Theophrastus, attracted light bodies, was the *tourmaline*, a Ceylon mineral, in which the Dutch had early recognized the same attractive property, whence it got the name of *Aschentrikker*, or attractor of ashes. In 1717 M. Lemery exhibited to the Academy of Sciences a stone from Ceylon which attracted light bodies; and Linnæus, in mentioning the experiments of Lemery, gives the stone the name of *Lapis Electricus*. The Duke de Noya was led in 1758 to purchase some of the stones called tourmaline in Holland, and, assisted by Daubenton and Adanson, he made a series of experiments with them, a description of which was published. The subject, however, had engaged the attention of Æpinus, a celebrated German philosopher, who published an account of them in 1756. Hitherto nothing had been said respecting the necessity of heat to excite the tourmaline; but it was shown by Æpinus that a temperature between 99½° and 212° Fahr. was requisite for the development of its attractive powers. Benjamin Wilson (*Phil. Trans.*, 1763, &c.), Priestley, and Canton continued the investigation; but it was reserved for the Abbé Haüy to throw a clear light on this curious branch of the science (*Traité de Mineralogie*). He found that the electricity of the tourmaline decreased rapidly from the summits or poles towards the middle of the crystal, where it was imperceptible; and he discovered that if a tourmaline is broken into any number of fragments, each fragment, when excited, has two opposite poles. Haüy discovered the same property in the Siberian and Brazilian topaz, borate of magnesia, mesotype, prehnite, sphene, and calamine. He also found that the polarity which minerals receive from heat has a relation to the secondary forms of their crystals,—the tourmaline, for example, having its resinous pole at the summit of the crystal which has three faces, and its vitreous pole at the summit which has six faces. In the other pyro-electrical crystals above mentioned, Haüy detected the same deviation from the rules of symmetry in their secondary crystals which occurs in tourmaline. Brard discovered that pyro-electricity was a property of the axinite; and it was afterwards detected in other minerals. In repeating and extending the experiments of Haüy, Sir David Brewster discovered that various artificial salts were pyro-electrical; and he mentions tartrate of potash and soda, and tartaric acid, as exhibiting this property in a very strong degree. He also made many experiments with the tourmaline when cut into thin slices, and reduced to the finest powder, in which state each particle preserved its pyro-electricity; and he showed that *scolezite* and *mesolite*, even when deprived of their water of crystallization and reduced to powder, preserve their property of becoming electrical by heat. When this white powder is heated and stirred about by any substance whatever, it collects in masses like new fallen snow, and adheres to the body with which it is stirred. (For Sir David Brewster's work on pyro-electricity see *Trans. R.S.E.*, 1845; *Phil. Mag.*, Dec. 1847; *Edinburgh Journal of Science*, Oct. 1824 and 1825).

In addition to his experiments on the tourmaline, Æpinus made several on the electricity of melted sulphur; and in conjunction with Wilcke, he investigated the subject of electric atmospheres, and discovered a beautiful method of charging a plate of air by suspending large wooden boards coated with tin, and having their surfaces near each other and parallel. Æpinus, however, has been principally distinguished by his ingenious theory of electricity, which he has explained and illustrated in a separate work (*Tentamen Theoriæ Electricitatis et Magnetismi*) which appeared at St Petersburg in 1759. This theory is founded on the following principles. 1. The particles of the electric fluid repel each other with a force decreasing as the distance increases. 2. The particles of the electric fluid attract the particles of all bodies, and are attracted by them, with a force obeying the same law. 3. The electric fluid exists in the pores of bodies; and while it moves without any obstruction in non-electrics, such as metals, water, &c., it moves with extreme difficulty in electrics, such as glass, rosin, &c. 4. Electrical phenomena are produced either by the transference of the fluid from a body containing more to one containing less of it, or from its attraction and repulsion when no transference takes place.

The electricity of fishes, like that of minerals, now began to excite very general attention. The ancients, as we have seen, were acquainted with the benumbing power of the torpedo, but it was not till 1676 that modern naturalists attended to this remarkable property. The Arabians had long before given this fish the name of *raad* or lightning; but Redi was the first who communicated the fact that the shock was conveyed to the fisherman by means of the line and rod which connected him with the fish. Lorenzini published engravings of its electrical organs; Reaumur described the electrical properties of the fish; Kämpfer compared the effects which it produced to lightning; but Bancroft was the first person who distinctly suspected that the effects of the torpedo were electrical. In 1773 Walsh (*Phil. Trans.*, 1773–5) and Ingenhousz proved, by many curious experiments, that the shock of the torpedo was an electrical one; and Hunter (*Phil. Trans.*, 1773–5) examined and described the anatomical structure of its electrical organs. Humboldt (*Ann. de Chim. et de Phys.*, i. 15), Gay-Lussac, and Geoffroy pursued the subject with success; and Cavendish (*Phil. Trans.*, 1776) constructed an artificial torpedo, by which he imitated the actions of the living animal. The subject was also investigated by Todd, Sir Humphrey Davy (*Phil. Trans.*, 1829), John Davy, and Faraday (*Exp. Res.*, vol. ii.). The power of giving electric shocks has been discovered also in the *Gymnotus electricus*,[1] the *Malapterurus electricus*,[2] the *Trichiurus electricus*,[2] and the *Tetraodon electricus*.[2] The most interesting and the best known of these singular fishes is the *Gymnotus* or Surinam eel. Humboldt gives a very graphic account of the combats which are carried on in South America between the gymnoti and the wild horses in the vicinity of Calabozo.

