PART I.

ELECTROSTATICS.

CHAPTER I

DESCRIPTION OF PHENOMENA.

Electrification by Friction.

27.] EXPERIMENT I. Let a piece of glass and a piece of resin, neither of which exhibits any electrical properties, be rubbed together and left with the rubbed surfaces in contact. They will still exhibit no electrical properties. Let them be separated. They will now attract each other.

27.1 If a second piece of glass be rubbed with a second piece of resin, and if the pieces be then separated and suspended in the neighbourhood of the former pieces of glass and resin, it may be observed—

(1) That the two pieces of glass repel each other.

(2) That each piece of glass attracts each piece of resin.

(3) That the two pieces of resin repel each other.

27.2 These phenomena of attraction and repulsion are called Electrical phenomena, and the bodies which exhibit them are said to be electrified, or to be charged with electricity.

27.3 Bodies may be electrified in many other ways, as well as by friction.

27.4 The electrical properties of the two pieces of glass are similar to each other but opposite to those of the two pieces of resin: the glass attracts what the resin repels and repels what the resin attracts.

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27. *resin*: a viscous secretion of some plants, especially trees, that hardens upon drying. Amber (Arabic *anbar*), whose Greek name, *elektron*, has given “electricity” its name, is a fossilized resin. Amber is used in jewelry, while other resins are used in the manufacture of varnishes, lacquers, and perfumes.

27.5 If a body electrified in any manner whatever behaves as the glass does, that is, if it repels the glass and attracts the resin, the body is said to be vitreously electrified, and if it attracts the glass and repels the resin it is said to be resinously electrified. All electrified bodies are found to be either vitreously or resinously electrified.

27.6 It is the established practice of men of science to call the vitreous electrification positive, and the resinous electrification negative. The exactly opposite properties of the two kinds of electrification justify us in indicating them by opposite signs, but the application of the positive sign to one rather than to the other kind must be considered as a matter of arbitrary convention, just as it is a matter of convention in mathematical diagrams to reckon positive distances towards the right hand.

27.7 No force, either of attraction or of repulsion, can be observed between an electrified body and a body not electrified. When, in any case, bodies not previously electrified are observed to be acted on by an electrified body, it is because they have become electrified by induction.

Electrification by Induction.

28.] EXPERIMENT II.* Let a hollow vessel of metal be hung up by white silk threads, and let a similar thread be attached to the lid of the vessel so that the vessel may be opened or closed without touching it.

28.1 l.et the pieces of glass and resin be similarly suspended and electrified as before.

28.2 Let the vessel be originally unelectrified, then if an electrified piece of glass is hung up within it by its thread without touching the vessel, and the lid closed, the outside of the vessel will be found to be vitreously electrified, and it may be shewn that the electrification outside of the vessel is exactly the same in whatever part of the interior space the glass is suspended.

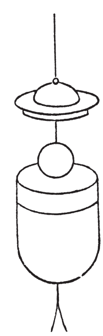

Fig. 4.

*This, and several experiments which follow, are due to Faraday, 'On Static Electrical Inductive Action,' … *Exp. Res.*, vol. ii. p. 279.

27.5 *vitreous*: of, or of the nature of, glass (Latin *vitrum*).

27.6 *exactly opposite properties of the two kinds of electrification*: The two kinds are "opposite" inasmuch as they are capable of nullifying one another. Maxwell will give examples in paragraphs 29.6, 30., and 31.2.

28. *white silk threads*: Not dyed, as dyeing might impair the insulating ability of the silk.

28.3 If the glass is now taken out of the vessel without touching it, the electrification of the glass will be the same as before it was put in, and that of the vessel will have disappeared.

28.4 This electrification of the vessel, which depends on the glass being within it, and which vanishes when the glass is removed, is called electrification by Induction.

28.5 Similar effects would be produced if the glass were suspended near the vessel on the outside, but in that case we should find an electrification, vitreous in one part of the outside of the vessel and resinous in another. When the glass is inside the vessel the whole of the outside is vitreously and the whole of the inside resinously electrified.

