ci., 1857) has published a remarkable molecular theory of electrolysis, which is free from some of the objections to the views of Grotthuss and his followers.

The advances made in the experimental study of electrolysis reacted on the theory of the galvanic battery. It was now recognized that the cause of the inconstancy of batteries is the opposing electromotive force due to the existence of the products of decomposition at the plates of the battery. Gautherot, in 1802, observed the polarization current from electrodes which had been used for electrolysis. Ritter confirmed his discovery, and constructed on the new principle his secondary pile. Ohm also experimented on this subject. Fechner and Poggendorff suspected the existance of a transition resistance (*Uebergangswiderstand*) at the places where the chemical products were evolved. But the experiments of Lenz, Beetz, and others soon showed that a *vera causa* existed in the electromotive force of polarization amply sufficient to explain their results. The influence of the strength of the current, the size and nature of the plates, time, &c., on polarization have been investigated by many physicists, among whom are prominent Beetz and Poggendorff. Determinations of the electromotive force of polarization have been made by Daniell, Wheatstone, Poggendorff, and Beetz, and recently by Tait and others. Among recent labours on polarization are to be mentioned those of Helmholtz and his pupils. We must not omit to notice here the gas battery of Grove, and the powerful secondary piles which have recently been constructed by Planté. We refer those interested in these and kindred subjects to the exhaustive accounts in Wiedemann's *Galvanismus*. Justice to all contributors to our knowledge is impossible in our limited space.

Contact and chemical theories of the pile.

This is perhaps the place to mention the great battle that raged so long between the upholders of the two rival theories of the action of the pile. Volta and his immediate successors held that the current was due to the electromotive force of contact between the dissimilar metals in the circuit, the function of the electrolyte being simply to transmit the electricity, there being no contact force between metals and liquids. The upholders of the chemical theory sought for the origin of the current in the chemical affinity between the zinc and the acid or their equivalents in the battery, and, in the first instance at least, denied the existence of the contact force of Volta. It was soon shown, however, on the one hand, that there *was* a contact force between metals and liquids, and, on the other, that an electric current could be generated without a heterogeneous metallic circuit at all.

Later holders of both theories modified their views as experiment established the necessity for so doing. Ohm and Fechner and other Continental philosophers inclined to a modified contact theory, and Sir William Thomson at present lends his weighty authority to that side. On the other side are the great names of Faraday, Becquerel, and De la Rive. The contact theorists devoted their attention more to the electrostatic phenomena of the pile, while the chemical theorists studied with great minuteness the phenomena of electrolysis, so that both theories have rendered good service to science. Now-a-days most physicists probably recognize too well the defects of both theories to think it worth while to attack either, and take refuge more or less in eclecticism.

Application of the principle of the conservation of energy.

There was one point which the older adherents of the contact theory overlooked, the importance of which was more or less dimly perceived by their chemical opponents. This was, in modern language, the question, where does the energy come from which appears as kinetic energy in the moving parts of electromagnetic engines, as heat in the conducting wires, through which a current is being driven, and so forth? It was not until the dynamical theory of heat had been perfected that the first answer to this question was given. Joule (*Phil. Mag.*, 1841) had arrived experimentally at the law which regulates the generation of heat in conductors by the electric current, and his law was verified by Lenz and Becquerel, both for metals and electrolytes. Reasoning from Joule's law on the case where the whole of the energy appears in the form of heat, Thomson (*Phil. Mag.*, 1851) established the important theorem that the electromotive force of an electro-chemical apparatus is, in absolute measure, equal to the mechanical equivalent of the chemical action on one electro-chemical equivalent of the substance. Calculations of the electromotive force of a Daniell's cell, from the results of Joule, Andrews, and Favre and Silbermann, have given numbers agreeing with the direct measurements of Bosscha. The total amount of the electromotive force in the circuit having been thus satisfactorily determined, the question between the rival theories is reduced to the determination of the seat of this force—At which of the junctions does it act?