Cavendish (1731–1810)

Among the cultivators of electricity Henry Cavendish is entitled to a distinguished place. Before he had any knowledge of the theory of Æpinus, he had communicated to the Royal Society a similar theory of electrical phenomena. As, however, he had carried the theory much further, and considered it under a more accurate point of view, he did not hesitate to give his paper to the world (*Phil. Trans.*, 1771). Cavendish made some accurate experiments on the relative conducting power of different substances. He found that electricity experiences as much resistance in passing through a column of water one inch long as it does in passing through an iron wire of the same diameter 400,000,000 inches long, whence he concluded that iron wire conducts 400,000,000 times as well as rain or distilled water. He found that a solution of one part of salt in one of water conducts a hundred times better than fresh water, and that a saturated solution of sea-salt conducts seven hundred and twenty times better than fresh water. Cavendish likewise determined by nice experiments that the quantity of electricity on coated glass of a certain area increased with the thinness of the glass, and that on different coated plates the quantity was as the area of the coated surface directly, and as the thickness of the glass inversely. Although electricity had been employed as a chemical agent in the oxidation and fusion of metals, yet it is to Cavendish that we owe the first of those brilliant inquiries which have done so much for the advancement of modern chemistry. By using different proportions of oxygen and hydrogen, and examining the products which they formed after explosion with the electric spark, he obtained a proportion of which the product was pure water (*Phil. Trans.*, 1784–5). The decomposition of water by the electric spark was first effected by Paets Van Troostwijk and Deiman; improved methods of effecting it were discovered and used by Pearson, Cuthbertson, and Wollaston (*Phil. Trans.*, 1801).

[1] Powerful. [2] Weak.

The great discovery made by Galvani in 1790, that the contact of metals produced muscular contraction in the frog, and the invention of the voltaic pile, in 1800, by Volta led to the recognition of a new kind of electricity called *Galvanic* or *Voltaic Electricity*, which is now proved to be identical with frictional electricity. The chemical effects of the voltaic pile far transcend those of ordinary electricity. In 1800 Nicolson and Carlisle discovered the power of the pile to decompose water; and in 1807 (*Bakerian Lecture*) Sir Humphry Davy decomposed the earths and the alkalies, and thus created a new epoch in the history of chemistry.

Coulomb (1736–1806).

Contemporaneous with Cavendish was Coulomb, one of the most eminent experimental philosophers of the last century. In order to determine the law of electrical action, he invented an instrument called a *torsion balance*, which has since his time been universally used in all delicate researches, and which is particularly applicable to the measurement of electrical and magnetical actions. Æpinus and Cavendish had considered the action of electricity as diminishing with the distance; but Coulomb proved, by a series of elaborate experiments, that it varied, like gravity, in the inverse ratio of the square of the distance. Dr Robison had previously determined, without, however, having published his experiments, that in the mutual repulsion of two similarly electrified spheres, the law was slightly in excess of the inverse duplicate ratio of the distance, while in the attraction of oppositely electrified spheres the deviation from that ratio was in defect; and hence he concluded that the law of electrical action was similar to that of gravity. Adopting the hypothesis of two fluids, Coulomb investigated experimentally and theoretically the distribution of electricity on the surface of bodies. He determined the law of its distribution between two conducting bodies in contact; he measured the density of the electricity at different points of two spheres in contact; he ascertained the distribution of electricity among several spheres (whether equal or unequal) placed in contact in a straight line; he measured the distribution of electricity on the surface of a cylinder, and its distribution between a sphere and cylinder of different lengths but of the same diameter. His experiments on the dissipation of electricity possess also a high value. He found that the momentary dissipation was proportional to the degree of electrification at the time, and that, when the charge was moderate, its dissipation was not altered in bodies of different kinds or shapes. The temperature and pressure of the atmosphere did not produce any sensible change; but he concluded that the dissipation was nearly proportional to the cube of the quantity of moisture in the air. In examining the dissipation which takes place along imperfectly insulating substances, he found that a thread of gum-lac was the most perfect of all insulators; that it insulated ten times as well as a dry silk thread; and that a silk thread covered with fine sealing-wax insulated as powerfully as gum-lac when it had four times its length. He found also that the dissipation of electricity along insulators was chiefly owing to adhering moisture, but in some measure also to a slight conducting power. For the memoirs of Coulomb see *Mém. de Math. et Phys. de l'Acad. de Sc.*, 1785, &c.

