metal we are considering, then, from what has been shown (10), Tait's conjecture leads to the result that this curve is a straight line; and if the standard metal be lead, for which, according to Le Roux's results, the Thomson effect is zero, then the coefficient k of the Thomson effect is the tangent of the inclination of the representative line to the axis of abscissæ. And not only so, but it follows from formulæ (9) and (7) that, if A′AN, B′BN (fig. 54) be the lines corresponding to two metals, say Cu and Fe (of which the former is above the latter in the thermoelectric series at ordinary temperatures), and if AB, A′B′ be the ordinates corresponding to θ and θ', then the electromotive force in a circuit of the two metals whose junctions are at the temperatures θ and θ', tending to send a current from Cu to Fe across the hotter junction, is represented by the area ABB′A′. The Peltier effects at the two junctions are represented by the rectangles ABba and A′B′$b'a'$, and the Thomson effects, in the Cu and Fe respectively, by AA′DC and BB′GF, or by AA′$a'a$ and BB′$b'b$, which are equal to these. At N, where the lines intersect, the Peltier effect vanishes. N therefore is the neutral point; and, if the higher temperature lie beyond it, the electromotive force must be found by taking the difference of the areas NA′B′ and NAB, and so on. All the phenomena of inversion may be studied by means of this diagram, and the reader will find it by far the best means for fixing the facts in his memory.

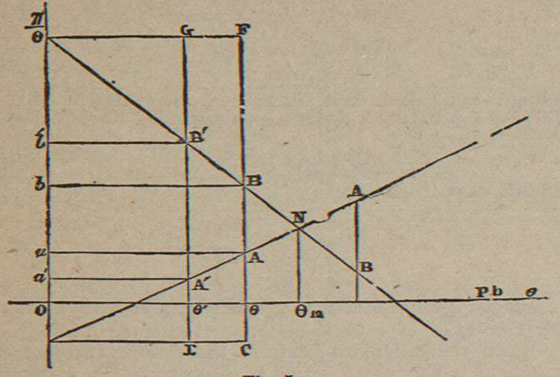

Fig. 54

Experiments of Tait, &c.

For several years back Tait[1] and his pupils have been engaged in verifying the consequences of this conjecture; and it has been shown, first, for temperatures within the range of mercury thermometers, and latterly for temperatures considerably beyond this range, that the hypothesis accords with experience. The methods employed by Tait in his experiments at high temperatures are of great interest and importance. One of these was to construct a curve whose ordinate and abscissa are the simultaneous readings of two thermoelectric circuits whose hot and whose cold junctions are kept at common temperatures. It is a consequence of the foregoing assumption that the curve thus obtained ought to be a parabola. Very good parabolas *were* in many cases obtained. In some cases, however, the curves, so far from being parabolas, were actually curves having points of contrary flexure. This anomaly led Tait to the discovery of the astonishing fact that the Thomson effect in iron changes its sign certainly once at a temperature near low red heat, if not a second time near the melting point. It was found that the inflected curves could be represented by piecing together different parabolas. Hence the line for iron in the thermoelectric diagram is a broken line made up of two if not three straight pieces. This peculiarity of the iron line was very strikingly shown by forming circuits of iron with the alloys PtIr or PtCu. Such circuits exhibit *two or even three neutral points* (see fig. 55). Another very elegant method of verification consisted in using along with an iron wire a multiple wire of Au and Pd, the resistances of whose branches could be modified at will. It is easy enough to show that the line for the Au-Pd wire is a straight line, passing through the neutral point of Au and Pd, and such that it divides the part of an ordinate lying between the Au and Pd lines in the ratio of the respective conductivities of the Au and Pd branches. Thus, by increasing ratios of the conductivities of the Pd and Au branches from 0 up to ∞, we can make the Au-Pd line sweep through the whole of the space between Au and Pd (fig. 55), and thus explore the part of the Fe line lying in the space. We get in this way first one neutral point, then two, then one, and then none in our Fe, Au–Pd circuit.

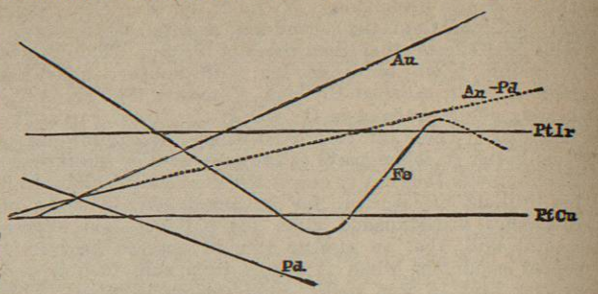

Fig. 55.

Current from Thomson effects alone

Tait has pointed out that, by using PtIr and Fe, and keeping the hot and cold junctions at the two neutral temperatures, we get a current maintained solely by the excess of the heat absorbed in the hotter iron over that developed in the colder. The electromotive force is represented by the area inclosed by the part of the zigzag on the Fe line cut off by the PtIr line (fig. 55). A similar case of thermoelectromotive force without Peltier effects may be obtained with three metals, such as Fe, Cd, Cu, whose neutral points lie within reasonable limits. The electromotive force in this case is represented by the triangle between the three lines.

Tait's results.