Besides his great services in other branches of electricity, Faraday did much to advance electrostatics. His experimental investigations on electrostatic induction are of great interest, and his discovery of the effect of the medium between the electrified bodies opened out a new aspect of the phenomenon quite unsuspected by those who held too closely to the theories of action at a distance. He introduced the term specific inductive capacity, and measured the capacity of several solid substances, showing that in these it was much greater than that of air. He conceived that his results were at variance with any theory of action at a distance, and gave a theory of his own, which accounted for all his facts, and which guided him in his investigations. Matteucci and Siemens adopted the views of Faraday, and the latter introduced refined methods for measuring specific inductive capacities. Such measurements have been made in later times by Barclay and Gibson for paraffin, and by Silow for certain fluids. The most remarkable result thus obtained, however, are those of Boltzmann, who succeeded not only in detecting but in actually measuring the differences between the specific inductive capacities of different gases. Faraday had looked in vain for such differences, and concluded that the specific inductive capacity was the same for all gases. The phenomenon of the residual discharge was recognized and experimented on by Faraday. Kohlrausch, Gaugain, Wüllner, and others have also experimented on it; and quite recently Mr Hopkinson has obtained some very interesting results regarding the superposition of residual discharges. These results are analogous to the curious phenomena of "elastic recovery" observed by Kohlrausch.

Sir W. Snow Harris was a very able experimenter, and did much to improve electrostatical apparatus. He used the electrical balance and the bifilar suspension balance invented by himself. On the strength of his results he questioned the soundness of the views of Coulomb. The work of Harris on the influence of the surrounding medium on the electric spark is of great importance. Faraday made a series of beautiful experiments on this subject, and arrived at a body of results which still form a good portion of the *established* facts on this subject. Very important in this connection are the measurements of Sir W. Thomson of the electromotive force required to produce a spark in air between two conductors, which he has found to be disproportionally smaller for large distances than for small.

The luminous phenomena attending the electric discharge, especially in vacuum tubes such as those of Geissler, are exceedingly beautiful, and have of late formed a favourite subject of experimental study. Many interesting results have been obtained, the significance of which we may

not yet rightly comprehend. Among the older labours in this field we may mention those of Plücker and Hittorf, De la Rive, Riess, Gassiot, and Varley. But even as we write our knowledge of the subject is extending, and we refrain from referring to more modern results; for historical sketching—a difficult task in any case—is unsafe in an open field like this, where some apparently insignificant fact may contain the germ of a great discovery. We may here mention the experiments of Wheatstone on the velocity of electricity, valuable less for the results he obtained than for the ingenious application of the rotating mirror, then used for the first time, which has since been applied with much success in the study of the electric discharge.

One of the greatest names in electrical science is that of Riess. In his classical research on the heating of wires by the discharge from a battery of Leyden jars, he did for electricity of high potential what Joule did for the voltaic current. The electro-thermometer which he used in these researches was an improvement on the older instruments of Kinnersley and Harris. Riess repeated and extended the experiments of Coulomb, and effected many improvements in the apparatus for electrostatical experiments. His *Reibungselectricität* is a work of great value, and was for long the best book of reference open to the experimental student. Happily we have now another in the recently published work of M. Mascart.

Sir William Thomson revolutionized experimental electricity by introducing instruments of precision. Chief among these are his quadrant and absolute electrometers. His portable electrometer and water-dropping apparatus are instruments of great value to the meteorologist in the study of atmospheric electricity, a science which he has done much in other ways to forward. Besides this, we owe to him many valuable suggestions for electrical apparatus and experimental methods, some of which have been carried out by his pupils.

Electromatical theory.