Laplace, Lavoisier, and Volta.

Towards the end of the last century a series of experiments was made by Laplace, Lavoisier, and Volta (*Phil. Trans.*, 1782, or *Collezione dell' Op.*), from which it appeared that electricity is developed when solid or fluids bodies pass into the gaseous state. The bodies which were to be evaporated or dissolved were placed upon an insulating stand, and made to communicate by a chain or wire with a Cavallo's electrometer, or with Volta's condenser, when it was suspected that the electricity increased gradually. When sulphuric acid diluted with three parts of water was poured upon iron filings, hydrogen was disengaged with a brisk effervescence; and at the end of a few minutes the condenser was so highly charged as to yield a strong spark of negative electricity Similar results were obtained when charcoal was burnt on a chafing dish. Volta, who happened to be at Paris when these experiments were made, and who took an active part in them, subsequently observed that the electricity produced by evaporation was always negative. He found that burning charcoal gives out negative electricity; and in other kinds of combustion he obtained distinct electrical indications. In this state of the subject Saussure (*Voyage dans les Alpes*, t. ii. p. 808, *et seqq.*) undertook a series of elaborate experiments on the electricity of evaporation and combustion. In his first trials he found that the electricity was sometimes positive and sometimes negative when water was evaporated from a heated crucible of iron; but he afterwards found it to be always positive both in an iron and a copper crucible. In a silver and a porcelain crucible the electricity was negative. The evaporation of alcohol and of ether in a silver crucible also gave negative electricity. Saussure made many fruitless trials to obtain electricity from combustion, and he likewise failed in his attempt to procure it from evaporation without ebullition. Many valuable additions were about this time made to electrical apparatus, as well as to the science itself, by Van Marum, Cavallo, Nicholson, Cuthbertson, Brooke, Bennet, Read, Morgan, Henley, and Lane; but these cannot here be noticed in detail.

Saussure.

Application of analysis to electricity

The application of analysis to electrical phenomena may be dated from the commencement of the present century. Coulomb had considered only the distribution of electricity on the surface of spheres; but Laplace undertook to investigate its distribution on the surface of ellipsoids of revolution, and he showed that the thickness of the coating of fluid at the pole was to its thickness at the equator as the polar is to the equatorial diameter. Biot (*Traité de Physique Exp. et Math.*) has extended this investigation to all spheroids differing little from a sphere, whatever may be the irregularity of their figure. He likewise determined analytically that the losses of electricity form a geometrical progression when the two surfaces of a jar or plate of coated glass are discharged by successive contacts; and he found that the same law regulates the discharge when a series of jars or plates are placed in communication with each other. It is to Poisson (*Mém. de l'Inst. Math. et Phys.*, 12, 1811, &c.) however, that we are mainly indebted for having brought the phenomena of electricity under the dominion of analysis, and placed it on the same level as the more exact sciences. Assuming the hypothesis of two fluids, he deduced theorems for determining the distribution of the electric fluid on the surface of two conducting spheres when they are either placed in contact or at any given distance. The truth of these theorems had been established by experiments performed by Coulomb long before the theorems themselves had been investigated.

Biot

Voltaic electricity had now absorbed the attention of experimental philosophers. The splendour of its phenomena, as well as its association with chemical discovery, contributed to give it popularity and importance; but the discoveries of Galvani and Volta were destined, in their turn, to pass into the shade, and the intellectual enterprise of the natural philosophers of Europe was directed to new branches of electrical and magnetical science. Guided by theoretical anticipations, Professor H. C. Oersted of Copenhagen (*Experimenta circa effectum conflictus electrici in acum magneticam*) in 1820 discovered that the electrical current of a galvanic battery, when made to pass through a platinum wire, acted upon a compass needle placed below the wire. He found that a magnetic needle placed in the neighbourhood of an electric current always places itself perpendicular to the plane through the current and the centre of the needle; or, more definitely, that a magnetic north pole, carried at a constant distance round the current in the direction of rotation of an ordinary cork-screw advancing in the positive direction of the current, would always tend to move in the direction in which it is being carried.

Electro-dynamics. Ampère's theory.

Scarcely had the news of Oersted's discovery reached France when a French philosopher, Ampère, set to work to develop the important consequences which it involved. Physicists had long been looking for the connection between magnetism and electricity, and had, perhaps, inclined to the view that electricity was somehow to be explained as a magnetic phenomenon. It was, in fact, under the influence of such ideas that Oersted was led to his discovery. Ampère showed that the explanation was to be found in an opposite direction. He discovered the ponderomotive action of one electric current on another, and by a series of well-chosen experiments he established the elementary laws ef electrodynamical action, starting from which, by a brilliant train of mathematical analysis, he not only evolved the complete explanation of all the electromagnetic phenomena observed before him, but predicted many hitherto unknown. The results of his researches may be summarized in the statement that an electric current in a linear circuit of any form is equivalent in its action, whether on magnets or other circuits, to a magnetic shell bounded by the circuit, whose strength at every point is constant and proportional to the strength of the current. By his beautiful theory of molecular currents, he gave a theoretical explanation of that connection between electricity and magnetism which had been the dream of previous investigators. If we except the discovery of the laws of the induction of electric currents made about ten years later by Faraday, no advance in the science of electricity can compare for completeness and brilliancy with the work of Ampère. Our admiration is equally great whether we contemplate the clearness and power of his mathematical investigations, the aptness and skill of his experiments, or the wonderful rapidity with which he elaborated his discovery when he had once found the clue.

