the original ring is shown in Fig. 10*a*. He began his experiments on that day by coupling them up in a manner described in the subjoined extract from his diary. It was as if there were two independent coils on the ring, one joined to a battery, the other to a galvanometer. If the galvanometer circuit were the first to be completed there would be a momentary current in it when the battery circuit was completed and the current began to flow. It may have been that in his first trials he again missed the effect, but he did observe it and recorded the result in his diary. The event is so important, being in fact one of the great experiments of electromagnetism, that his entry may be repeated in full. Here it is :—

Aug. 29th, 1831.

1. Expts. on the production of Electricity from Magnetism, etc. etc.

2. Have had an iron ring made (soft iron), iron round and 7/8 inches thick and 6 inches in external diameter. Wound many coils of copper wire round one half, the coils being separated by twine and calico—there were 3 lengths of wire each about 24 feet long and they could be connected as one length or used as separate lengths. By trial with a trough each was insulated from the other. Will call this side of the ring A. On the other side but separated by an interval was wound wire in two pieces together amounting to about 60 feet in length, the direction being as with the former coils ; this side call B.

3. Charged a battery of 10 pr. plates 4 inches square. Made the coil on B side one coil and connected its extremities by a copper wire passing to a distance and just over a magnetic needle (3 feet from iron ring). Then connected the ends of one of the pieces on A side with battery; immediately a sensible effect on needle. It oscillated and settled at last in original position. On *breaking* connection of A side with Battery again a disturbance of the needle.

4. Made all the wires on A side one coil and sent current from battery through the whole. Effect on needle much stronger than before.

5. The effect on the needle then but a very small part of that which the wire communicating directly with the battery could produce.

6. Changed the simple wire from B side for one carrying a flat helix and put the helix in the plane of the Mag. Meridian to the west of the S pole of the needle, so as to shew best its influence when a current passed through it—the helix and needle were about 3 feet from the iron ring and the ring about a foot from the battery.

7. When all was ready, the moment the battery was communicated with both ends of wire at A side, the helix strongly *attracted* the needle; after a few vibrations it came to a state of rest in its original and natural position; and then on *breaking* the battery connection the needle was strongly *repelled*, and

after a few oscillations came to rest in the same place as before.

Faraday had learnt in the course of ten years of experiments, his own and others', that the current in the battery circuit A had produced magnetism in the iron ring. He now learnt that while this magnetism was being generated by the rising current there was a temporary current in the circuit which he called B: there must have been a temporary electromotive force to generate it. But when the current and the magnetism had reached their full value there was no longer such an electromotive force. The mere presence of the magnet did nothing: only when the ring was becoming magnetised was the electromotive force excited. Trial showed that a momentary current ran the opposite way when the battery circuit was interrupted or reversed, so that the magnetism was withdrawn from the coil connected to the galvanometer. The surprise was that the primary current and the magnetism which was due to it had to be changing in order to exert any electromotive effect. Stationary magnets or magnetism have no electric effect: just as stationary electricity has no magnetic effect. It is only when magnets or magnetism are moving or changing that they exert electromotive force: and only when electricity is moving that it exerts magnetomotive force. Faraday now understood why previous experiments had been unsuccessful.

The third fundamental principle had now been established and progress in the development of electromagnetism became rapid. It was true that the second and fourth principles still remained to be worked out completely : the part which they played was as yet imperfectly understood. As regards the fourth principle Ohm had published in 1827 a very important set of experiments in which he showed that the relative resistances offered to the passage of electricity by wires of various lengths, diameters and materials could be expressed in simple terms. He showed that there was something measurable which might appropriately be called resistance, as we know it now ; and Ohm's name has very properly been chosen as the name of the unit in terms of which the magnitude of a resistance is expressed. This form of the fourth principle was quite enough for the time being. So also the still imperfect understanding of the second principle was sufficiently formed to allow the electromagnetic experiments to proceed.

Many of these electromagnetic experiments were made by Faraday : they are all recorded in his diary, and in his publications. Although this work of Faraday's fits naturally into our story and indeed plays a leading part in it, other experimenters had been feeling their way along the same lines. In the United States Joseph Henry discovered the third principle at the same time as Faraday, and years before Ampere made an experiment which showed that he had observed the principle in action. This was at Geneva in 1822.

The illustration in Fig. 11 shows an experiment now well known. A bar of iron is inserted in a coil of wire connected to a galvanometer. The bar is held in a position nearly vertical : it is consequently magnetised by the magnetism of the earth. The needle of the galvanometer is at rest, because there is no current : the mere presence of magnetism in the coil has no effect. But when the bar and coil are turned upside down, there is a temporary current. The magnetism in the bar has been reversed, and that is a form of magnetic change ; consequently according to the third principle electromotive force is generated in the coil.