The theory of statical electricity has made great progress since Poisson's time. Among its successful cultivators we may mention Murphy (*Electricity*, 1833), and Plana (1845). The latter went over much the same ground as Poisson, extending his results. It was, however, by Green (*Essay on The Application of Mathematical Analysis to the Theories of Electricity and Magnetism*, 1828; or *Mathematical Papers*, edited by N. M. Ferrers), a self-taught mathematician, that the greatest advances were made in the mathematical theory of electricity. "His researches," as Sir William Thomson has observed, "have led to the elementary proposition which must constitute the legitimate foundation of every perfect mathematical structure that is to be made from the materials furnished in the experimental laws of Coulomb. Not only do they afford a natural and complete explanation of the beautiful quantitative experiments which have been so interesting at all times to practical electricians, but they suggest to the mathematician the simplest and most powerful methods of dealing with problems which, if attacked by the mere force of the old analysis, must have remained for ever unsolved." One of the simplest applications of these theorems was to perfect the theory of the Leyden phial, a result which (if we except the peculiar action of the insulating solid medium, since discovered by Faraday) we owe to his genius. He has also shown how an infinite number of forms of conductors may be invented, so that the distribution of electricity in equilibrium on each may be expressible in finite algebraical terms,—an immense stride in the science, when we consider that the distribution of electricity on a single spherical conductor, an uninfluenced ellipsoidal conductor, and two spheres mutually influencing one another, were the only cases solved by Poisson, and indeed the only cases conceived to be solvable by mathematical writers. The work of Green, which contained these fine researches, though published in 1828, had escaped the notice not only of foreign, but even of British mathematicians; and it is a singular fact in the history of science that all his general theorems were rediscovered by Sir William Thomson, Chasles and Sturm, and Gauss (see *Reprint* of Thomson's papers). Sir William Thomson, however, pushed his researches much further than his fellow-labourers. He showed that the experimental results of Sir William Snow Harris, which their author had supposed to be adverse to the theory of Coulomb, were really in strict accordance with that theory in all cases where they were sufficiently simple to be submitted to calculation. He was guided in his earlier investigations by an analogy between the problems involved in steady flux of heat and the equilibrium of electricity on conductors. He showed in 1845 how the peculiar electric polarization discovered by Faraday in dielectrics, or solid insulators subjected to electric force, is to be taken into account in the theory of the Leyden iar, so as to supply the deficiency in Green's investigations. We also owe to Sir William Thomson new synthetical methods of great elegance and power. The theory of electric images, and the method of electric inversion founded thereon, constitute the greatest advance in the mathematical theory of electrostatics since the famous memoir of Green. These he has applied in the happiest manner to the demonstration of propositions which had hitherto required the resources of the higher analysis, and he has also found by means of them the distribution on a spherical bowl, a case of great interest in the theory of partially closed conductors, which had never been attacked or even dreamt of as solvable before. The work of Professor Clerk Maxwell on *Electricity and Magnetism*, which appeared in 1873, has already exerted great influence on the study of electricity both in England and on the Continent. In it are fully given his valuable theory of the action of the dielectric medium. He regards the electrical forces as the result of stress in the medium, and calculates the stress components which will give the observed forces, and at the same time account for the equilibrium of the medium. The striking discovery recently made by Mr Kerr of Glasgow, of the effect on polarized light exerted by a piece of glass under the action of strong electric force, is of great importance in connection with Maxwell's theory, and realizes a cherished expectation of Faraday, of whom Maxwell is the professed exponent. We must allude here once more to Maxwell's electromagnetic theory of light, the touchstone of which is the proposition that in transparent media, whose magnetic inductive capacity is very nearly equal to that of air, the dielectric capacity is equal to the square of the index of refraction for light of infinite wave length. Although, as perhaps was to be expected, owing to disturbing influences such as heterogeneity, this proposition has not been found in good agreement with experiment in the case of solids, yet for liquids (Silow, *Pogg. Ann.*, clv. clviii.) and gases (Boltzmann, *Ibid.* clv.) the agreement is so good as to lead us to think that the theory contains a great part of the whole truth.

In the earlier stages of the science several units were introduced for the measurement of quantities dealt with in electricity. As examples of these we may mention the wire of Jacobi, and the mercury column of Siemens, a metre long, with a section of a square millimetre, which at given temperatures furnished units of resistance; the Daniell's cell, which furnished the unit of electromotive force, the chemical unit of current intensity, &c. All these units were perfectly arbitrary, and there was no connection of any kind between them. The introduction of a rational system of unitation, based on the fundamental units of time, mass, and length, was one of the greatest steps of our time. The impulse came from the famous memoir of Gauss, *Intensitas Vis Magneticæ Terrestris ad Mensuram absolutam revocata*, 1832. In conjunction with Weber, he introduced his principles into the measurement of the earth's magnetic force. To Weber belongs the credit of doing a similar service for electricity. He not only devised three different systems of such units—the electrodynamical, the electrostatical, and the electromagnetic—but he carried out a series of measurements which practically introduced the last two systems. The fundamental research in this subject is to determine in electromagnetic measure the resistance of some wire from which, by comparison, the electromagnetic unit of resistance can be constructed. Measurements of this kind were made by Kirchhoff in 1849; more carefully in two different ways by Weber in 1851; by the committee of the British Association in 1863, &c.; by Kohlrausch in 1870; and by Lorenz in 1873. Accounts of these important researches will be found in Wiedemann and Maxwell, and in the collected reports of the British Association on "Electrical Standards." The ratio of the electrostatic to the electromagnetic unit of electric quantity is a velocity (according to Maxwell's electromagnetic theory of light it is the velocity of light), the experimental determination of which is of the greatest theoretical and practical importance. Such determinations have been made by Weber and Kohlrausch in 1856, by Maxwell in 1868, and by Thomson in 1869. The results are not so concordant as might be desired, but the research is a very difficult one.