We subjoin a table, calculated by Professor Everett from Tait's diagram. The thermoelectric power is given in electromagnetic (C.G.S.) units, in terms of the temperature (t) in centigrade degrees, by means of the formula $\alpha+\beta t$, where α and β have the tabulated values :—

	α	β		α	β
Fe	−1734	+4·87	Cd	− 266	− 4·29
Steel	−1139	+3·28	Zn	− 234	− 2·40
Pt Ir ?	− 839	+0·00	Ag	− 214	− 1·50
Pt Ir (5 p.c. Ir)	− 662	+0·55	Au	− 283	− 1·02
Do. (10 do.)	− 593	+1·34	Cu	− 136	− 0·95
Do. (15 do.)	− 709	+0·63	Pb	+ 0	+ 0·00
Do. (15 do.)	− 577	+0·00	Sn	+ 43	− 0·55
Pt soft	+ 61	+1·10	Al	+ 77	− 0·39
Pt hard	− 260	+0·75	Pd	+ 625	+ 3·59
Pt Ni	− 544	+1·10	Ni to 175° C.	+2204	+ 5·12
Mg	− 224	+0·95	Do. 250° to 310° C.	+8449	−24·10
German silver	+1207	+5·12	Do. from 340° C.	+ 307	+ 5·12

We need scarcely warn the reader that the results in this table must not be rashly applied to any specimens of the metals taken at random. The temperature limits lie between 18° C. and 420° C.

It would be extremely interesting to compare the results

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[1] *Trans. R. S. E.*, 1873.

Comparison of heat and electric measurements.

of absolute measurements of the Peltier effect with Tait's theory; but, unfortunately, no data that we know of are available for the purpose. It is absolutely necessary for this purpose to have heat measurements and determinations of the lines of the metals in the same specimens. The data of Edlund[1] and Le Roux are quite useless for such a purpose. One result of Le Roux's is, however, interesting. He finds for the amount of heat developed at the junction BiCu, the values 3·09 and 3·95 at 25° C. and 100° C. respectively. Since the neutral temperature of BiCu is very high, the Peltier effect ought, according to Tait's theory, to vary as the absolute temperature. The absolute temperatures corresponding to 25° C and 100° C. are 298° and 373°, and we have $3{\cdot}95\div3{\cdot}09=1{\cdot}278$, while $373\div298=1{\cdot}252$; the agreement between these numbers bears out the theory so far.[2]

Seat of electromotive force.

General Considerations regarding the Seat of Electromotive Force.—Before proceeding to notice the remaining cases of the origin of electromotive force, in which the phenomena are more complicated, and the experimental conditions less understood, it may be well to call attention to a principle that appears to hold in most of the cases already examined. In most of these cases the seat of the electromotive force appears to be at the places where energy is either taken in or given out in the circuit.[3]

It is very natural to ask ourselves what the consequences would be if we applied this principle to the voltaic circuit. It would probably be admitted by most that the energy in the voltaic circuit is taken in mainly at the surface of the electropositive metal. This admission, taken in conjunction with the general principle above stated, leads us to the conclusion that the electromotive force resides mainly at the surface of the electropositive metal. The absorption or evolution of energy at the junction of the dissimilar metals is quite insignificant, and we should, on the same view, deny that any considerable part of the electromotive force resides there.

This view appears to be at variance with the theory of metallic contact, as now held by Sir William Thomson and others; and the burden of explaining the experiments made by him and others on the contact force of Volta is doubtless thrown on those who adopt this view. The position of such would very likely be that there is an uneliminated source of uncertainty in all these experiments[4] (see above, p. 85). On the other hand, those who adopt the contact force of Volta at the junction of copper and zinc as the main part of the electromotive force of Daniell's element are under the necessity of distinguishing this from the electromotive force corresponding to the Peltier effect, which must be a distinct effect, since it is but a very small fraction of that of a Daniell's cell.

We are, however, so very ignorant of the nature of the motion which is the essence of the electric current that the very form in which we have put the question may be misleading. If this motion be in the surrounding medium, as there is great reason to believe it to be, it would not be surprising to find that speculations as to the exact locality of the electromotive force *in the circuit* were utterly wide of the mark. The very language which we use implies a certain mode of analysing the problem which may be altogether wrong. The only thing of which we can as yet be sure is that the mathematical equations deduced from Ohm's law and other proximate principles are in exact accordance with experiment.

Pyroelectricity.—Some account of this interesting subject has already been given in the Historical Sketch at the beginning of this article. It will be well, however, to state here some of the conclusions of those who have recently investigated the matter. It seems now to be settled that it is not merely high or low temperature, *but change of temperature*, which gives rise to the electrical phenomena of pyroelectric crystals. The properties exhibited by tourmaline may be described thus. One end A of the crystal is distinguishable from the other end B by the dissymmetry of the crystalline form. A is called the *analogous* pole of the crystal, and B the *antilogous* pole. When the temperature of the crystal is increasing uniformly throughout, the analagous pole is positively electrified and the antilogous pole negatively electrified. When the temperature is decreasing uniformly throughout, the analogous pole is negative and the antilogous pole positive. This law was originally discovered by Canton,[5] but it seems to have been lost sight of again and rediscovered both by Bergman and by Wilcke in 1766. When the temperature is uniform, the positive and negative regions are symmetrically distributed about the central zone of the crystal, which is neutral. If the ends be unequally heated. this symmetry no longer obtains. It must not be forgotten that complications may arise from the crystal becoming electrical as a whole by friction, usually positive, like most other vitreous bodies.

Gaugain.

Gaugain[6] made a series of interesting experiments on the electrical properties of tourmaline, and concluded that a tourmaline whose temperature is varying may be compared to a voltaic battery of great internal resistance, consisting of an infinite number of cells, each of infinitely small electromotive force; so that the electromotive force is proportional to the length of the tourmaline, and its internal resistances is proportional to the section inversely and to the length directly. He also concluded that the amount of electricity furnished by a tourmaline, while its temperature varies either way between two given temperatures, is always the same.

Thomson's theory

In order to explain the properties of the tourmaline, it has been supposed[7] that the crystal is naturally in a state of electrical polarization, like that assumed by Maxwell in a medium, under the influence of electromotive force, or more nearly (since no sustaining force having an external origin is supposed) like that of a permanent magnet. The intensity of this polarization is supposed to be a function of the temperature. Supposing the tourmaline to remain for some time at the same temperature, a surface layer of electricity would be formed, which would completely mask the electrical polarization of the crystal, inasmuch as it would destroy all external electrical action. This neutralization would be instantly effected by running the crystal through the flame of a lamp. If, however, the temperature increase, then the polarization will, let us say, increase, so that the surface electrification no longer balances it. We shall thus get polar electrical properties of a certain kind. If the temperature decrease, the polarization will decrease, and we shall thus get polar properties of the opposite kind.