Recent progress of electro-dynamics.

In 1821 Faraday, who was destined a little later to do so much for the science of electricity, discovered electro-magnetic rotation (*Quarterly Journal*, xii.), having succeeded in causing a horizontal wire carrying a current to rotate continuously across the vertical lines of a field of magnetic force. The experiment was very soon repeated in a variety of forms by De la Rive, Barlow, Ritchie, Sturgeon, and others; and Davy (*Phil. Trans.*), in 1823, observed that, when two wires connected with the pole of a battery were dipped into a cup of mercury placed on the pole of a powerful magnet, the fluid metal rotated in opposite directions about the two electrodes. The rotation of a magnet about a fixed current and about its own axis was at once looked for, and observed by Faraday and others. The deflection of the voltaic arc by the magnet had been observed by Davy in 1821 (*Phil. Trans.*); and in 1840 Walker observed the rotation of the luminous discharge in a vacuum tube. For many beautiful experiments on the influence of the magnet on the strata, &c., in vacuum tubes, we are indebted to Plücker, De la Rive, Grove, Gassiot, and others who followed them.

Electro-magnetic engines.

One of the first machines in which a continuous motion was produced by means of the repulsions and attractions between electromagnets and fixed magnets or electro-magnets was invented by Ritchie (*Phil. Trans.*, 1833). The artifice in such machines consists in reversing the polarity of one of the electromagnets when the machine is near the position of equilibrium. For a general theory of these machines, showing the reasons why they are not useful as economic motive powers, see Jacobi (*Mémoire sur l'Application de l'Électro-magnétisme au Mouvement des Machines*, Potsdam, 1835), and Joule (*Mech. Mag.*, xxxvi.). Electro-magnetic engines have, however, found a restricted use in scientific workshops, such as Froment's, in driving telegraphic apparatus, &c.

Magnetization by electric current.

In 1820 Arago (*Ann. de Chim. et de Phys.*, t. xv.) and Davy (*Annals of Philosophy*, 1821) discovered independently the power of the electric current to magnetize iron and steel. Savary (*Ann. de Chim. et de Phys.*, t. xxxiv., 1827) made some very curious experiments on the alternate directions of magnetization of needles placed at different distances from a wire conveying the discharge of a Leyden jar. The dependence of the intensity of magnetization on the strength of the current was investigated by Lenz and Jacobi (*Pogg. Ann.*, xlvii., 1839), and Joule found that magnetization did not increase proportionately with the current, but reached a maximum (Sturgeon's *Ann. of El.* iv. 1839). The farther development of this subject, which really belongs to magnetism, has been carried on by Weber, Müller, Von Waltenhofen, Dub, Wiedemann, Quintus Icilius, Riecke, Stoletow, Rowland, and others. The use of a core of soft iron, magnetized by a helix surrounding it, has become universal in all kinds of electrical apparatus. Electromagnets of great power have in this way been constructed and used in electrical researches by Brewster, Sturgeon, Henry, Faraday, and others.

Recent progress of electro-dynamics.

The most illustrious among the successors of Ampère was Wilhelm Weber. He greatly improved the construction of the galvanometer, and invented the electro-dynamometer. To these instruments he applied the mirror scale and telescope method of reading, which had been suggested by Poggendorff, and used by himself and Gauss in magnetic measurements about 1833. In 1846 he proceeded with his improved apparatus to test the fundamental laws of Ampère. The result of his researches was to establish the truth of Ampère's principles, as far as experiments with closed circuits could do so, with a degree of accuracy far beyond anything attainable with the simple apparatus of the original discoverer. The experiments of Weber must be looked upon as the true experimental evidence for the theory of Ampère, and as such they form one of the corner-stones of electrical science.

Theory of electro-dynamics.

While experiment was thus busy, theory was not idle. In 1845 Grassmann published (*Pogg. Ann.*, lxiv.) his *Neue Theorie der Electrodynamik*, in which he gives an elementary law different from that of Ampère, but leading to the same results for closed circuits. In the same year F. E. Neumann published yet another law. In 1846 Weber announced his famous hypothesis connecting electrostatical and electrodynamical phenomena. Much has been written on the subject by Carl Neumann, Riemann, Stefan, Clausius, and others. Very important are three memoirs by Helmholtz, in *Crelle's Journal* (1870–2–4), in which a general view is taken of the whole question, and the works of his predecessors are critically handled. We shall have occasion, in the body of the article, to refer to the dynamical theory of Clerk Maxwell, which promises to effect a revolution in this part of electrical science.