For convenience in practice the British Association committee have recommended certain multiples of the absolute unit, to which they have given names—*e.g.*, the Ohm, the Volt, the Farad, &c. These have become current to a great extent among practical electricians in this country. For practical purposes, an empirical standard of electromotive force has been introduced by Latimer Clark, whose value in volts is given as 1·457. It is very important, in order to be able to reduce chemical to absolute measure, to know accurately the electro-chemical equivalent of water. Values for this have been found by Weber (1840), Bunsen (1843), Casselman (1843), and Joule (1851). Kohlrausch (1873) made a careful determination of the electro-chemical equivalent of silver, from which the electro-chemical equivalent of water can be calculated.

GENERAL SKETCH OF PHENOMENA.

Fundamental experiment.

If a piece of glass and a piece of sealing-wax be each rubbed with a dry woollen cloth, it will be found that both the glass and the wax have acquired the property of attracting indiscriminately any small light body in the neighbourhood; and it will be further observed, in many cases, that the small bodies, after adhering for a little to the glass or wax, will be again repelled.

These actions have at first sight a likeness to the attractions and repulsions of magnetic bodies, but they are sufficiently distinguished from these—1st, By their origin,—being excited by friction and other causes in a great variety of bodies, whereas magnetic action is powerfully exhibited and communicated only by certain varieties of iron and iron ore, by nickel and cobalt, and by certain arrangements which we shall have to mention by-and-by; 2d, By the nature of the bodies acted on; for these may be, in the case of excited glass or wax, light particles of any substance, whereas the only bodies powerfully acted on magnetically are either magnets or their equivalents, or iron, nickel, and cobalt; and 3d, By the fact that every magnet has two poles possessing opposite properties, whereas an electrified body may have similar properties in every part of its surface.

If the experiment were carefully tried it would be found that a piece of glass excited as above repels another piece of glass similarly excited, but attracts an excited piece of wax. A convenient way of exhibiting these actions, which also brings under our notice another fact of fundamental importance, is as follows. Two gilt balls of elder pith are fastened to the ends of a light needle of shellac, which is balanced horizontally on a point carried on a vertical stand (fig. 1). To the stand a stop is fixed for convenience, to prevent the needle from spinning more than half round. If we touch the ball A with a piece of excited glass, and B with a piece of excited sealing-wax, and touch a ball C, fastened to a shellac stem, with a piece of excited glass, then C will chase A away till it is brought up by the stop, while it will, on the other hand, attract B. If, again, C be touched with a piece of excited wax, it will attract A and repel B.

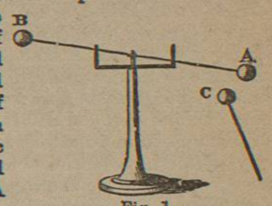

Fig. 1.

Definition of electrification and conduction.

Pieces of glass or wax excited in this way are said to be *electrified*, and the balls which by contact have acquired properties similar to those of the originally electrified bodies are said to be *electrified by conduction*.

It appears from the above experiment that the electrifications of glass and sealing-wax, when rubbed with woollen, have opposite properties, which they communicate to bodies brought into contact with them. A body which has similar electrification to a piece of glass rubbed with woollen is said to be vitreously or positively electrified; a body with similar electrification to a piece of sealing-wax rubbed with woollen is said to be resinously or negatively electrified. The result of the above experiment may then be summarized thus:—

Bodies similarly electrified, whether positively or negatively, repel each other.

Bodies oppositely electrified attract each other.

Conductors and non-conductors.

We have seen that a pith ball becomes, by contact with a positively electrified piece of glass, itself positively electrified. If we take two pith balls, electrify one of them positively, and then touch both simultaneously by a piece of thin wire, suspended by white silk, and test them with the electroscopic needle described above, they will be found both positively electrified; each will repel A and attract B, though less powerfully than the originally electrified ball did, before the connection between them was made. The success of the experiment will be found independent of the length or shape of the wire, and will be equally good with silver, gold, iron, lead, or any other metal. But, if we use a thread of glass or shellac to connect the balls, the electrification of the first ball will be found unaltered, and the second will remain neutral—that is, it will not attract or repel another neutral ball, and will *equally attract* both balls, A and B, of the electroscopic needle. The difference in the power of transmitting electrical properties from one body to another, or of aiding in electrification by *conduction*, leads us to divide all substances into two classes—conductors, which do very readily, and non-conductors, which do not, or do not very readily, transmit electrification from one body to another. If we connect an electrified conductor by means of another conductor to a very large conducting body, such as the earth, it will be found that so much electrification has been carried away from the small body that it is left sensibly neutral.

Insulation and insulators.

If, accordingly, we wish a conducting body to preserve its electrification unaltered, we must support it on some non-conducting substance. When thus supported the body is said to be *insulated*, the non-conducting support being called the *insulator*, a name which has on that account been given to non-conductors generally.