Another famous experiment may be looked on as one of the first conceptions of the dynamo. The underlying idea was that it must be just as effective to move a mass of metal past a magnet, as to move a magnet past a mass of metal ; in either case electromotive force must be generated in the metal. So Faraday made a brass disc revolve between the poles of a magnet. In Fig. 12, which is taken from the diary, the magnet is " the great magnet of the Royal

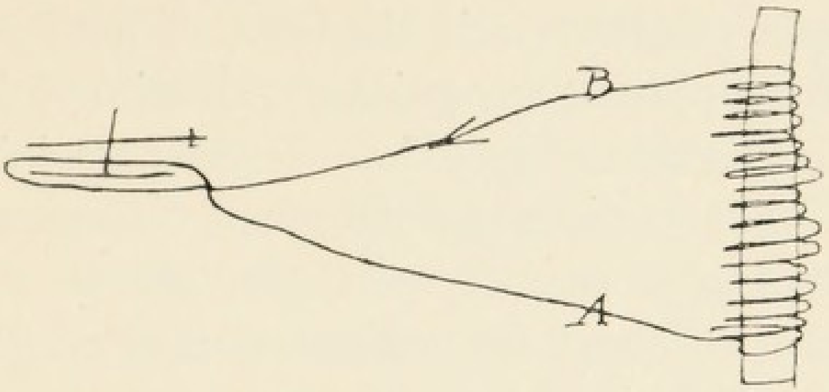


FIG. 11. When the bar of soft iron is inverted the magnetism due to the earth's action is reversed. The induced current affects the magnetic needle. (Vol. I, p. 396.)

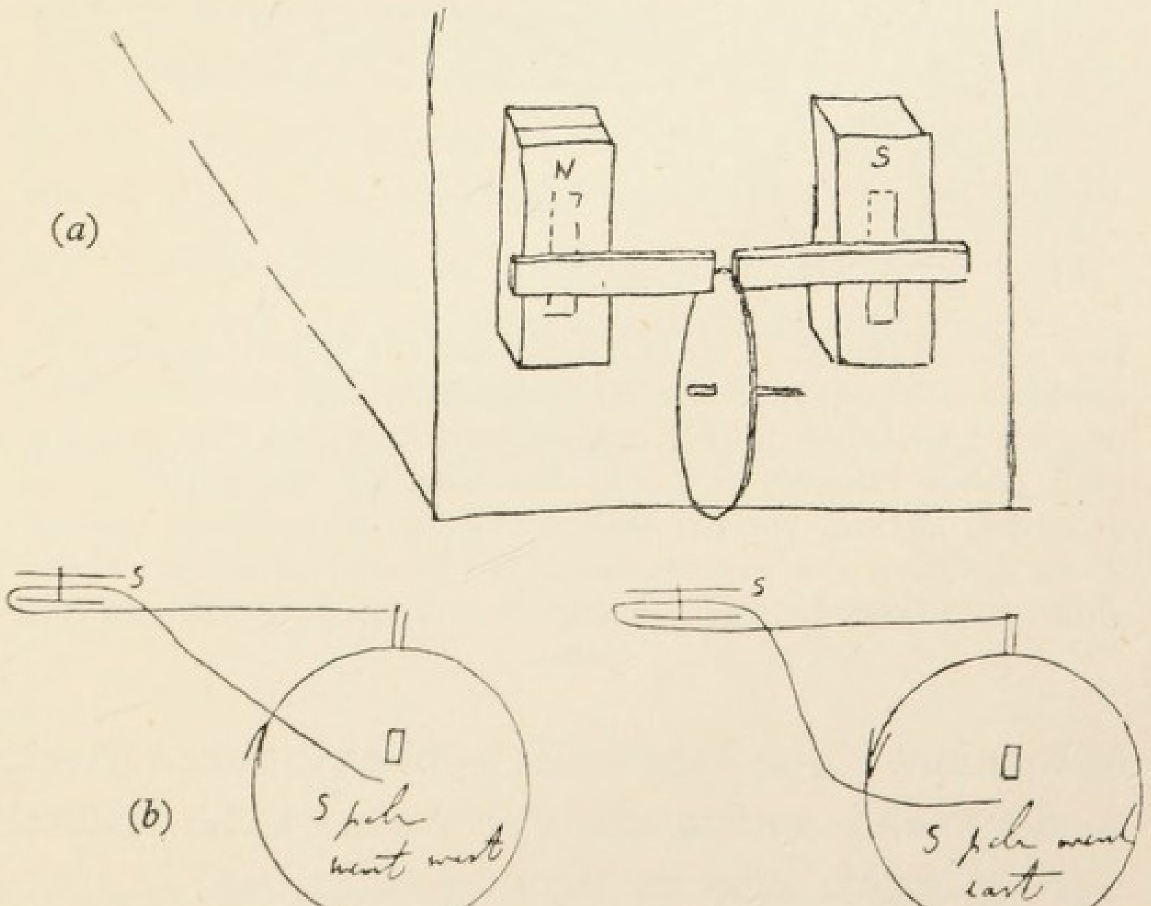


FIG. 12. (*a*) A sketch by Faraday showing how a disc was arranged to spin between the poles of a magnet. (Vol. I, p. 381.) (*b*) A sketch showing some of the experimental results (Vol. I, p. 385). One of the wires coming from the galvanometer makes rubbing contact with the rim of the disc, the other with the axle.