Thermo-electricity.

By his discovery of thermo-electricity in 1822 (*Pogg. Ann.*, vi.), Seebeck opened up a new department. He found that when two different metals are joined in circuit there will be an electric current in the circuit if the junctions are not at the same temperature; he arranged the metals in a thermo-electric series, just as Volta and his followers had arranged them in a contact series. Cumming (*Annals of Phil.*, 1823) found that the order of the metals was not the same at different temperatures. This phenomenon has been called thermo-electric inversion. In 1834 Peltier discovered that if a current be sent round a circuit of two metals in the direction in which the thermo-electromotive force would naturally send it, then the hot junction is cooled, and the cool junction heated. This effect, which is reversible, and varies as the strength of the current, is called the Peltier effect. Sir W. Thomson made many experiments on thermo-electricity, and applied to the experimental results the laws of the dynamical theory of heat. His reasonings led him to predict a new thermo-electric phenomenon, the actual existence of which he afterwards verified by an elaborate series of very beautiful experiments (*Phil. Trans.*, 1856). He has given a general theory of the thermo-electric properties of matter, taking into account the effect of structure, &c. His experimental researches have been ably continued by Professor Tait, who, guided by theoretical considerations to the conjecture that the curves in what Thomson called the "thermo-electric diagram"[1] must be straight lines, made an extended series of experiments, and showed that they were in general very approximately either straight lines or made up of pieces of straight lines. Our knowledge of thermo-electricity has been advanced by Becquerel, Magnus, Matthiessen, Leroux, Avenarius, and others. Thermo-electric batteries of considerable power have been constructed by Markus, Noë, and Clamond, and employed more or less in the arts.

Magnetism of rotation.

In 1824 Arago (*Ann. de Chim. et de Phys.*, t. xxvii. &c.) made a remarkable discovery, which led ultimately to results of the greatest importance. He found that when a magnetic needle is suspended over a rotating copper disc the needle tends to follow the motion of the disc. This phenomenon, which has been called the "magnetism of rotation," excited great interest; Barlow (*Phil. Trans.*, 1825), Herschel, Seebeck (*Pogg. Ann.*, vii., 1826), and Babbage (*Phil. Trans.*, 1825) made elaborate researches on the subject; and Poisson (*Mém. de l'Acad.*, vii., 1826) attempted to give a theoretical explanation in his memoir on magnetism in motion. The true explanation was not arrived at until Faraday took up the subject a little later. We may mention, here, however, the experiments of Plücker, Matteucci, and Foucault on the damping of the motions of masses of metal between the poles of electromagnets. The damping of a compass needle suspended over a copper plate, observed by Seebeck (*l. c.*), has been taken advantage of in the construction of galvanometers.

In 1831 Faraday began, with the discovery of the induction of electric currents, that brilliant series of experimental researches which has rendered his name immortal. The first experiment which he describes was made with two helices of copper wire wound side by side on a block of wood, and insulated from each other by intervening layers of twine. One of these helices was connected with a galvanometer, and the other with a battery of a hundred plates, and it was found that on making and breaking the battery circuit a slight sudden current passed through the galvanometer in opposite directions in the two cases. He also discovered that the mere approach or removal of a circuit carrying a current would induce a current in a neighbouring closed circuit, and that the motion of magnets produces similar effects. To express in a concise manner his discoveries, Faraday invented his famous conception of the lines of magnetic force, or lines the direction of which at any point of their course coincides with that of the magnetic force at that point. His discovery can be thus stated:—Whenever the number of lines of force passing through a closed circuit is altered, there is an electromotive force tending to drive a current through the circuit, whose direction is such that it would itself produce lines of force passing through the circuit in the opposite direction. Nothing in the whole history of science is more remarkable than the unerring sagacity which enabled Faraday to disentangle, by purely experimental means, the laws of such a complicated phenomenon as the induction of electric currents. The wonder is only increased when we look to his papers, and find the first dated November 1831,[2] and another January 1832, in which he shows that he is in complete possession of all the general principles that are yet known on the subject. Faraday very soon was able to show that the current developed by induction had all the properties of the voltaic current, and he made an elaborate comparison of all the different kinds of electricity known,—statical, dynamical or voltaic, magneto-, thermo-, and animal electricity,—showing that they were identical so far as experiment could show.

Law of Lenz.

In 1833 Lenz made a series of important researches (*Pogg. Ann.*, xxxi., 1834, xxxiv., 1835), which, among other results, led him to his celebrated law by means of which the direction of the induced current can be predicted from the theory of Ampère, the rule being that the direction of the induced current is always such that its electromagnetic action tends to oppose the motion which produces it. This law leads to the same results as the principles of Faraday. The researches of Ritchie and Henry about this time, and of Dove a little later, are also of importance.