We have remarked above that a neutral pith ball attracts equally the positive and negative balls of the electroscopic needle; this leads us to remark, more explicitly than we have hitherto done, that an electrified body in general and in the first instance attracts a neutral or unelectrified body. The explanation of this action is that the originally neutral body in presence of the electrified body becomes itself electrified for the time. It is said to be electrified by *induction*, and it is very easy to show, by using large bodies, not only that the originally neutral body is actually electrified, but that it is oppositely electrified in different parts. Thus (fig. 2) A and B are two bodies suitably insulated and placed one above the other. If B be originally neutral, and A be positively electrified, then the lower end of B will be negatively, and the upper end positively electrified; as may be easily shown by exploring with a small positively electrified pith ball suspended by a dry white silk thread; the little ball will be attracted towards the lower end of B, and repelled from the upper. If we remove the body A, or, which (as we have seen) amounts to the same thing, connect it with the earth, and so "*discharge*" its electrification, we shall find that all traces of electrical action in B have disappeared—*i.e.*, the small positively electrified pith ball will be *attracted* everywhere; and, if we discharge it too, it will neither be attracted nor repelled anywhere.

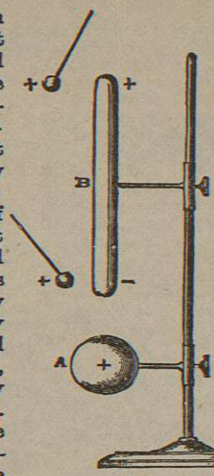

Fig. 2.

Provisional Theory.

Before going further into detail, it will be convenient to give a working theory of electrical phenomena, so far as we have considered them. The use of such a theory at the present stage is to enable us to co-ordinate and classify the results of experiment, and to furnish a few leading principles under which we may group results which appear to be due to a common cause. Such a theory is invaluable as a *memoria technica* for experimental results, and is useful in suggesting directions for experimental inquiry; but in framing it we must be careful to make it contain as little as possible beyond the results of actual experiment, and in using it we must be on our guard against allowing it to prepossess our minds as to what may be the ultimate explanation of the phenomena we are considering.

Use of terms "Electricity," &c.

Following the caution of Coulomb and the example of Sir William Thomson, we shall avoid the use of the term *electrical fluid*, and substitute instead the more succinct and less misleading word *electricity*. We suppose that a body which exhibits electrical properties (as above defined) has associated with its mass a certain quantity of something which, without attempting further definition, we shall call *electricity*. Of our right to use the word *quantity* here we shall give experimental justification by-and-by, and then the question of the appropriate unit will (*vide infra*, "electric quantity") be discussed. We may suppose that electricity is distributed throughout the whole mass of a body, and speak of electrical "*volume density*," meaning the quantity of electricity in an element of volume divided by the element of volume. We shall also speak of an *element of electricity*, meaning the electricity in an element or very small portion of a body. In certain cases we shall find that electricity resides on the surface of a body; electrical "*surface density*" then means quantity of electricity on an element of surface divided by the element of surface, and element of electricity the electricity on an element of surface.

For shortness, we shall denote positive or vitreous electricity by the mathematical sign +, and resinous or negative electricity by the sign −, remarking that the choice of the signs is arbitrary, and reserving for the present the question of how far we may associate with these signs the corresponding mathematical ideas.

We shall assume that every element of electricity repels every other element of the same sign, and attracts every other element of opposite sign. The precise law of this force will be investigated further on

This force considered as acting on any element of electricity we shall call an electric force. In perfectly conducting substances electricity moves with perfect freedom under any electromotive force, however small. In perfect non-conducting substances electricity will not move under any electromotive force, however great. Any case in nature lies somewhere between these extremes, but into questions of gradation, &c., we do not enter for the present.

When the forces due to other electrical elements acting on the electricity in any element of a body have a resultant, that resultant acts on the element itself, and is called the ponderomotive force, to distinguish it from the electromotive[1] (or electric) force which tends to move + electricity in one direction and − electricity in the opposite direction.

When a body is neutral, we shall assume that it contains *equal* and *equally distributed* quantities of + and − electricity, and we shall further suppose those to be practically unlimited in amount. A + electrified body is then to be conceived as a body which has excess of + electricity and a − electrified body as one which has excess of − electricity. Communication of + electricity to a body is in accordance with this to be regarded as equivalent to the abstraction of an equal amount of − electricity, and conversely.