In many pyroelectric crystals there are more than one electric axis, so that we have several analogous and corresponding antilogous poles. An enumeration of the various crystals in which pyroelectric properties have been found, and a discussion of the peculiarities in their crystalline form, belongs more properly to the science of Mineralogy. Much has been done in this department by Köhler,[8] Gustav Rose and Riess,[9] and Hankel.[10] For some very interesting researches by Friedel see *Annales de Chimie et de Physique*, 1869.

Contact of nonconductors.

Frictional Electricity.—In accordance with the general principle laid down at the beginning of this section, we should expect to find an electromotive force at the surface which separates two different non-conducting media, just as we have found it at the boundary of two different conducting media. The effect of such a contact force would be very different however in the former of these cases, from what we have seen it to be in the latter. In the case of non-conductors the electricity cannot leave the surface of separation, but will simply accumulate on the two sides of it, till the force arising from electrical separation is equal to the contact force. On separating the bodies, in certain cases, we may carry away with us these surface layers of electricity, and it is an obvious consequence of our principles that the electrifications of parts of the two bodies that have been in contact must be equal and opposite. While the bodies are in contact the difference of potential between the layers of electricity corresponding to very considerable surface density may be very small, just as in Volta's condensing electroscope (see above, p. 34); but when we separate the bodies work is done against the electrical attractions, and the potential increases enormously.

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[1] Wied. *Galv.*, Bd. i. § 694.

[2] Since the above was written further experimental evidence in support of the theory has appeared. See Naccari and Bellati, *Atti del R. Ist. Veneto di Sc. Litt. ed Arti*, November 1877.

[3] Maxwell, vol. i. § 249. By "being taken in," in the case of heat for instance, is meant "disappearing as heat and appearing as electrokinetic energy." In a thermoelectric circuit this transformation occurs wherever there is Peltier or Thomson effect.

[4] Maxwell, *l.c.*

[5] *Phil. Trans.*, 1759.

[6] Mascart, t. ii.

[7] Thomson, *Phil. Mag.*, 1878, p. 26; or Nichol's *Cyclopædia of the Physical Sciences*, 1860.

[8] *Pogg. Ann.*, xvii., 1829.

[9] *Abh. der Berl. Akad.*, 1836 and 1843.

[10] *Pogg. Ann.*, xlix., l., lvi., 1840–2; also cxxxi., cxxxii., 1867, &c.

These hypothetical results tally very well with the electrical phenomena observed when non-conducting bodies are lightly rubbed together; and the above is nearly the explanation that most physicists of the present day would probably give (if they gave any) of what is called the "frictional generation of electricity."

All experimenters are agreed that equal quantities of positive and negative electricity appear in this case as in every other case of electrical separation; an experiment to prove the contrary would have to be very demonstrative indeed before it would now be accepted as conclusive. A single case of exception would revolutionize our fundamental ideas completely. The reader should consult on this point Faraday's *Experimental Researches*, series xi. ¶ ii.

The other consequences of our hypothesis are by no means so firmly established. One of these is that we ought to be able to arrange non-conducting bodies in a series such that any body rubbed with one below it in the series becomes positive, and rubbed by one above it negative.

Many electricians have attempted to establish such electromotive series, but the experimental conditions (see the admirable remarks of Riess, *Reibungselectricität*, § 907) are so complicated that nothing absolute has been attained. Yet it would appear that, if we could make sure that we were always dealing with definite materials under definite surface conditions, electromotive series could be constructed in which every different body would have a fixed position. As it is, the body bearing the same name in the lists of different experimenters was in all probability not exactly of the same material in all cases, and (we might say certainly) was not under the same surface conditions. We refer the reader to Riess (*l.c.*) for an admirable résumé of the work of different electricians in this department. Mascart has given a very interesting account of the matter (t. ii. § 834, &c.) from a more modern point of view. From these sources, together with indications in Young's *Lectures on Natural Philosophy*, the reader will be able to follow up the literature of this somewhat uninviting department of electricity.

Frictional series.

We give two instances of frictional electromotive series which may be useful in giving the reader a *general* idea how different bodies stand.

Wilcke.

The following is Wilcke's series[1] (1758):—Glass, woollen cloth, feathers, wood, paper, shellac, white wax, ground glass, lead, sulphur, metals.

Faraday.

Faraday[2] gives—cat and bear skin, flannel, ivory, feathers, rock crystal, flint glass, cotton, linen, white silk, the hand, wood, shellac, metals (iron, copper, brass, tin, silver, and platinum), sulphur.

To which Riess adds (in order) the highly negative bodies—gutta-percha, electrical paper,[3] collodion, gun cotton.

Peclet's experiments.

Considered as evidence for the contact hypothesis, the experiments of Peclet seem to be important. He used an apparatus which was virtually a Nairne's machine (see below, p. 101), in which the rubber could be varied at will. His general conclusions are quite in accordance with the contact theory. He found, for instance, that for the great majority of materials the quantity of electricity generated was independent of the pressure and of the breadth[4] of the rubber, and varied as the angular velocity of the cylinder, and it even appeared to be the same for rolling friction as for sliding friction, so long as the material of the rubber was unchanged.

Contact of conductor with non-conductor.

Besides the case of two non-conductors, we might consider the case of a conductor and a non-conductor in contact. Much of what has just been said would apply to this case also, an excellent example of which is furnished by a frictional electrical machine of the ordinary construction when the cushions are well furnished with amalgam. This is the place to give a short account of these time-honoured pieces of electrical apparatus. For a *history* of them we cannot do better than refer to Mascart[5] (*l.c.*), who has devoted much attention to the theory as well as the history of electrical machines in general.