Electrification by Conduction.

29.] EXPERIMENT III. Let the metal vessel be electrified by induction, as in the last experiment, let a second metallic body be suspended by white silk threads near it, and let a metal wire, similarly suspended, be brought so as to touch simultaneously the electrified vessel and the second body.

29.1 The second body will now be found to be vitreously electrified, and the vitreous electrification of the vessel will have diminished.

29.2 The electrical condition has been transferred from the vessel to the second body by means of the wire. The wire is called a *conductor* of electricity, and the second body is said to be *electrified by conduction*.

Conductors and Insulators.

29.3 EXPERIMENT IV. If a glass rod, a stick of resin, or gutta-percha, or a white silk thread, had been used instead of the metal wire, no transfer of electricity would have taken place. Hence these latter substances are called Non-conductors of electricity. Non-conductors are used in electrical experiments to support electrified bodies without carrying off their electricity. They are then called Insulators.

28.4 *Induction*: From Latin *inducere*, lead into or within; hence to bring about, give rise to. Note the important qualification, “which vanishes when the glass is removed.” Electrification by induction is maintained only in the presence of the inducing body. Electrification by conduction, which will be described in Experiment III, remains even after the electrifying body has been withdrawn.

29.3 *gutta-percha*: a tough plastic substance obtained from the milky secretion of the Malaysian percha and other trees.

Non-conductors ... Insulators: Note that the first term names the *property*, the second names the *use* of the material. From Latin *insula*, island.

29.4 The metals are good conductors; air, glass, resins, gutta-percha, vulcanite, paraffin, &c. are good insulators; but, as we shall see afterwards, all substances resist the passage of electricity, and all substances allow it to pass, though in exceedingly different degrees. This subject will be considered when we come to treat of the motion of electricity. For the present we shall consider only two classes of bodies, good conductors, and good insulators.

29.5 In Experiment II an electrified body produced electrification in the metal vessel while separated from it by air, a non-conducting medium. Such a medium, considered as transmitting these electrical effects without conduction, has been called by Faraday a Dielectric medium, and the action which takes place through it is called Induction.

29.6 In Experiment III the electrified vessel produced electrification in the second metallic body through the medium of the wire. Let us suppose the wire removed, and the electrified piece of glass taken out of the vessel without touching it, and removed to a sufficient distance. The second body will still exhibit vitreous electrification, but the vessel, when the glass is removed, will have resinous electrification. If we now bring the wire into contact with both bodies, conduction will take place along the wire, and all electrification will disappear from both bodies, indicating that the electrification of the two bodies was equal and opposite.

29.4 *vulcanite, paraffin*: Vulcanite, also called ebonite or hard rubber, is made by treating natural rubber with sulfur for increased strength. Paraffin is an inflammable wax obtained by distillation from oil. Its name derives from Latin *parum*, little + *affinis*, related—expressing its low chemical activity.

29.5 *Dielectric*: From Greek *dia*, through. The reference to action *through* something reflects Faraday's conviction—one which Maxwell shares—that induction is not action at a distance, rather, the medium plays a role in sustaining the effect. Notice that when describing *conduction* (29.2), Maxwell described the electrical condition as having been transferred "by means of" the conductor, not "through" it. Whatever the nature of conduction, Maxwell is not adopting the locution of electricity moving "through" a conductor as water flows through a pipe.

29.6 *the vessel … will have resinous electrification*: It would appear, then, that while the vessel and the second body were joined by the conductor they constituted a single body, resinously electrified at the vessel "end" and vitreously electrified at the other extremity.

the electrification of the two bodies was equal and opposite: This is the first example of the "opposite properties" which Maxwell ascribed to vitreous and resinous electricity in (27.6) above.

30.] EXPERIMENT V. In Experiment II it was shewn that if a piece of glass, electrified by rubbing it with resin, is hung up in an insulated metal vessel, the electrification observed outside does not depend on the position of the glass. If we now introduce the piece of resin with which the glass was rubbed into the same vessel, without touching it or the vessel, it will be found that there is no electrification outside the vessel. From this we conclude that the electrification of the resin is exactly equal and opposite to that of the glass. By putting in any number of bodies, electrified in any way, it may be shewn that the electrification of the outside of the vessel is that due to the algebraic sum of all the electrifications, those being reckoned negative which are resinous. We have thus a practical method of adding the electrical effects of several bodies without altering their electrification.