Society". Collectors in the form of brass springs could be applied at any points on the rim of the disc or on its surface or its axle. These were joined to wires leading to a galvanometer. Current was generated, and as had been expected its amount could be observed for various speeds of rotation, various positions of the collectors or for either sense

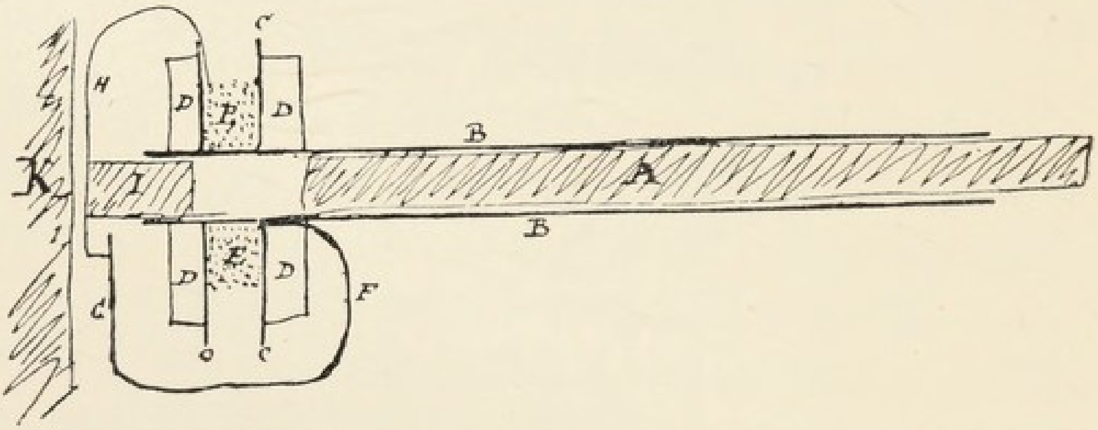


FIG. 13. A sketch (Vol. II, p. 297) of the apparatus for producing an electric spark by the interruption of a current. The magnet A is moved quickly from right to left. As its advancing pole passes through the coil, indicated by the stippling, it generates current therein and the circuit is suddenly broken when A strikes the wooden block I. The break occurs at the point of contact between G and H. A spark appears at this point.

of rotation. The long series of observations served to shape and confirm Faraday's ideas: the results were of course what we should now expect.

One more experiment must be described because it reminds us of the fact that in those days the static electricity of the machines which developed it by rubbing was not known for certain to be the same as that of Volta's pile and battery. The former was readily capable of producing sparks. Could the latter do the same? One form of the experiment is shown in Fig. 13. A magnet can be thrust violently into a coil: as its advancing pole passes through it will be in the best position for generating an electromotive force which depends on its strength and its speed of motion. At the moment when the speed is greatest the magnet comes up against a stop, and the shock breaks a loose connection which is part of the circuit of the coil. A spark is seen to pass across the gap between the ends of the separated wires, due to the action of the current in forcing its way across the gap for as long as it can do so. The property of producing a spark was therefore possessed by both forms of electricity: and this helped to establish the fact that they were actually the same.

V

WE now come to a very interesting part of our story. The first and third principles were well established; the second and fourth were sufficiently grasped for the time being. In his endeavour to picture to himself the actions which he was investigating Faraday found it helpful to use a conception based on the

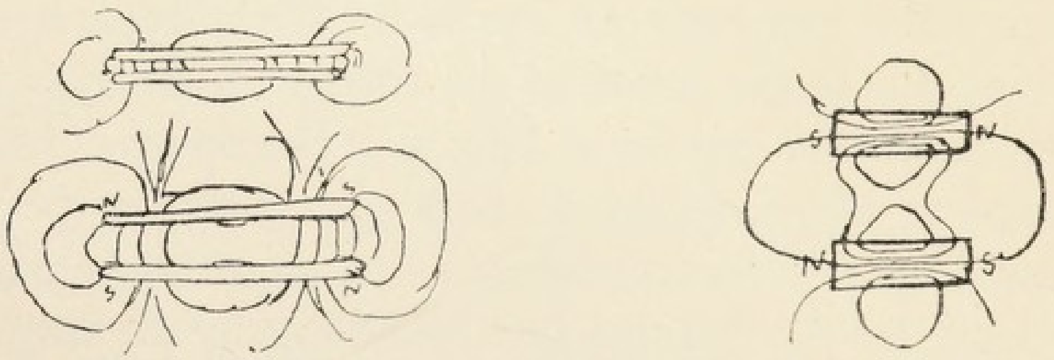


FIG. 14. Sketches showing Faraday's use of lines of filings to map the course of magnetic induction between two magnets. Note how the induction is supposed to be continued through the magnet, so that the lines form closed curves. (Vol. VI., p. 5.)

behaviour of iron filings scattered near magnets or current-carrying wires. They were already well known, but Faraday now began to study them carefully. A number of actual arrangements of filings which he made and fixed himself are still preserved. To him the lines of filings stretching from a N to S pole were indications of something existing in the space between the poles. The filings were, so to speak, only the straws which showed the way that a wind was blowing. A something which could be defined by lines, and even spoken of as lines, was there whether the filings were there or not. The something need not of course be along sharply defined lines only, any more than latitude and longitude are confined to the lines which are drawn on the map. He supposed that the conditions in the space between the magnets were defined by the lines, and that the conditions were the agents of the magnetic action.

On account of the parallelism between electricity and magnetism which was now clear, the conception of lines of force should be just as applicable in the electric as in the magnetic case. We now use the conception freely in both cases.