A very common form of machine, called Ramsden's, is pictured in fig. 56. It consists, like all other frictional machines, essentially of three parts—(1) the rubbed or moving body, (2) the rubbers, and (3) the collectors and prime conductors. In the present instance the rubbed body is a disc of glass, which can be turned about a horizontal axis by means of a suitable handle. The efficiency of the machine depends very much on the quality of the glass of which the disc is made. According to Mascart, glass of old manufacture is superior to the more modern specimens, owing to the smaller proportion of alkali in the former; it appears, however, that the disc improves in most cases with age and use. Many other materials have been proposed to replace glass, which is somewhat costly when large discs are required. Ebonite has been tried a good deal of late, and has great advantages so far as its electrical properties are concerned; but it has the disadvantage that it warps very readily if heated incautiously, and its surface will not keep good for any length of time. Owing to decomposition under the action of light, a layer of sulphuric acid forms on the surface, after which it is very difficult to restore the electrical virtue so remarkable in the new material, although washing with hot water or immersion in a blast of steam are said to be effective in some degree.

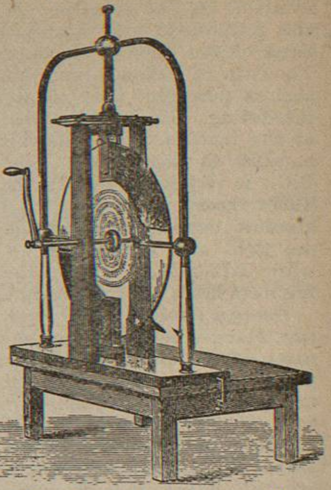

FIG. 56.—Ramsden's electrical machine.

The rubbers consist of two rectangular pieces of wood, hinged to supports attached to the framework of the machine, and fitted with springs and screws, so that they can be made to clip the plate with any required pressure. The rubbing surfaces are usually formed of leather, stretched as smooth and flat as possible (oiled silk is sometimes used, but it is not so durable). Before the leather cushions are fit for use, they must be carefully coated with amalgam. The amalgam most commonly used is Kienmayer's, which is a composition of two parts of mercury with one of zinc and one of tin. A great variety of different compounds of this kind have been used by different electricians, bisulphide of tin being a general favourite. The amalgam must be powdered as finely as possible, all grit being carefully removed. The cushions are then to be lightly smeared with lard, and worked together till the surface is very smooth and the greasiness almost gone; then the amalgam is to be carefully spread over them, and the surfaces again worked together till a uniform metallic surface is attained;[6] they are then ready for use. The amalgam aids the action of the machine in two ways,—first, by presenting a surface which is highly negative to glass; secondly, by allowing the negative electricity evolved by friction to flow away without hindrance from the points of contact. In order to secure the second of these advantages still more perfectly, the cushions should be carefully connected by strips of tinfoil, or otherwise, with knobs, which can be put to earth during the action of the machine.

The collectors are two stout metal forks bestriding the glass disc at the ends of a horizontal diameter. They are armed, on the sides next the glass, with rows of sharp points, which extend across the rubbed part of the disc. The prime conductor in the specimen we are describing forms a metal arch rising over the framework of the machine, and insulated from the sole by two glass pillars. Various forms are given to this part of the machine, according to the fancy or convenience of the experimenter. One important thing to be seen to is, that there be no salient points on it which might facilitate the dissipation of electricity by brush, convective or spark discharge.

After what has been said, the action of the machine requires little explanation. The disc, electrified positively by contact with the amalgam, carries away a positive charge, whose potential rises rapidly as it leaves the cushion,—so high, in fact, that there is a tendency to discharge to the air, which is prevented by covering the excited parts of the disc by pieces of oiled silk. When the highly charged glass comes opposite the points of the collector, owing to the inductive action, negative electricity issues from the points and neutralizes the charged plate, which at this point is virtually inside a closed conductor. The result of this is that the prime conductor becomes positively charged. The neutralized parts of the disc now pass on to be rubbed by the other cushion, and so on. The electricity goes on accumulating in the prime conductor until the potential is so great that discharge by surface conduction, or by spark, takes place between the collectors and the cushion, or between the collectors and the axis.

If it is desired to obtain negative electricity from a machine with a glass disc, we have simply to connect the prime conductor to earth, insulate the cushions, and collect the electricity from them.

We have said that there is a limit to the potential to which the charge on the prime conductor can be raised. We can never get a longer spark from the machine than the length of the interval between the collector and the cushion or the axis, as the case may be. The limiting potential can, however, be increased by insulating the axis of the machine, or making the axis itself wholly or partially of insulating material, and by using only one rubber and one collector, and placing them at the extremities of a diameter. The machine of Le Roy, often called Winter's machine (fig. 57), is constructed on this pattern. We get, of course, *cæteris paribus*, only half as much electricity per revolution with a machine of this kind as with Ramsden's; but the spark is longer, in consequence of the greater insulation between the cushion (A) and the collector (B).

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[1] According to Riess, the earliest.

[2] *Exp. Res.*, 2141.

[3] The parchment-like paper obtained by treating ordinary paper with concentrated sulphuric acid.

[4] That is, the dimension of the rubber perpendicular to the axis of rotation.

[5] A few notices of the earlier machines will be found in the Historical Sketch.

[6] Mascart, *l.c.*

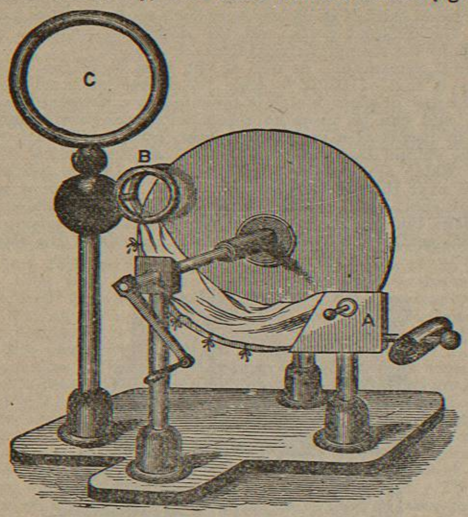

FIG. 57.—Le Roy's machine.