31.] EXPERIMENT VI. Let a second insulated metallic vessel, *B*, be provided, and let the electrified piece of glass be put into the first vessel *A*, and the electrified piece of resin into the second vessel *B*. Let the two vessels be then put in communication by the metal wire, as in Experiment III. All signs of electrification will disappear.

31.1 Next, let the wire be removed, and let the pieces of glass and of resin be taken out of the vessels wfthout touching them. It will be found that *A* is electrified resinously and *B* vitreously.

31.2 If now the glass and the vessel *A* be introduced together into a larger insulated metal vessel *C*, it will be found that there is no electrification outside *C*. This shews that the electrification of *A* is exactly equal and opposite to that of the piece of glass, and that of *B* may be shewn in the same way to be equal and opposite to that of the piece of resin.

31.3 We have thus obtained a method of charging a vessel with a quantity of electricity exactly equal and opposite to that of an electrified body without altering the electrification of the latter, and we may in this way charge any number of vessels with exactly equal quantities of electricity of either kind, which we may take for provisional units.

31.3 *equal quantities of electricity … which we may take for provisional units*: But the primary function of a *unit* is to enable us to *count*; and Maxwell has not yet shown how these "equal quantities of electricity" can so serve. In the series of experiments to follow he will outline how these quantities may be accumulated and compared with other quantities of electricity, thus making true measurement possible. In contrast to such "provisional" units, Maxwell will define a systematic unit of electricity, based on the law of electrical force, in Art. 41 below.

32.] EXPERIMENT VII. Let the vessel *B*, charged with a quantity of positive electricity, which we shall call, for the present, unity, be introduced into the larger insulated vessel *C* without touching it. It will produce a positive electrification on the outside of *C*. Now let *B* be made to touch the inside of *C*. No change of the external electrification will be observed. If *B* is now taken out of *C* without touching it, and removed to a sufficient distance, it will be found that *B* is completely discharged, and that *C* has become charged with a unit of positive electricity.

32.1 We have thus a method of transferring the charge of *B* to *C*.

32.2 Let *B* be now recharged with a unit of electricity, introduced into *C* already charged, made to touch the inside of *C*, and removed. It will be found that *B* is again completely discharged, so that the charge of *C* is doubled.

32.3 If this process is repeated, it will be found that however highly *C* is previously charged, and in whatever way *B* is charged, when *B* is first entirely enclosed in *C*, then made to touch *C*, and finally removed without touching *C*, the charge of *B* is completely transferred to *C*, and *B* is entirely free from electrification.

32.4 This experiment indicates a method of charging a body with any number of units of electricity. We shall find, when we come to the mathematical theory of electricity, that the result of this experiment affords an accurate test of the truth of the theory.

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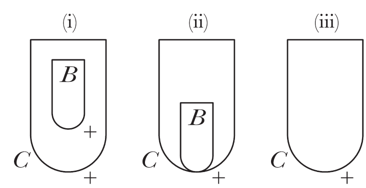
32. *Experiment VII*: The three steps of this experiment are illustrated in the drawing. Step (i): Body *B*, charged with unit positive electricity, induces an equal positive electrification of the exterior of *C*; this step is identical to Experiment II (28.2). Step (ii): When body *B* touches the interior of *C* the exterior electrification of *C* does not change; but what is the condition of *B* at that moment? Step (iii): *B* is removed to a great distance and is found to be fully discharged, while *C* retains unit positive electrification. It appears that *B* must have transferred its electricity to *C* by conduction, for *C* retains its charge even after *B* has been removed. And this can only have happened while *B* was in contact with *C* in step (ii). Evidently, then, *B* will have become discharged at the first moment of contact in step (ii); and the charge of *C*, which had formerly been maintained by induction so long as *B* and *C* were not in contact, now stands in its own right, just like the charge that was acquired by conduction in Experiment III (29.1–2).