It is easy to see that the above assumptions will explain in a general way the phenomena already described. Thus the + electricity of the electrified pith ball C acting on the + electricity of the ball A of the electroscopic needle repels it, and this force by our assumption is equally exerted on the matter of A, therefore A tends to move away from C, and will do so as long as it is free to move. The action on the − electrified ball B is similarly explained. Conduction and discharge to earth may be explained in a similar manner.

The attraction of an electrified body (+ let us suppose) A on a neutral insulated body B is thus explained. The + electricity on A (fig. 3) attracts the − electricity in B and repels the + electricity, so that, though there is still on the whole as much + electricity as − electricity, yet the distribution is no longer the same, for, the electricity being free to move, the − electricity under the attraction approaches A until the non-conducting air

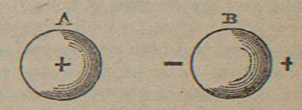

Fig. 3.

---

[1] It might be well to use the term "electric force" here, for "electromotive force" is afterwards used to mean the line integral of a force (see below, p. 24).

and the attraction of the separated + electricity on B stops it, and the + electricity recedes in similar fashion. When electrical equilibrium has been attained the action of the + electricity of A on the − electricity of B will exceed its action on the + electricity of B, which is on the whole more distant,[1] the electromotive force on the electricity of B will be on the whole attractive, and hence the ponderomotive force on B, will be also attractive.

The above explanation involves of course the general explanation of *electrification* by *induction*.

Experimental investigation of Electrical Quantity, Distribution, and Force.

In what follows we shall suppose that we have an instrument which will serve as an electroscope and to some extent as an electrometer; that is, which shall tell us readily whether a body brought into communication with it is + or − electrified or not at all, and also enable us to tell when one body is more strongly electrified + or − than another.

The gold-leaf electroscope of Bennet or the dry pile electroscope of Bohnenberger will meet these requirements, and have been much used in electrical researches. We shall, however, suppose that we are using the rudimentary form of Thomson's electrometer constructed by Elliot Brothers for lecture-room experiments, which is now much used in England, and answers very well. For a description of these and other electroscopes and electrometers, see article ELECTROMETER.

We shall also assume for the present that we have the means of producing and communicating to any body as much of either kind of electrification as we please, and pass on to consider the data of experiment regarding the distribution of statical electricity in conducting bodies. We are thus at the very outset brought face to face with the idea of electric quantity.

Electric Quantity.

We have to explain how the introduction of the term quantity into electrical science is justified by experiment, and how we can multiply and subdivide quantities of electricity. Although it is no doubt possible to introduce the notion of quantity independently of the *measure* of electric force, yet the most convenient and *practical measure* of quantity depends on the measurement of force, and the absolute electrostatic unit of quantity is stated in this way. We are naturally led, therefore, to combine with the study of quantity and distribution the experimental study of the laws of electric force.

We shall have occasion to allude to two leading experimental methods that have been used in investigating the present subject. These might be called the old method and the new.

The old method, which did so much for electrical science in the master hand of Coulomb, depended on the use of the torsion balance and proof plane, both invented by Coulomb himself. This method was used by Reiss and others up to Faraday's time.

Michell, about Coulomb's time or a little before, first suggested the idea of measuring small forces by the torsion of a wire. He proposed to apply the method to measure the attraction of gravitation between two bodies of moderate size, thus finding the mean density of the earth, and the method was actually carried out by Cavendish; but Coulomb was in all probability unaware of Michell's suggestion. He made careful preliminary experiments (the first of the kind) on the torsion of wires, and found that the couple required to twist a straight wire through a given angle varies as the angle of torsion multiplied by the fourth power of the diameter of the wire directly, and as the length of the wire inversely (*Mém. de l'Acad.*, 1784).

The balance used by Coulomb in most of his experiments is represented in figure 4.

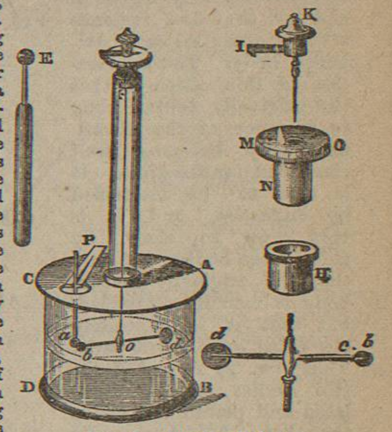

FIG. 4.—Torsion Balance.