Mathematical theory.

In 1845 F. E. Neumann did for magneto-electric induction what Ampère did for electrodynamics, by developing from the experimental laws of Lenz the mathematical theory of the subject (*Abh. der Berl. Akad. der Wissenschaft*, 1845–7). He discovered a function which has been called the "potential" (of one linear current on another or on itself), from which he deduced a theory of induction completely in accordance with experiment. About the same time Weber deduced the mathematical laws of induction from his elementary law of electrical action, which, as we have already seen, he applied to explain electrostatic and electromagnetic action. In 1846 Weber, applying his improved instruments, arrived at accurate verifications of the laws of induction, which by this time had been developed mathematically by Neumann and himself. In 1849 Kirchhoff determined experimentally in a certain case the absolute value of the current induced by one circuit in another; and in the same year Edlund made a series of careful experiments on the currents of self and mutual induction, which led to the firmer establishment of the received theories. Helmholtz gave the mathematical theory of the course of induced currents in various cases, and made a series of valuable experiments in verification of his theory (*Pogg. Ann.*, lxxxiii., 1851). Worthy of mention here are also the experiments and reasonings of Felici in 1852. In the *Philosophical Magazine* for 1855, Sir W. Thomson investigated mathematically the discharge of a Leyden jar through a linear conductor, and predicted that under certain circumstances the discharge would consist of a series of decaying oscillations. This oscillatory discharge was observed in 1857 by Feddersen (*Pogg. Ann.*, cviii.) The law of Weber has been applied

[1] A mode of representing the phenomena of thermo-electricity which has been greatly developed and improved by Tait.

[2] The first experiment seems to have been actually made on the 29th August 1831. See Bence Jones's *Life of Faraday*, vol. ii. p. 1.

by Kirchhoff to the case of conductors in three dimensions. The most important of all the recent contributions to this part of electrical science is the theory of Clerk Maxwell, which aims at deducing the phenomena of the electromagnetic field from purely dynamical principles with the aid of the fewest possible hypotheses (*Phil. Trans.*, 1864; *Electricity and Magnetism*, 1873). He has established the general equations which determine the state of the electric field, and he has by means of these equations constructed an electromagnetic theory of light, which is full of suggestions for the philosopher, whether speculative or experimental. The theory of Helmholtz, and his valuable criticisms on the works of those that have laboured in this department, are to be found in three memoirs already alluded to.

Magneto-electricity has been largely applied in the arts. One of the first machines for producing electricity by induction was made by Pixii. It consisted of a fixed horseshoe armature wound with copper wire, in front of which revolved about a vertical axis a horseshoe magnet. The machine was furnished with a commutator for delivering the alternating currents in a common direction. By means of this machine Faraday and Hachette decomposed water and collected the disengaged gases separately. Many variations of this type of machine were constructed by Ritchie, Saxton, Clark, Von Ettingshausen, Stöhrer, Dove, Wheatstone, and others. In 1857 Siemens effected a great improvement by inventing the form of armature which bears his name. The next improvement was to replace the fixed magnets by electromagnets, the current for which was furnished by a small auxiliary machine. Wilde's machine (1867) is of this kind. Siemens, Wheatstone, and others suggested that the fixed electromagnet should be fed by a coil placed on the armature itself, so that starting from the residual magnetism of the armature the machine goes on increasing its action up to a certain point. Ladd's machine (1867) is constructed on this principle. The most recent of these machines is that of Gramme, the peculiarity of which is that the coil of the armature is divided up into a series of coils arranged round an axis, the object being to produce a continuous instead of a fluctuating current. It has been proposed of late to employ electromagnetic machines in lighting streets and workshops, and the experiment has been tried with some success. They have been employed for some time back in lighthouse work. The most important inductive apparatus for the physicist is the induction coil or inductorium, which has been brought to great perfection in the workshop of Ruhmkorff. Poggendorff (*Annalen*, 1855) suggested several improvements in this kind of apparatus. Fizeau, who added the condenser (1853), Foucault, who designed the interrupter which bears his name (1855), and Ritchie, who devised the plan of dividing the coil into sections by insulating partitions, have all aided in bringing the instrument to perfection. Very powerful machines of this kind have been constructed. A large one in the Polytechnic Institution, London, gives a 29-inch spark, and one recently constructed by Apps for Mr Spottiswoode gives a spark of 42 inches. The mathematical theory of magneto-electric machines has been treated by Maxwell (*Proc. Roy. Soc.*, 1867). He has also given a theory of the action of the condenser in the inductorium (*Phil. Mag.*, 1868). Two papers by Strutt (now Lord Rayleigh) in *Phil. Mag.*, 1869–70, are very interesting in connection with the same subject.

Electromotive force, resistance, and current strength.