32.4 *a method of charging a body with any number of units of electricity*: The whole series of experiments has been directed to this end, for we now have a practical demonstration that electricity is a countable—that is to say a measurable—quantity.

33.] Before we proceed to the investigation of the law of electrical force, let us enumerate the facts we have already established.

33.1 By placing any electrified system inside an insulated hollow conducting vessel, and examining the resultant effect on the outside of the vessel, we ascertain the character of the total electrification of the system placed inside, without any communication of electricity between the different bodies of the system.

33.2 The electrification of the outside of the vessel may be tested with great delicacy by putting it in communication with an electroscope.

33.3 We may suppose the electroscope to consist of a strip of gold leaf hanging between two bodies charged, one positively, and the other negatively. If the gold leaf becomes electrified it will incline towards the body whose electrification is opposite to its own. By increasing the electrification of the two bodies and the delicacy of the suspension, an exceedingly small electrification of the gold leaf may be detected.

33.4 When we come to describe electrometers and multipliers we shall find that there are still more delicate methods of detecting electrification and of testing the accuracy of our theories, but at present we shall suppose the testing to be made by connecting the hollow vessel with a gold leaf electroscope.

33.1 *we ascertain … the total electrification of the system*: In the previous paragraph Maxwell invited us to "enumerate the facts we have already established." It may seem puzzling, then, that in the present paragraph he names only the one "fact" here cited; but he will continue the enumeration in the following Article.

Notice that the foregoing experiments have identified *physical operations* that are the analogs of the operations of arithmetic! Thus in (31.3) we had the unit; in (32.4) we had addition and hence multiplication; and now with the method of an "insulated hollow conducting vessel" we can manifest the overall electrification of any system and compare it to a known number of units. Electricity, therefore, is fully established as a quantity that can be represented mathematically. Maxwell will state this explicitly in (34.6) below.

33.3 *We may suppose the electroscope to consist…*: The instrument Maxwell here describes was introduced by Bohnenberger about 1814 and is of a distinctive design. The more usual electroscope consisted of a pair of gold leaves that would repel one another upon electrification, as is suggested at the bottom of the hollow vessel in Maxwell's drawing for Figure 4 (Art. 28). The charming instrument shown here, an example of Bohnenberger's design, was built by Joseph Naylor of Depauw University about 1900. The gold leaf is missing. Photograph by Thomas B. Greenslade, Jr.

33.5 This method was used by Faraday in his very admirable demonstration of the laws of electrical phenomena.*

34.] I. The total electrification of a body, or system of bodies, remains always the same, except in so far as it receives electrification from or gives electrification to other bodies.

34.1 In all electrical experiments the electrification of bodies is found to change, but it is always found that this change is due to want of perfect insulation, and that as the means of insulation are improved, the loss of electrification becomes less. We may therefore assert that the electrification of a body placed in a perfectly insulating medium would remain perfectly constant.

34.2 II. When one body electrifies another by conduction, the total electrification of the two bodies remains the same, that is, the one loses as much positive or gains as much negative electrification as the other gains of positive or loses of negative electrification.

34.3 For if the two bodies are enclosed in the hollow vessel, no change of the total electrification is observed.

34.4 III. When electrification is produced by friction, or by any other known method, equal quantities of positive and negative electrification are produced.

34.5 For the electrification of the whole system may be tested in the hollow vessel, or the process of electrification may be carried on within the vessel itself, and however intense the electrification of the parts of the system may be, the electrification of the whole, as indicated by the gold leaf electroscope, is invariably zero.

34.6 The electrification of a body is therefore a physical quantity capable of measurement, and two or more electrifications can be combined experimentally with a result of the same kind as when two quantities are added algebraically. We therefore are entitled to use language fitted to deal with electrification as a quantity as well as a quality, and to speak of any electrified body as 'charged with a certain quantity of positive or negative electricity.'