But how would the effect be transmitted along the lines? It would not be by some means so simple as mere push or pull. Influences are sent across apparently empty space by waves in the case of light, or across material bodies in the case of sound. In these cases the direction is normally in a straight line: if the medium through which they pass is uniform our rays of light and sound are straight. Could these lines of force though curved in any way be looked on as rays carrying vibrations?

Whether Faraday's thoughts moved in this way or not it is certain that he very quickly—at some time in the 30's—conceived the idea of " ray-vibrations ", *i.e.* waves running along his lines. This was many years before he expressed it publicly on a remarkable occasion in 1846. A certain well-known inventor had been asked to give the weekly public lecture at the Royal Institution. The lecture was to be given in the evening, and the inventor spent the morning and afternoon arranging and testing his demonstrations. Faraday helped him. When the audience assembled there was no lecturer: nervousness had overcome him. Faraday had to take his place, and as he had been helping in the day's preparations and understood what the lecturer had intended to say he carried on with success. But he had not so much to say about the subject as the lecturer would have had, and finished with time to spare. He then proceeded to talk of these " ray-vibrations ". He had long kept the idea to himself, but the occasion demanded something of him, and, anyway, he may have felt that his idea was by now sufficiently clear. Once explained in a lecture, it was right to send his reasonings to be published in more permanent form. He therefore contributed to the *Philosophical Magazine* in 1846 a paper called " Thoughts on Ray Vibrations ". It was this paper which some years later was studied by Clerk-Maxwell of Cambridge, who grasped its implications and put Faraday's conceptions into mathematical form. When this had been done the resulting mathematical equations indicated at once that there must be such things as electro-magnetic pulses or waves which travelled through space as Faraday had supposed and that the speed was actually that of light, 186,000 miles a second ; it was to be inferred that light itself was a form of electromagnetic waves. Light, therefore, was not a phenomenon entirely by itself ; it was simply a selection of electromagnetic waves which the eye was fitted to detect, and a very narrow selection at that. Waves might be of all lengths. In these days we work with X-rays which are waves far shorter than those of light, and radio waves which are far longer. Of course these last possibilities were not known at that time, and in mentioning them I am merely indicating the direction which our story is taking.

We have still to consider more fully the ideas which were the basis of Maxwell's famous mathematical equations. Each of the four equations represented one of the fundamental principles which I have described above. The first was based on Oersted's experiment, the third on the experiment of 1831. The second and fourth were more gradually established. We must now examine them a little more closely.

VI

THE second principle says that magnetomotive force tends to excite magnetism, or, to speak more carefully, magnetic induction in any body or empty space to which it is applied. The idea that there was something or some condition in the space between two magnets which was the agent in their mutual attractions or repulsions, led naturally to the further idea that the nature of any medium occupying that space might affect the actions. Iron clearly stood by itself. The lines of force which were indicated by the arrangements of filings were greatly modified in form and concentration when any mass of iron was introduced into the space through which they passed. Other substances did not appreciably affect the disposition of the lines. Oersted himself had found that the action of an electric current on a magnet was not affected if glass or wood or brass were introduced into the space between the wire and the magnet. Was it to be accepted that magnetism affected one or two substances only, such as iron and to a smaller degree bismuth and perhaps a few more? Or was magnetism capable of existence without matter to carry it? If the latter were the truth, then empty space should rather be considered as the standard, and all forms of matter should be classed according to their capacity, as compared with space, to respond to magnetomotive force. In the case of iron the response was relatively great. In other cases it certainly differed little from that of space itself. There might be bodies that were less responsive than empty space. It might be that if various bodies were placed under strong magnetic influence, *i.e.* subjected to great magnetomotive force, some would shrink away in order to avoid the effect, and not be drawn as iron would be into places where the magnetic influence was strong.

When we weigh bodies we test the gravitational force by which the earth draws them towards itself. But some bodies, for example, a balloon filled with hydrogen, tend to rise from the earth as if they were repelled. We do not say, however, that here is negative weight, or that there is negative gravitational force. We realise that all our observations are made on bodies immersed in air ; and that the tendency of the balloon to rise does not mean that hydrogen has negative weight, but merely that it is less strongly drawn to the earth than the air. In the same way such a substance as bismuth is not to be reckoned as magnetically negative, but as less magnetic than empty space, in which a magnetomotive force can cause more magnetic induction than it can in bismuth.

Faraday proceeded to test a number of substances. One of the first was a famous experiment with a piece of very heavy glass. He had accumulated specimens of this kind in the course of a research on glass conducted at the request of the Government,