In the year 1827 Dr G. S. Ohm rendered a great service to the science of electricity by publishing his mathematical theory of the galvanic circuit (*Die Galvanische Kette mathematisch bearbeitet*). Before his time the quantitative circumstances of the electric current had been indicated in a very vague way by the use of the terms "intensity" and "quantity," to which no accurately defined meaning was attached. Ohm's service consisted in introducing and defining the accurate notions—electromotive force, current strength, and resistance. He indicated the connection of these with experiment, and stated his famous law that the electromotive force divided by the resistance is equal to the strength of the current. The theory on which Ohm based his law may be and has been disputed, but the law itself and the applications which Ohm and others have made of it are in the fullest agreement with all known facts. The merit of Ohm really consists in having satisfactorily analysed a great group of phenomena which had up to his time baffled all those who attempted the task. How great his service was is easily seen when we remark the progress of those who adopted his ideas as compared with those who for a time hesitated to do so. Ohm was guided in his mathematical work by analogy with the problem of the flux of heat, and introduced for the first time into the theory of the pile, the equivalent of the modern word *potential*. Ohm's word was *electroscopic force* or *tension* (*Spannung*), and he showed that the fall of the potential is uniform along a homogeneous linear conductor. He considered that the potential was analogous to the temperature, and the flow of electricity to the flow of heat, so that the former just as much as the latter obeys the law of continuity. Ohm verified his theoretical conclusions with thermo-electric piles, and he observed, as Erman (*Gilb. Ann.*, 1801) had done before him, the differences of potential at different points of the circuit. Davy, Pouillet, and Becquerel laboured at the experimental verification of Ohm's law, and a great body of evidence was given by Fechner in his *Maasbestimmungen über die Galvanische Kette* (1831). The law of the fall of potential was verified by the elder Kohlrausch, who employed in his researches Volta's condenser and Dellmann's electrometer (*Pogg. Ann.*, lxxv., 1848). Later researches of a similar nature were made by Gaugain and Branly. Among recent investigations bearing on Ohm's law, the most remarkable is the verification for electrolytes by Kohlrausch (the younger) and Nippoldt. They principally used alternating currents in their researches, which were furnished by a "sine inductor," the measuring instrument employed being the electro-dynamometer of Weber. In the report of the British Association for 1876 an account is given of some experiments,[1] in which the testing of this law seems to have been carried to the limit of experimental resources. It must now be allowed to rank with the law of gravitation and the elementary laws of statical electricity as a *law of nature* in the strictest sense. Many remarkable applications of Ohm's law have been made of late, in particular to linear conductors by Ohm, Poggendorff, and especially Kirchhoff (*Pogg. Ann.*, 1845–7–8). The works of Helmholtz, Smaasen, and Kirchhoff on conduction in three dimensions must also be mentioned. Very important, on account of the experimental results with which they deal, are the calculations of Du Bois Reymond (*Pogg.*, lxxi., 1845) and Riemann (*Werke*, Leipsic, 1876) on Nobili's rings, and of Kirchhoff (*Pogg.*, lxvii., 1848), W. R. Smith (*Proc. Roy. Soc. Edin.*, 1869–70), Quincke, Stefan, Adams, and others on conduction in plates. Theoretical applications to the varying currents in submarine cables of great interest have been made by Thomson (*Phil. Mag.*, 1856) and Kirchhoff (*Pogg. Ann.*, 1857), while practical researches of the greatest importance to telegraphy have been made on this and kindred subjects by Faraday, Wheatstone, Guillemin, Varley, Jenkin, and others.

Measurement of current. Galvanometers.

Great improvements in galvanometers and galvanometry have been made in our time. One of the first to use an electro-magnetic instrument for measuring or indicating currents was Schweigger, who in 1820 invented the "multiplier." Nobili used (1825) the astatic "multiplier" with two needles, which is sometimes named after him. Becquerel (1837) used the electromagnetic balance, which was employed in an improved form by Lenz and Jacobi. Pouillet invented the sine and tangent compasses (1837). The defects of the latter instrument were pointed out by Poggendorff, and remedies suggested by him as well as Wheatstone and others. Weber effected great improvements in the construction and use of galvanometers, adapted them for the measurement of transient currents, and elaborated the method of oscillations which had been much used by Fechner. In 1849 Helmholtz invented the tangent compass with two coils which bears his name. Great improvements in delicacy and promptness of action have been made by Sir William Thomson in galvanometers destined for the measurement of resistance, and for indicating the feeble currents of submarine cables.

[1] Suggested mainly by Prof. Clerk Maxwell, and carried out by the present writer.

Resistance measurement.