Nairne's machine.

The cylinder machine, also called Nairne's machine, was one of the first machines in which all the essential parts of the modern frictional machine appeared. It consists of a glass cylinder, which can be turned about a horizontal axis by a multiplying gear, or (as is now more usual) by means of a winch handle simply. The cushion is affixed to one horizontal metal cylinder, and the collector to another. It is necessary to insulate the axis in this machine, owing to its proximity to the ends of the conductors. Positive or negative electricity can be obtained with equal readiness by insulating either of the conductors, and connecting the other with the earth.

Those who desire more minute information concerning the functions of the different organs of the frictional machine, are referred to Mascart, tom. ii. § 834, &c. In the same place will be found a description of the famous machine with double plates constructed by Cuthbertson for Van Marum, and still to be seen in Teyler's Museum at Haarlem. A description of another of Van Marum's machines will be found in the article "Electricity" in the *Encyclopædia Metropolitana*. We take this opportunity of calling the scientific reader's attention to that article, which contains a great quantity of very valuable matter. Much of the work of the earlier electricians that we have been obliged to pass over in silence is fully described there.

Electric machines have also been constructed of less costly materials than glass or even vulcanite—of cloth and paper, for instance—for an account of these, see Riess, Bd. ii. §§ 936, 937.

Many experiments have been made on the electrification of sifted powders. We have already, in describing Lichtenberg's figures, alluded to some cases of this kind. As a rule, either the results are very uncertain, or the conditions of the experiment very complicated, so that the experiments are, in most cases, more curious than valuable, from a scientific point of view. Such as desire it will find abundant indications of the sources of information in Riess, Bd. i. §§ 938 *sqq.*, and *Ency. Metrop.*, art. "Electricity," §§ 193 *sqq.* One case of this kind, however, was so famous in its day, that we ought to mention it. In the year 1840 a workman at Newcastle, having accidentally put one hand in the steam which was blowing off at the safety valve of a high-pressure engine boiler, while his other hand was on the lever of the valve, experienced a powerful electric shock in his arms. Armstrong investigated the matter, and was led to construct his famous hydroelectric machine. This apparatus consists simply of an insulated boiler for generating high-pressure steam, fitted with a series of nozzles, kept cool by a stream of water. The steam issues from these nozzles and impinges on a conductor armed with points for collecting the electricity. The boiler gets electrified to a high potential, and a torrent of dense sparks may be drawn from it. The machine far surpassed any ordinary electrical machine in the quantity of electricity furnished in a given time. By means of it water was decomposed, and the gases collected separately. It was reserved for Faraday to trace the exact source of the electromotive force. He demonstrated, by a series of ingenious experiments, that the electrical action arose from the friction of the particles of water in the condensed steam against the wood of the nozzles.[1]

Remaining Cases.—Of these the most important are atmospheric electricity,[2] which belongs properly to meteorology, animal electricity, comprehending the study of the properties of the electrical fishes, and the electric phenomena of nerve and muscle. We have already indicated the literature of the former subject, and the latter belongs, for the present at least, to physiology. Evaporation, combustion, and in fact chemical action generally, have been brought forward by some experimenters as sources of electromotive force. About the last of all there is, of course, in one well-known case no doubt. As to the experiments generally alluded to under the other two heads—in particular, those of Laplace and Lavoisier, Volta, Pouillet, and others—there has been considerable difference of opinion, and we need not occupy space here with fruitless discussion of the matter.[3] Similar remarks apply to the electrification caused by pressure, cleavage, and rupture.

Electrophorus.

Machines founded on Induction and Convection.[4]—The oldest electric machine on this principle is the electrophorus of Volta, 1775. This consists of a plate of resinous matter (now usually vulcanite) backed by a plate of metal, and a loose metal plate, which we may call the collector, fitted with an insulating handle. The vulcanite is electrified by flapping it with a cat-skin, the collector is placed upon it, uninsulated for a moment by touching it with the finger,[5] and then lifted by the insulating handle. The collector plate is then found to be charged (positively) to a high potential, and sparks of some length may be drawn from it. The explanation of the action of the electrophorus is simple enough, if we keep clearly in view the *experimental fact* that the surface electrification of a non-conductor, like vulcanite, will not pass to a metal plate in contact with it under ordinary circumstances. If the surface density of the electrification be very great, discharge to the metal may no doubt take place; and if the collector be kept for a very long time in contact with the vulcanite, it is said that it may become negatively electrified. In the normal state, however, the negative electricity of the vulcanite remains upon it, and the thin layer of air intervening between it and the collector forms the dielectric in a condenser of very great capacity, so that a quantity of electricity collects on the lower surface of the condenser very nearly equal to that on the vulcanite. The difference of potential between the plates is very small (just as in Volta's condensing electroscope, see above, p. 34). When the collector is raised it carries away the positive charge—the potential of which, owing to the decrease in the capacity of the collector, rises enormously. It is to be noticed that the potential of the charge on the vulcanite rises to a corresponding extent. This remark partly explains the remarkable fact that, when the collector is kept on the excited vulcanite, its electrification may be kept for a long time (for weeks under favourable circumstances), whereas it speedily dissipates if the vulcanite be left uncovered. According to Riess, the fact that a plate of metal laid on an excited piece of glass tends to preserve its electrification was discovered by Wilcke in 1762.

If each time we charged the collector it were discharged by contact with the interior surface of a hollow conductor A, it is obvious that we could raise A by a sufficient number of such contacts to as high a potential as we please, provided it were sufficiently well insulated. This remark brings Volta's electrophorus into the present category of electrical machines.