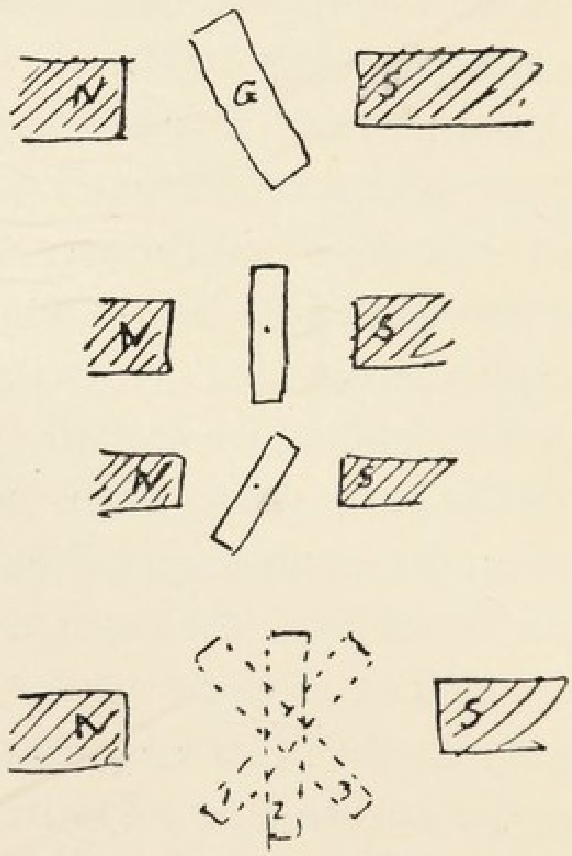


FIG. 15. Sketches showing the effect of a strong magnetic field on a piece of heavy glass. The glass avoids the poles. In the lower sketch the glass is set swinging by timed application of the magnetic forces. (Vol. IV, p. 313.)

who had become concerned at the scarcity in England of glass for optical instruments. The arrangement of his experiment is reproduced in Fig. 15, which is taken from the drawing in Faraday's diary. The piece of glass moves always so as to get away from the places where the influence of the magnet is greatest and therefore the lines of magnetic induction, if they are used to describe that influence, are most strongly crowded together. The glass is said to be diamagnetic ; an unfortunate description because it suggests that the body offers an exceptional facility for the passage of lines through it, whereas the exact opposite is the truth. It is sometimes said, incorrectly, that a diamagnetic body tends to set across the lines of force. It only does so when it thereby moves on the whole from stronger to weaker fields. In a uniform field it must actually direct itself very feebly along the lines, but the effect would be very difficult to detect. Faraday found that although most ordinary substances differed little from empty space in their reaction to magnetomotive force, yet there were numerous distinct variations. He would have been interested to know that liquid oxygen is remarkably responsive ; the exhibition of this property was a favourite experiment of Sir James Dewar's, who made liquid oxygen in his pioneering work on the liquefaction of gases in quantity. It is curious to see liquid oxygen leaping up to cling to the poles of a strong electromagnet.

By many experiments of the kind that Faraday made, and others also, the relation between magnetomotive force and magnetic induction became clear.

A current did not directly produce magnetism in a piece of iron, nor, more generally, in any bodies, nor in empty space, but a definite force, the effect of which depended on the form and volume of the bodies on which it acted. The point is extremely important. It was by no means fully appreciated by philosophers in Faraday's time and even for some time afterwards. Clerk-Maxwell gave it a clear form in his mathematics; if he had not done so he could not have established the electromagnetic theory of light.

The fourth fundamental principle asserts that electromotive force produces an effect which depends on its own magnitude and on the nature of the space to which it is applied. Ohm's experiments showed that an electromotive force applied to a conductor set up a current which was inversely proportional to the resistance of the conductor. But this is not the whole story. If this were the only effect of electromotive force the parallelism between electricity and magnetism would break down. It does not break down; although there is nothing magnetic to correspond to the electric current. Beside this production of current, an electromotive force can also produce an effect which is exactly analogous to the magnetic effects we have been considering. It will be remembered that in Fig. 1 we imagined that the closing of the key in the circuit, which included the battery and the first link of the chain, started a flow of electricity; a flow which would quickly become steady, would be proportional directly to the electromotive force and inversely to the resistance of the circuit. Suppose now that a gap is made in the circuit; the link is cut across at some point, and the current can no longer flow steadily. But there is still a momentary flow when the key is closed. We picture to ourselves a piling up of positive electricity on one side of the gap and of negative on the other, or if we like to put it so an excess of positive electricity on one side and a defect on the other. The medium in the gap is now in a condition which is analogous to the magnetic state in the space near a magnet. Its presence and its disposition can be tested as in the magnetic case; but of course we can no longer use iron filings. If the electromotive force is large enough, the effect can be demonstrated to the eye by using small crystals such as those of quinine sulphate immersed in a non-conducting liquid.

In customary language the gap is called an electric condenser, again a rather unfortunate choice of term since there is nothing which can be said to be condensed. The gap is rather to be compared to an indiarubber diaphragm stretched across a pipe through which water is urged under pressure. The pipe corresponds to the wire carrying the current.

When the pressure is applied the rubber yields and the water flows until the reaction of the stretched rubber matches the applied force. Nothing has been condensed. Of course, if the rubber were removed or broken there would be a continuous flow.

If this is the more correct picture the nature and form of the diaphragm becomes a matter of importance. A thin or wide diaphragm will yield more than a thick one or one of small surface. A rubber diaphragm will yield more than one made of a more rigid substance. Just so the charge on the electric condenser depends on its dimensions and on the nature of the dielectric, *i.e.* of the medium in the gap which is crossed by lines of electric induction. Faraday made a number of appropriate experiments in order to discover the laws of this effect. His gap was usually the space between two concentric metal spheres ; the materials which he tested were various waxes and liquids. Two such pieces of apparatus of similar dimensions charged by the same electromotive force would take up different charges if the dielectrics in them reacted differently to the force ; and the charges could be compared with the help of an electrometer. The electromotive force required was high, and was obtained from a friction machine. The experiments gave the relative values of what Faraday called the specific inductive capacities of the materials. The capacity of the condenser itself, to use our customary term, would depend not only on the material between the conductors but also on the form and geometry of the arrangement. But this was not examined completely by Faraday. As we