ABDC is a cylinder of glass 1 foot in diameter and 1 foot high. This cylinder is closed by a glass lid pierced centrically and eccentrically by two openings, each about 20 lines wide. Into the middle opening is cemented a glass tube 2 feet high, to the upper end of which is fitted a torsion head; the separate parts of the head are shown larger at the side of the figure. H is a collar cemented to the glass tube; MO a metal disc, divided on the edge into 360 degrees; this disc is fastened to a tube N, which slips into the collar H. K is a button whose neck turns easily in a hole in MO; to the lower part of the button is fastened a small clamp, which seizes the wire of the balance. I is an arm with a small projecting piece which slips over the edge of the disc MO. This piece has a fiducial mark on it, which enables us to read off the position of the arm on the graduated edge of MO. The horizontal arm *bd* consists of a silk thread or fine straw covered with sealing wax terminated by a thread of shellac at *b* about 18 lines long, which carries a pith ball 2 or 3 lines in diameter. At the other end of the arm is a vertical disc of oiled paper, which serves as a counterpoise to the pith ball, as a damper to the oscillations, and as an index by means of which the position of the horizontal arm can be read off on a graduation carried round the glass cylinder. The eccentric hole in the cover of the balance allows the introduction of the fixed ball *a*; this is carried on a shellac stem fastened to a clamp P, which by means of fiducial marks can be placed in a fixed position on the cover. The wire in Coulomb's balance was of silver, about 30 cm. long. Its diameter was ·0035 cm., and it weighed about ·003 gm. He found by the method of oscillations that a couple equivalent to the weight of ·17 milligramme, acting at the end of an arm a decimetre long, would keep the wire twisted through 360°.

Besides this form of balance Coulomb used others, some more delicate for electroscopic purposes, and others less so, but of larger dimensions, into which he could introduce electrified bodies of considerable size.

Faraday used Coulomb's balance, and Snow Harris used the bifilar balance, which is a modification of Coulomb's. In the second volume of his *Experimental Researches*, however, Faraday gives a general method of experimenting, which to a great extent has superseded the older method. This may be called the "cage method;" it depends for its success on the use of some delicate instrument for measuring differences of potential; this was supplied by the quadrant electrometer of Sir William Thomson, which has thus completely revolutionized the whole system of electrostatic measurement.

Faraday's experiment was as follows (*Exp. Res.*, vol. ii. p. 279):—

> Let A (fig. 5) be an insulated hollow conductor with an opening to allow admission to the interior. Faraday used a pewter ice pail,[2] $10\frac{1}{2}$ in. high and 7 in. in diameter. Connect the outside of A with one electrode of an electrometer E, which may for most purposes be the rudimentary form of Thomson's electrometer mentioned above. Connect the other electrode of the electrometer with the earth. If now we introduce a positively electrified body, say a brass ball C, suspended by a white silk string, we shall find that the electrometer needle is deflected through a certain angle, the spot of light going a certain distance to the right, say, of the scale. It will be found that, provided the ball C is more than a certain depth (about 3 in. in Farady's experiment) below the mouth of the pail, no further motion of the ball, right or left, up or down, will affect the indications of the electrometer. It will also be found that the same indications will be got to whatever point of the *outside* of the pail the electrometer wire is attached. If we diminish or increase the + electrification of C, the electrometer deflection will diminish or increase accordingly. If we introduce a negatively electrified ball C′, the deflection will be to the left, and everything else as before. If C gives a certain positive (right) deflection, and C′ an equal (left) deflection, then if we introduce C and C′ together, the deflection will be zero. If C and C′ be both + electrified and give equal + deflections, then introduced together they will give a double + deflection, and if three such balls, all giving equal + deflections, be introduced together, they will give a treble + deflection.

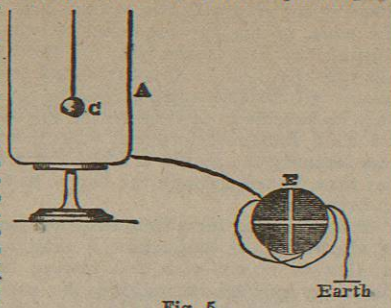

Fig. 5.

It is obvious that this experiment of Faraday's not only gives a very ready test of the electrical state of bodies, but at once suggests the notion of electrical quantity, and a theoretically possible electrostatic unit. Suppose, in fact, we take for our test the deflection of a Thomson's electrometer of given sensibility, then we might specify as a unit of electrical quantity the quantity of + electricity on or in a brass ball of given size, which will produce with a given cage a certain given deflection of the electrometer.

To make this definition useful we must have the means of transferring a given charge from one body to another, and charging a body with any multiple or submultiple of our unit, and of charging a body with any multiple or submultiple of the unit of negative electricity, which we may define as the quantity of − electricity which will just annul the action of the unit of + electricity in the electric cage.