The measurement of resistance has been carried to great perfection, chiefly owing to the labours of those who have busied themselves in perfecting the electric telegraph. Among such the highest place must be assigned to Sir Charles Wheatstone; his memoirs in the *Philosophical Transactions* (1843) gave a great impulse to this department of our science. He invented the rheostat, which underwent several modifications, but is now superseded by the resistance box which was first used by Siemens. The earlier methods of Ohm, Wheatstone, and others for measuring resistance were defective, because they depended on the constancy of the battery which furnished the current. These defects are completely obviated in the more modern "null methods," which may be divided into two classes—those which depend on the use of the differential galvanometer introduced by Becquerel, and those which are modifications of the Wheatstone's bridge method, invented by Christie and brought into use by Wheatstone. As examples of the latter, we may mention the methods of Thomson, and of Matthiessen and Hockin, for measuring small resistances, and Thomson's method for measuring the resistance of the galvanometer (see Maxwell's *Electricity and Magnetism*, pp. 404, 410). Many determinations of the specific resistances of metals and alloys have been made by Davy, Ohm, Becquerel, Matthiessen, and others. To Matthiessen in particular science is indebted for great improvements in method and a large body of valuable results in this department. The metals have been arranged in a series according to their conducting powers; and this series is found to be nearly the same for electricity as for heat. The conductivity of metals decreases as the temperature increases, the rate of decrease being nearly the same for most pure metals, but much smaller and more variable for alloys, which, on the other hand, have in general a large specific resistance. The earlier attempts to measure the resistance of electrolytes were not satisfactory, owing to insufficient allowance for polarization. In later times this difficulty has been overcome or avoided, and concordant results have been obtained by Beetz, Paalzow, Kohlrausch, Nippoldt, and Grotrian. The three last, using the electro-dynamometer and sine inductor, have made elaborate researches, establishing among many other interesting results that the conductivity of electrolytes increases with the temperature (*Pogg. Ann.*, 1869–74).

The measurement of the electromotive force and that of internal resistance of batteries in action are problems which, in their most general form, are inextricably connected. It is easy to measure with considerable accuracy the electromotive force of an open battery. We have merely to connect its poles with a Thomson's electrometer, and compare the deflection thus obtained with that due to some standard electromotive force. Another very satisfactory method is Latimer Clarke's modification of Poggendorff's compensation method (see Maxwell, 413). It is likewise not difficult to measure by a variety of methods, the most satisfactory being that of Mance (Maxwell, 411), the internal resistance of a battery when it is only traversed by a feeble current. But the measurement of the electromotive force and internal resistance of a battery working a strong current has hardly as yet been achieved with success; not that we undervalue the ingenious and important methods of Paalzow, Von Waltenhofen, Beetz (Wiedemann, i. § 181), and Siemens (*Pogg. Ann.*, 1874). The concordant results of the last two are indeed very remarkable. Still all these methods are more or less affected by the fact that the electromotive force of a battery depends on the current which it is sending (see Beetz in *Pogg. Ann.*, cxlii.).

Batteries.

The "crown of cups" of Volta was the parent of a great many other arrangements for the production of voltaic electricity. These had for their end either compactness or diminution of the internal resistance by enlarging the plates; we may mention the batteries of Cruickshank (1801), Wollaston (1815), and Hare (1822). In 1830 Sturgeon introduced the capital improvement of amalgamating the zinc plates. In 1840 Smee used platinum or silver plates instead of copper; by platinizing these he avoided to a considerable extent polarization by adhering hydrogen. In 1836 Daniell invented the two-fluid battery which bears his name. This battery is the best *constant* battery hitherto invented, and is, under various modifications, largely used in practical and scientific work. In the same year Grove invented his well-known battery, which surpasses Daniell's in smallness of internal resistance and in electromotive force, although, on the other hand, it is more troublesome to manage and is unsuited for long-continued action. Cooper, in 1840, replaced the expensive platinum plates of Grove's battery by carbon. This modification was introduced in a practical form into the battery of Bunsen (1842), which is much used on the Continent, and combines to a certain extent the advantages of Grove and Daniell. Among the more recent of one-fluid batteries may be mentioned the bichromate battery of Bunsen and the Léclanché cell. It is impossible here even to allude to all the forms of battery that have been invented. We may, however, in passing notice the gravitation batteries of Meidinger and Varley, and the large tray cell of Sir William Thomson.

Electrolysis.

Following up the discoveries of Nicholson, Carlisle, Davy, and others, Faraday took up the investigation of the chemical decompositions effected by the electric current. In 1833 he announced his great law of electro-chemical equivalents, which made an epoch in the history of this part of electricity. He recognized and for the first time thoroughly explained the secondary actions which had hitherto masked the essential features of the phenomenon. Faraday's discovery gave a new measure of the current, and he invented an instrument called the voltameter, which was much used by those who followed out his discoveries. Space fails us to notice in detail the labours of those who verified and developed Faraday's discovery. De la Rive, Becquerel, Soret, Buff, Beetz, Hittorf, Matteucci, Daniell, Miller, and many others have worked in this field.

Theories of electrolysis.

Many theories of electrolysis have been given. That of Grotthuss (1805) has been held under various modifications by many physicists; but none of these theories have done more than give us a convenient mode of representing experimental results. Clausius (*Pogg. Ann.*,