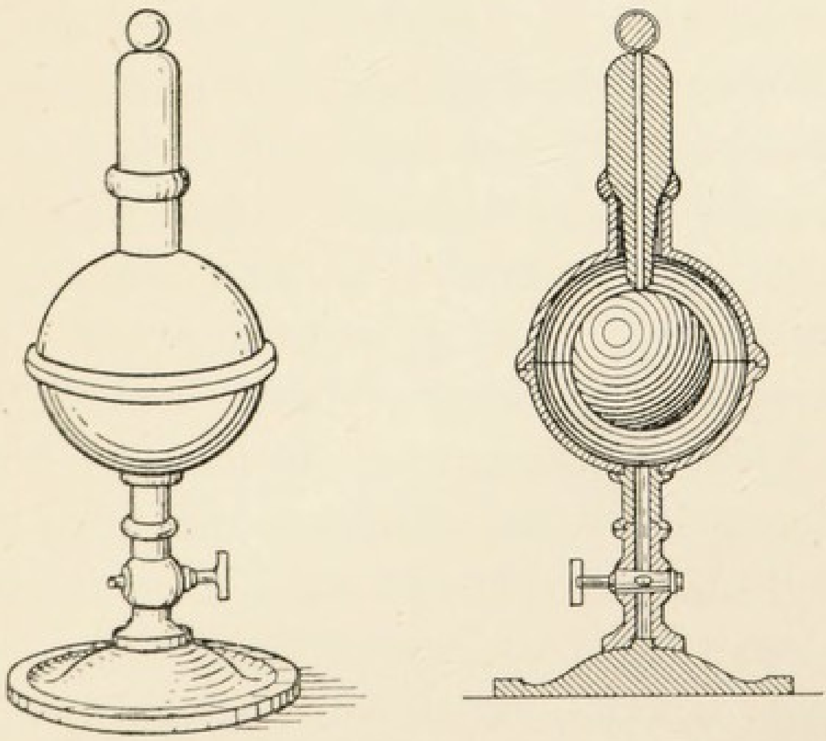


FIG. 16. The apparatus used in the original determinations of specific inductive capacity. The sectional drawing shows the outer and inner metallic cases, which are separated by the material under examination. In the figure the material is solid : a gas or liquid may be tested also.

know, there are quite large differences between the specific inductive capacities of various substances ; for instance, the specific inductive capacity of various kinds of glass is usually seven or eight times that of empty space ; that of ebonite rather less than three times, that of sulphur about four times and so on. There are no startling differences as in the analogous case of magnetic "permeability", where iron is thousands of times as permeable to magnetic induction as the air.

VII

WHEN Clerk-Maxwell constructed his " equations of the electromagnetic field " in 1865 he used all the knowledge of electromagnetic relations which had been acquired at that time, and he was inspired by Faraday's paper on " Thoughts on Ray Vibrations ". His conclusion was, as I have already said, that " radio " waves must exist, and that light was one form of them. Faraday could not have proved so much ; he did not possess the mathematical skill in the first place, and moreover the actual quantitative determinations of those effects which had been discovered, largely by himself, had not been made. Maxwell points this out in his paper of 1865. A few years ago I had occasion to consult a book in the library of the Royal Society, and as I opened it a slip of paper fell out. It was a note signed by Clerk-Maxwell saying that :—

> The Electromagnetic Theory of Lt (Light) as prop^{d} by him (Faraday) in " Thoughts on Ray Vibrations " (Phil. Mag. 1846 May) or Ex. Res. (Experimental Researches) III p. 447 is the same in substance as that which I have begun to develope in this paper (" . A Dyn^{e} Theory of the E^{c}

Field Phil. Trans. 1865) except that in 1846 there were no data to calculate the velocity of propagation.

J. C. M.

Clerk-Maxwell had already said as much as this in his printed papers, but it was of no small interest to come across this additional reference after it had lain hidden for seventy years or so.

As soon as Clerk-Maxwell had formed the four mathematical equations representing the four principles which had been slowly evolved by much labour and thought, radio as we now call it became a possibility. The solution of the equations showed that electromagnetic disturbances must travel through space with the same velocity as light, which was one of their forms. Their speed would be affected by the presence of material in the space through which they travelled. We know that light travels more slowly in glass, for instance, than in a vacuum or in air, and hence light is refracted in passing from air to glass or vice versa. Radio waves can also be refracted for similar reasons ; they can be reflected as light is reflected. It is of first importance that the radio waves possess these properties.

The mathematician who handles Maxwell's equations sees at once why radio waves behave like light. But it may well seem a long way from the four principles of electromagnetism to a statement that radio is merely a form of light which the eye does not detect, or more accurately, light is a particular kind of radio. To put it in metaphorical language, the river is easy to cross if there is the mathematical bridge. But if the bridge is not there the river can still be crossed in other ways which may not be so short and convenient. Let us therefore try to form an appreciation of the wave character without recourse to mathematical expressions. Let us go back to the chain of links formed alternately of copper and iron, shown in Fig. 1.