All these requirements may be satisfied by suitably modifying Faraday's experiment.

We saw that we might move the ball about in the middle of our electric cage without affecting the electrometer deflection; we find, moreover, that when we withdraw the electrified ball without touching the cage, the needle returns to zero. If, however, before withdrawing the ball we cause it to touch the inside of the cage, the electrometer deflection remains the same as before, and after the ball has been removed the deflection is still the same, while if we examine the ball, we find that all traces of electrification have disappeared.

To transfer a given quantity of electricity.—If we provide ourselves with two cages, a large one G, and a small one H, and take a ball C, electrified positively with unit quantity as above defined, then testing C in cage G, in connection with the electrometer, we get a certain deflection D. If now we transfer the electrification of C to H, by the process just described, and then put H inside G, we shall get the same deflection D as before. It appears, therefore, that we can transfer electrification from one body to another without loss; we thus fulfil one of our requirements, and give an additional justification of the use of the word quantity in the present case.

To get any multiple or submultiple of the electric unit.—We may repeat the process above performed on the small cage H by touching its inside with the ball C, again electrified to unit quantity. All the electrification will pass to H as before, and if we now test H in G we shall get a deflection 2 D. We can in this way get any multiple we please of the unit charge. If we take the electrified brass ball C and touch it by a perfectly equal neutral ball C′, on introducing C into G we shall get deflection $\frac{1}{2}$ D; if we touch C again by C′, previously rendered neutral, we shall get deflection $\frac{1}{4}$ D, and so on; if we had touched C *simultaneously*, as in fig. 6, with two equal neutral balls, we should have got deflection $\frac{1}{3}$ D, and so on. We can thus get any submultiple of our unit charge.

Fig. 6.

To get a given multiple and submultiple of the negative unit.—This is possible when we can get a quantity of − electricity, which will just destroy the action of a given quantity of + electricity in the electric cage. If we introduce our given quantity of + electricity into the cage H, without allowing the conductor carrying it to touch the cage and at the same time put the outside of the cage in communication with the ground, then if we remove the conductor with the given quantity of + electricity and put it in G, it will give the same + deflection as before, while H tested in the same way will give a negative deflection exactly equal to the former, and if both be introduced together there will be no deflection. We can, therefore, in this way get a − quantity equal and opposite to a given + quantity.[1]

Electrical Distribution.

Experiments had been made before Coulomb's time to determine what effect the nature of a body has on electrical distribution. Gray and White concluded, from an experiment with two cubes of oak, one hollow and the other solid, "that it was the surface of the cubes only which attracted." Le Monnier[2] showed that a sheet of lead gave a better spark when extended than when rolled together. These experiments point to the conclusion that electrical distribution in conducting bodies depends merely on the shape of the bounding surface.

We may make experiments confirmatory of this conclusion with the electric cage. If we electrify a brass sphere A, and then touch it with another sphere B, and test the electrification of B in the cage, we shall find that the amount of electricity taken by B is always the same, whatever its material may be, so long as the radius of its external surface is the same. Experiment is unable to detect any difference in this respect between a solid sphere of lead and the thinnest soap-bubble of the same radius. Coulomb took a large cylinder of wood, in which he made several holes four lines in diameter and four lines deep. Having electrified the cylinder and insulated it, he examined its electrical condition by means of the proof-plane. This instrument, so much used by Coulomb, consisted merely of a small disc of gilt paper (in this case a line and a half in diameter) fastened to the end of a needle of shellac. The disc is applied to any point of a body whose electrification we wish to test so as to be in the tangent plane to the surface of the body. Assuming for a moment, what we shall by-and-by prove, that electricity resides on the surface of bodies, it is natural to suppose that the proof-plane, when placed as described, will form part of the bounding surface, and will therefore take up as much electricity as was originally on the part of the surface which it

---

[1] It is here tacitly assumed that the attraction between two elements of electricity decreases as the distance between them increases.

[2] A cylinder of wire gauze will answer equally well, and allows the experimenter to see better what he is doing. Such a cylinder we shall call for shortness as "electric cage."

[1] The substance of the above and a good deal of what follows is taken from Maxwell's *Electricity and Magnetism*, vol. i. We recommend the student to read his remarks on quantity, § 35, venturing to suggest, as an illustration of the transmission of energy by action at a distance, the case of two bar magnets, in which the energy of vibration is transmitted and retransmitted periodically. See Tait's *Recent Advances in Physical Science*, p. 179.

[2] Mascart t. i. p. 90.