In the rest of the induction machines to be described the excited dielectric is dispensed with, and an electrified conductor substituted in its place.

The earliest apparatus that involved the principle of such machines appears to have been Bennet's doubler.[6] The principle of this apparatus may be explained thus. Let A and C be two fixed discs, and B a disc which can be brought at will within a very short distance of either A or C. Let us suppose all the plates to be equal, and

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[1] *Exp. Res.*, ser. xviii. 2075.

[2] See Riess, § 1028 *sqq.*, and Thomson's papers in *Reprint* already alluded to; also *Ency. Metrop.*, art. "Electricity," § 219, for bibliography of older investigators.

[3] See Riess, §§ 943 *sqq.*

[4] This highly-descriptive title is Sir William Thomson's.

[5] In most modern specimens this is rendered unnecessary by a brass pin, which is in metallic connection with the metal backing of the vulcanite, and comes up flush with the surface of the vulcanite, so as to touch the collector when it is *in situ*.

[6] *Phil. Trans.*, 1787.

let the capacities of A and C in presence of B be each equal to p, and the coefficient of induction between A and B, or C and B, be q. Let us also suppose that the plates A and C are so distant from each other that there is no mutual influence, and that p' is the capacity of one of the discs when it stands alone. A small charge Q is communicated to A, and A is insulated, and B, uninsulated, is brought up to it; the charge on B will be $-\frac{q}{p}Q$. B is now uninsulated and brought to face C, which is uninsulated; the charge on C will be $\frac{q^2}{p^2}Q$. C is now insulated and connected with A, which is always insulated. B is then brought to face A and uninsulated, so that the charge on A becomes rQ, where

$$r=\frac{p}{p+p'}\left(1+\frac{q^2}{p^2}\right).$$

A is now disconnected from C, and here the first operation ends. It is obvious that at the end of n such operations the charge on A will be r^nQ, so that the charge goes on increasing in geometrical progression. If the distance between the discs could be made infinitely small each time, then the multiplier r would be 2, and the charge would be doubled each time. Hence the name of the apparatus.

Darwin. Cavallo. Nicholson.

Darwin, Cavallo, and Nicholson[1] devised mechanism for effecting the movements which in Bennet's instrument were made by hand. Cavallo's was a reciprocating movement, but in the machines of Darwin and Nicholson the motion was continuous and rotatory. Nicholson's doubler is a very elegant instrument. A drawing of it is given by Mascart (t. ii. § 845); the specimen there represented is very like one which was found among the late Professor Willis's apparatus, and is now in the Cavendish Laboratory at Cambridge. A still more elegant machine is "Nicholson's spinning condenser," which bears a remarkable resemblance to the induction machine of Töpler.[2] A description, with a figure, will be found in the *Encyclopædia Metropolitana*, art. "Electricity," § 112.

It is obvious that if any conductor be connected with the part of any of these machines corresponding to the conductor A in the above description, and the potential of A be raised to any small positive or negative value,[3] we can by means of the machine increase the charge, and therefore the potential, up to any required amount. We have, in fact, an electric machine which may be used for all the ordinary purposes. It was not with this view, however, that these pieces of apparatus were first invented, but rather for the purpose of demonstrating small electric differences. In this they were but too successful, for it was found that it was impossible to prevent them from indicating electric differences unavoidably arising within the apparatus itself. It was this difficulty no doubt that led to their being ultimately abandoned, and for a time forgotten, although they were once in high favour. Of late, however, they have been taken up as electromotors with great success.

Typical convecto-inductive machine.

The type of all these machines is an arrangement of the following description. A conductor or carrier C, or a series of carriers, is fastened upon the circumference of an insulating disc. At the ends of a diameter are two hollow conductors, A and B, embracing the disc on both sides, so that twice in the course of a revolution the carrier is virtually in the interior of a hollow conductor. Inside each conductor are two springs: one of these is in metallic connection with the conductor, and may be called the receiving spring; the other, called the inductor spring, is insulated from the conductor, and is connected either to earth or with the corresponding spring belonging to the other conductor. Suppose A to be at a small positive potential, and B at zero potential; starting with C in connection with the inductor spring inside A, it becomes negatively electrified and carries away its charge; it next comes in contact with the receiving spring in B, and, being now part of the interior of a hollow conductor, it parts with the whole of its charge to B; then it passes on and is charged positively at B's inductor spring; then discharges to A at A's receiving spring; and so on. The positive and negative charges are each a little increased every revolution, and the difference of potentials accordingly augmented. This is the principle of Varley's machine[4] (1860), and of Thomson's mouse mill and replenisher[5] (1867); is virtually that of Bennet's doubler.

Closely allied to these machines is Thomson's water-dropping potential equalizer. This consists of an insulated reservoir of water, with a long pipe, from the nozzle of which water is allowed to break in drops. It is obvious that if the potential of the reservoir be above that of the air surrounding the spot where the water breaks into drops, each drop will carry away with it a positive charge, and this will go on till the potentials are equalized. This device was introduced by Thomson in observations on atmospheric electricity. The burning match which he uses in conjunction with the portable electrometer acts in the same way. He has also constructed a water-dropping electric machine on a similar principle. Two streams of water break into drops inside two inductors connected with the internal armatures of two Leyden jars, A and B; the drops from each inductor fall into a receiver connected with the other inductor. A very small difference of potential between the jars starts or reverses the action of the apparatus; in fact, it will in general start of itself, and very soon sparks are seen passing between the different parts, and the drops are scattered in all directions by the strong electrical forces developed.