Suppose that in some way, by means of a battery or otherwise, a current is made to run in the first copper link. Its magnetomotive force will excite magnetism or magnetic induction in the first iron link. That is to say something takes place in the link of the same kind as would be found in a permanent bar magnet bent into a ring so that the two poles were joined together, and there were no longer separate North and South poles. The lines of induction then run round the ring, Fig. 17.

This penetration of the magnetism carried by the first iron link into the second copper link sets up, while the penetration proceeds, an electromotive force in the copper, and this causes a current to spring up. That has its magnetic effect on the second iron ring, and so on along the chain. It is a pulse that passes along the chain to its end; and after it has passed over any link the electric or magnetic conditions in that link cease to exist. If now we stop or reverse the current in the first link a

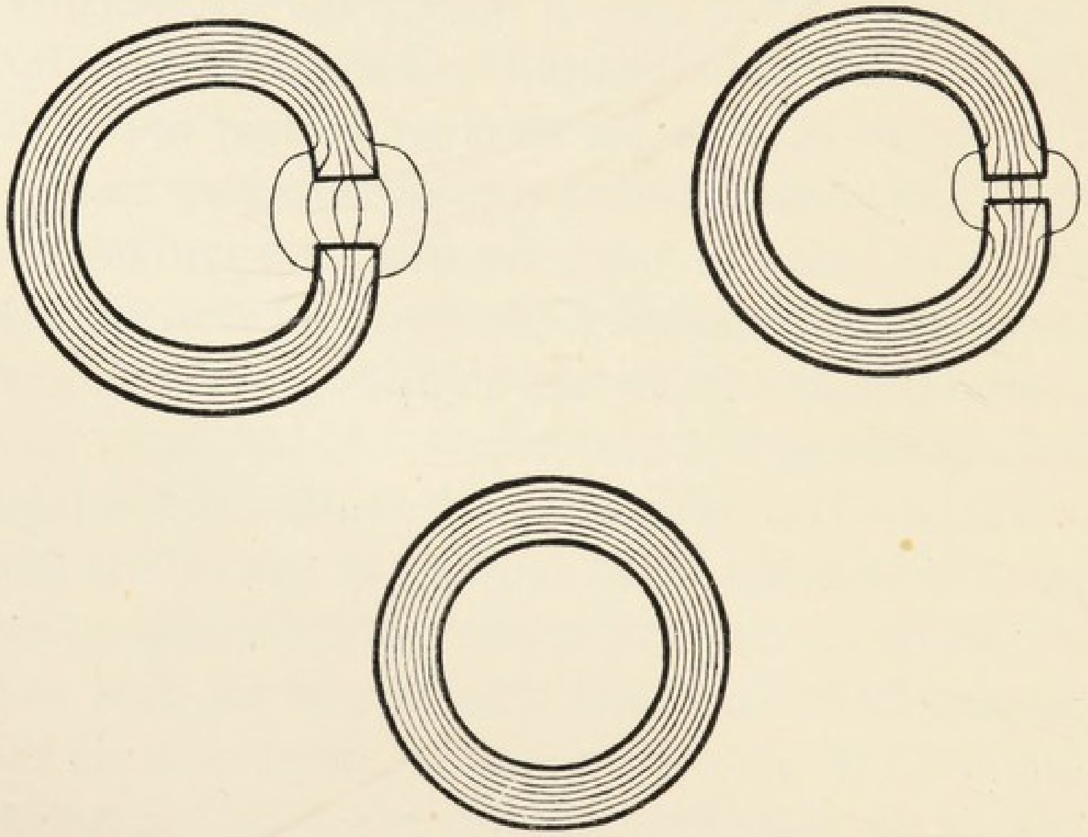


FIG. 17. If a magnet were bent into circular form so that the poles came into contact the lines representing the magnetic induction would gradually close up, as shown, and become more and more internal to the magnet. When one of the iron links of Fig. 1 is magnetised the lines are within the link, and do not emerge anywhere.

second pulse follows the first along the chain; it will be of an opposite character, the temporary currents in the copper links will run the opposite way. By continually reversing the current in the first link a succession of pulses is sent along the chain; and this is indeed a wave motion since such a motion is a succession of pulses spaced regularly.

But we have now to see how a series of such pulses can travel through space without the aid of the links of copper and iron. Suppose that we strike out the

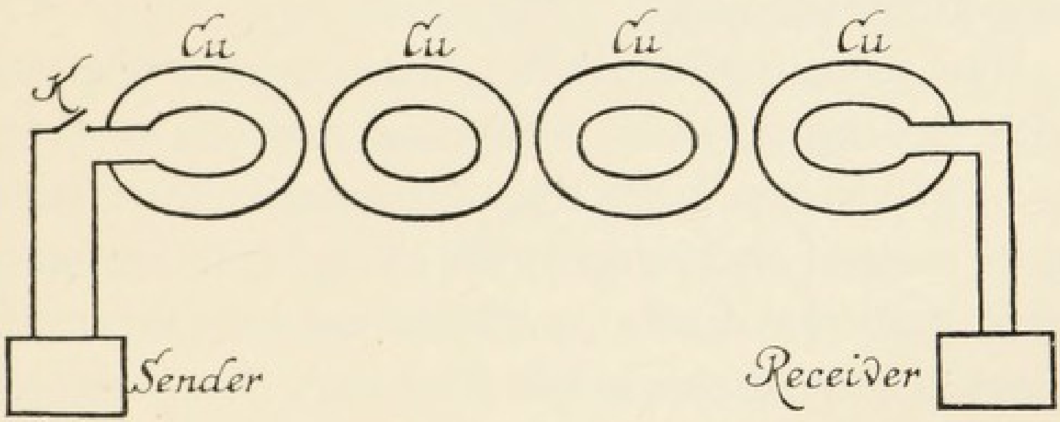


FIG. 18 (*a*). The copper links of the chain of Fig. 1, the iron links being suppressed.

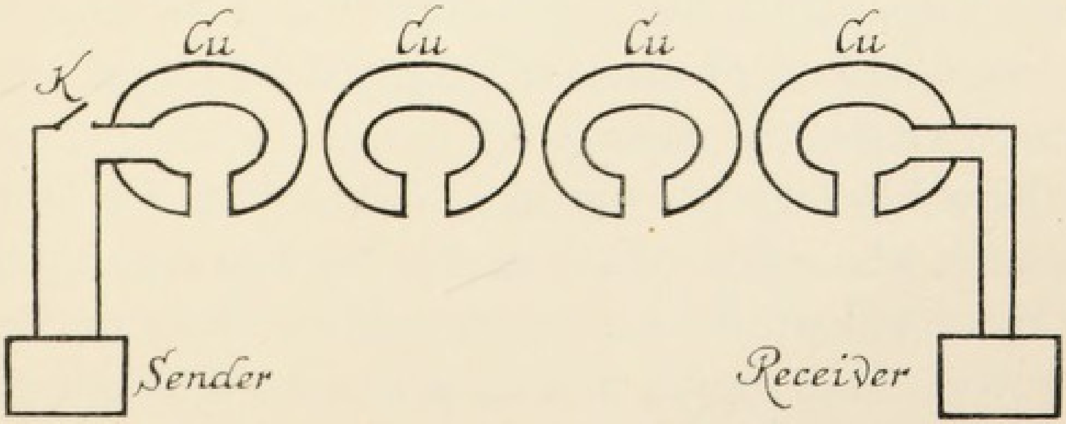


FIG. 18 (*b*). Gaps in the copper links act as condensers.

links of iron and leave those of copper. We have now taken away the iron which guided through the second copper link a large proportion of the lines of magnetic induction due to the current in the first copper link ; but some lines remain. If the space about the links were mapped out by iron filings the effect would be clearly seen. More simply still, a magnetic needle placed in the middle of the second copper link would be deflected by the current in the first. So from copper link to copper link the pulse runs along the line.

Now we can go further. We can even dispense with the copper links. Suppose that one of them had a gap in it. When the electromotive force came to be exerted on it, due to the changing of the magnetic induction in the neighbouring iron or empty space, a current would run for a very short interval. It would charge the condenser formed by the air gap, as explained already; it could not run permanently. But this temporary flow is all that is wanted, and the presence of the gap does not prevent the passing of the pulse.

How big may the gap be? The wider it is, the less the whole flow of electricity, but however big it is there will still be a temporary flow. Why not do away with the copper link altogether? Why not do away with all the copper links except the first, which must be maintained in some form in order to set the pulses going? The first copper link is the "aerial" of ordinary practice.

It seems odd that it should be possible to dispense with the copper and the iron links in which the moving electricity and the changing magnetism are concentrated. The point is, however, that magnetic induction and electric induction can exist in space where there is no material. The presence of material affects the amount and disposition of either induction, but induction can do without material. Of course, where the pulses still continue to speed away after the removal of the links, it is no longer possible to conceive of links of definite form round which the inductions go; the positions of the inductions in space have no longer any definite boundaries. But at every point over which the pulses travel they have their temporary magnitude, each of them alternating from one sign to another, *i.e.* heading in different directions alternately. When the electric pulse rushes up the vertical aerial, there are actually horizontal rings of magnetic induction round the aerial, and the electromotive force due to this rise of magnetic induction generates increases of electric induction, that is to say temporary current, in space, and these increases are broadly linked chain-wise with the magnetic ring and so on. There are no metal rings, but there are rings of induction in space which travel outwards continuously; they have no definite boundaries though they have maxima and minima like waves on the sea, and by them their travel can be observed and measured.

Though Clerk-Maxwell proved in 1865 that radio waves must exist, no one seems to have made any successful attempt to observe them before Heinrich Hertz gave practical demonstrations of their existence in his laboratory at Bonn in 1888. The distance between emitter and detector in these early experiments was but a few yards; it is not surprising that the early apparatus was extremely inefficient. The means of detection were particularly feeble. Hertz's method may be said to be that of the chain of links of which only the first and last copper links existed, and he looked for a spark in a gap made in the last link. The method was of course extremely insensitive. The invention of the coherer by Branly was a considerable step forwards. But it was the "valve" that made it possible to take giant strides forwards; and led to the amazing progress of the last twenty-five years.

Here our story ends and makes way for another which deals with the discovery of the electron and with all the consequences of that discovery.

My object in this short account of the discovery of the fundamental principles of electromagnetism has been to show how they came gradually to be recognised. They are the basis of all electromagnetic developments, including that of transmission by radio: and are necessarily referred to implicitly or explicitly in the solution of all the problems that are met with in practice.