The most remarkable, as well as the most useful, of all these machines is that of Holtz.[6] Here the convection is effected by means of a disc of glass, which is mounted on a horizontal axis F (fig. 58), and can be made to rotate with considerable angular velocity by means of a multiplying gear, part of which is seen at X. Close behind this glass disc is fixed another vertical disc of glass, in which are cut two windows, B, B. On the side of the fixed disc next the rotating disc are pasted two sectors of paper, A, A, with short blunt points attached to them, which run out into the windows towards the rotating disc, without quite touching it. Two metal combs C are placed on the other side of the rotating disc (that nearest the reader), the teeth being put opposite the parts of A, A which lie towards the windows. The combs are fixed to metal shanks, which pass through a stout horizontal bar of ebonite. One of these shanks terminates in a couple of balls at E, and the other carries a sliding electrode D with a long ebonite handle. The framework which carries the horizontal ebonite bar and supports the fixed plates, &c., will be understood from the figure.

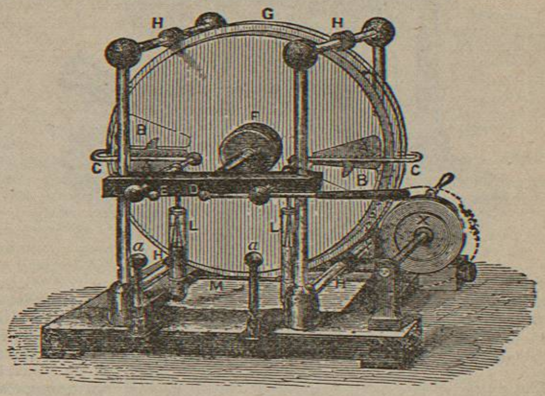

FIG. 58.—Holtz's machine.

The machine, as originally constructed by Holtz, contained only the parts we have described. Poggendorff doubled all the parts (except, of course, the electrodes D and E). The figure represents Ruhmkorff's modification of this construction. Behind the fixed disc there is another fixed disc, with windows and armatures like the first, and, beyond that, another movable disc mounted on the axis F. The combs are double, as will be seen from the figure. To start the machine, D and E are brought together, and one of the armatures (or one pair), say the right hand one, is electrified in any manner, let us say positively, and the disc set in rotation. After a little time a hissing noise is heard, and the machine becomes sensibly harder to turn, as if the disc were moving through a resisting medium. If the room be dark, long curved pencils of blue light will now be seen issuing from the points of the left hand comb, and running along the surface of the disc in a direction opposite to its motion, while little stars shine upon the points of the right-hand comb. After this state has been reached, the balls D, E may be separated, and a continuous series of brush discharges will take place between them, even when the distance is very considerable. If two Leyden jars, L, L, be hung upon the conductors which support the combs, the outer coatings being connected by a conductor M, then a succession of brilliant and sonorous sparks will take the place of the brushes. Instead of using the two jars L, L, we may connect D and E with the internal and external armatures of a condenser; it will then be found that, as we augment the capacity of the condenser (the angular velocity of the disc being constant), the frequency of the sparks diminishes, while their brilliancy increases. If we insert a high resistance galvanometer between D and E, it will indicate a current flowing from D to E, the intensity of which, under given atmospheric conditions and given state of the machine, will vary as the angular velocity, being independent, within very wide limits, of the resistance[1] between D and E.

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[1] *Phil. Trans.*, 1788.

[2] *Pogg. Ann.*, 1865.

[3] By connecting the conductor with the positive or negative pole of small galvanic battery, for instance.

[4] Jenkin, *Elect. and Mag.*, cap. xix.

[5] Described in the art. ELECTROMETER.

[6] *Pogg. Ann.*, 1865.

It is not difficult to give a general account of the action of this machine, although it is very hard to assign the precise importance of the individual parts, very slight modifications of which greatly affect the efficiency. Suppose D and E in contact; the right-hand armature, charged +, acts by induction on the right-hand comb, causing − electricity to issue from the points upon the disc. At the same time the positive electricity of the right comb passes through DE to the left comb, and issues from its teeth upon the parts of the disc at the other end of the horizontal diameter. This + electricity electrifies the left armature − by induction, + electricity issuing from the blunt point upon the further side of the rotating disc. The charges thus deposited on the disc are carried along, so that the upper half is electrified − on both sides, and the lower half + on both sides, the sign of the electrification being reversed as the disc passes between the combs and the armature by the electricity issuing from the combs and from the armatures. If it were not for dissipation in various ways, the electrification everywhere would obviously go on increasing; but in practice a stationary condition is soon attained, in which the loss from the armatures is just balanced by the gain owing to the action of the blunt points. After this, both sides of the disc are similarly electrified, the upper half[2] always −, the lower always +; + electricity continually issuing from the points of the right comb, − electricity from the points of the left. This is, of course, accompanied by a current of + electricity from right to left through DE.

Modification of Holtz's machine.

The machine of Holtz, as we have described it, is somewhat uncertain in its action in our moist climate; but a slight modification of it gives excellent results. Upon the axis X is fixed a disc of ebonite, large enough just to reach between the paper armatures. This disc is fitted with a small rubber attached to the frame of the apparatus, and forms a small electric machine, which keeps the armatures continually electrified.[3] The whole is inclosed in a glass case, with a beaker of sulphuric acid to dry the air. There is a machine of this kind at present in the Cavendish laboratory at Cambridge, which never fails when the auxiliary apparatus is at all in good order.

A very remarkable phenomenon often occurs when the electrodes of Holtz's machine are in connection with the armatures of a condenser of considerable capacity, and are so far separated that a spark does not pass. The machine charges the condenser up to a certain point, and then the condenser discharges along the surface of the disc. If the experiment be conducted in a dark room, a flash of light will be seen to pass along the surface of the disc, and thereafter it will be observed that the long positive brushes have shifted from one comb to the other; after a little the condenser discharges again, and the brushes will now be seen in their old place, and so on. This phenomenon, though interesting to study, is often inconvenient in practice. To prevent it, Holtz introduced the diagonal conductor which is seen on many machines. For an account of this, and for other details concerning these machines, we refer the reader to Mascart, t. ii. § 847 *sqq.*, whose account of the more obvious principles of this apparatus is among the most lucid we have seen. His account of the experiment of causing one Holtz's machine in action to turn the disc of another by the electrical reaction is of peculiar interest.

Induction coil.

Electromagnetic Induction Machines.—The type of these is the induction coil or inductorium, sometimes called Ruhmkorff's coil, after the great Parisian instrument-maker who first brought the instrument to perfection. The object of such machines is to obtain great electromotive force from sources which furnish large quantities of electricity, but have only small electromotive force.

The principles on which the action is founded has been sufficiently indicated above in our section on the induction of electric currents. We have also given in the Historical Sketch (p. 12) some notices of the literature of the subject; a brief enumeration of the essential parts of the machine is all that is necessary here.

We have first the primary coil—of thick wire and few windings, so as to have a small resistance and a small coefficient of self induction; the secondary coil surrounding the primary is of thin wire ($\frac{1}{10}$ mm. or so), with many windings, the length in large machines being often 100,000 metres. In order to avoid the danger of disruptive discharge between parts of the insulated wire, the coil is divided up by insulating septa, so that parts at very different potentials are separated. In the centre of the primary is placed a bundle of iron wires; this greatly strengthens the action, and a good deal depends on the quality of the iron, which should be very soft. The interruptor is simply a lever, worked by the coil itself or by an electromagnet separate from the coil, by means of which the circuit of the primary is made and broken automatically. A variety of forms have been given to the part of the apparatus; the interruptor of Foucault is a very common one.[4] For some purposes a break driven by clock-work is used. The condenser, a very important part of the apparatus, is made of a number of sheets of tinfoil, interleaved with sheets of oiled silk or varnished paper. One set of leaves of the condenser is connected with one side of the break, and the alternate set with the other side. The function of the condenser is to provide a way for the electricity when the circuit is broken, and thus to prevent the intense spark of the extra current in the primary, which destroys the contact surfaces of the break, and, what is worse, prolongs the fall of the primary current, and thereby reduces the average electromotive force of the induction current.

Other devices have been tried for effecting the same object as the condenser, such as inserting a fine metallic wire or an electrolyte as an alternative circuit to the break; and these answer the purpose to a considerable extent. An important improvement affecting this part of the apparatus has recently been introduced by breaking the primary circuit between the poles of a magnet, the effect of which is that the spark is suddenly drawn aside (blown out as it were). A considerable increase of striking distance between the poles of the secondary results from this arrangement.

ABSOLUTE MEASUREMENTS.

We have already indicated the considerations which determine the fundamental units in the two systems that have come into practical use. We ought now to explain how practical standards can be constructed to represent these fundamental units, or at least known multiples of them. It is necessary to have such standards in order that we may be able to measure electrical quantities in absolute measure by simple and expeditious methods of comparison, it being obviously impossible in practice to make absolute measurements directly on all occasions.

Measure of E. M. F.

Electrostatical System.—By means of Thomson's absolute electrometer we can determine any electromotive force in absolute measure. In this way Thomson found the electromotive force of Daniell's battery to be ·00374 C.G.S. electrostatical units.[5]

Resistance.

By using the absolute electrometer (see art. ELECTROMETER), or another that had been compared with it, we could by the method given above, p. 46, find a resistance (which was large enough to suit the method) in electrostatical measure.

Current.

Then, having standards of electromotive force and resistance, we could easily measure a current in electrostatic measure by applying Ohm's law. The same thing might be done by constructing the standard of quantity, which is the charge on an isolated sphere of unit radius charged to unit potential. By comparing the throw of a galvanometer when unit quantity is discharged through it with the deflection produced by any current, we could determine the latter in absolute measure by observing the time of oscillation of the galvanometer and the logarithmic decrement of its oscillation (see Maxwell, vol. ii. § 749).

Dielectric strength.

Among the absolute measurements in the present system of units, we must not omit to mention Sir Wm. Thomson's determinations of the dielectric strength of different thicknesses of air. From these, and from the measurement of the electromotive force of Daniell's cell just mentioned, he concluded that a Daniell's battery of 5510 elements would be competent to produce a spark between two slightly curved metallic surfaces at $\frac{1}{3}$ of a centimetre asunder in ordinary atmospheric air.[6]

Electromagnetic measure.

Electromagnetic System.—The great majority of the absolute determinations hitherto made have reference to this system. We make no attempt here to instruct the reader concerning the details of this subject; such an attempt would lead us into technical particulars intelligible only to a few scientific men. We are fortunate, however, in being able to refer the English reader to two books which contain in a collected form all, or nearly all, the requisite information, viz. Maxwell's *Electricity and Magnetism*, and the collected Reports of the Committee of the British Association on Electrical Standards.[7]

As a specimen of the *theoretical* considerations involved, the reader may take Maxwell's method for determining the coefficient of self-induction of a coil (given above, p. 80). If we know the value of L (in centimetres) from calculation, then equation (33) might be used to find x in absolute measure. This would not be a practicable method, inasmuch as the calculation of L would be difficult if not impossible; we might, however, determine L by comparison[8] with a coefficient of mutual induction which *could* be calculated.

The earliest absolute measurement of the resistance of a wire (by

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[1] We speak of resistances of 1 to 10,000 or 100,000 ohms.

[2] The line of division is not horizontal, however, if, indeed, it be exactly a diameter. See Mascart.

[3] Compare Carré's machine, Mascart, t. ii. § 856.

[4] See Wiedemann's *Galv.*, or Du Moncel, *Notice sur l'Appareil de Ruhmkorff*.

[5] *Reprint of Papers*, § 305, &c.

[6] *Reprint of Papers*, § 340.

[7] Such as wish to go deeply into the matter must read the *Maassbestimmungen* of Weber.

[8] Maxwell, vol. ii. § 756.