35.] While admitting electricity, as we have now done, to the rank of a physical quantity, we must not too hastily assume that it is, or is not, a substance, or that it is, or is not, a form of energy, or that it belongs to any known category of physical quantities. All that we have hitherto proved is

* Exp. Res., vol. ii. p. 279.

34.3 *For if the two bodies are enclosed in the hollow vessel*: The bodies are first to be enclosed in the vessel, and then brought into contact.

that it cannot be created or annihilated, so that if the total quantity of electricity within a closed surface is increased or diminished, the increase or diminution must have passed in or out through the closed surface.

35.1 This is true of matter, and is expressed by the equation known as the Equation of Continuity in Hydrodynamics.

35.2 It is not true of heat, for heat may be increased or diminished within a closed surface, without passing in or out through the surface, by the transformation of some other form of energy into heat, or of heat into some other form of energy.

35.3 It is not true even of energy in general if we admit the immediate action of bodies at a distance. For a body outside the closed surface may make an exchange of energy with a body within the surface. But if all apparent action at a distance is the result of the action between the parts of an intervening medium, it is conceivable that in all cases of the increase or diminution of the energy within a closed surface we may be able, when the nature of this action of the parts of the medium is clearly understood, to trace the passage of the energy in or out through that surface.

35.4 There is, however, another reason which warrants us in asserting that electricity, as a physical quantity, synonymous with the total electrification of a body, is not, like heat, a form of energy. An electrified system has a certain amount of energy, and this energy can be calculated by multiplying the quantity of electricity in each of its parts by another physical quantity, called the Potential of that part, and taking half the sum of the products. The quantities 'Electricity' and 'Potential,' when

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35.] *if the total quantity … within a closed surface is increased or diminished, the increase or diminution must have passed in or out through the closed surface*: A quantity that obeys this principle is said to be *conserved*. In succeeding paragraphs Maxwell will assert that *matter* is conserved, but *heat* is not.

35.3 *It is not true even of energy in general if we admit the immediate action of bodies at a distance*: That is, *energy* will not be conserved, if action at a distance really exists. Since the principle of conservation of energy had by this time become fully accepted among British physicists, such a statement implicitly makes a *reductio ad absurdum* argument against action at a distance.

For a body outside the closed surface may make an exchange of energy with a body within the surface: Suppose electrified bodies A and B, mutually attracted; then each will have potential energy with respect to the other. If then the electrification of B were to increase, the potential energy of A would likewise increase. But if electrical attraction is truly "at a distance," that energy increase cannot have passed through a closed surface surrounding A—contradicting the final statement in paragraph 35.

35.4 *this energy can be calculated by … taking half the sum of the products*: Maxwell is anticipating; he will derive this calculation in Art. 84 below.

multiplied together, produce the quantity 'Energy.' It is impossible, therefore, that electricity and energy should be quantities of the same category, for electricity is only one of the factors of energy, the other factor being 'Potential.'

35.6 Energy, which is the product of these factors, may also be considered as the product of several other pairs of factors, such as

A Force	× A distance through which the force is to act.
A Mass	× Gravitation acting through a certain height.
A Mass	× Half the square of its velocity.
A Pressure	× A volume of fluid introduced into a vessel at that pressure.
A Chemical Affinity	× A chemical change, measured by the number of electro-chemical equivalents which enter into combination.

35.7 If we ever should obtain distinct mechanical ideas of the nature of electric potential, we may combine these with the idea of energy to determine the physical category in which 'Electricity' is to be placed.

36.] In most theories on the subject, Electricity is treated as a substance, but inasmuch as there are two kinds of electrification which, being combined, annul each other, and since we cannot conceive of two substances annulling each other, a distinction has been drawn between Free Electricity and Combined Electricity.

Theory of Two Fluids.

36.1 In what is called the Theory of Two Fluids, all bodies, in their unelectrified state, are supposed to be charged with equal quantities of positive and negative electricity. These quantities are supposed to be so great that no process of electrification has ever yet deprived a body of all the electricity of either kind. The process of electrification, according to

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36. *In most theories on the subject, Electricity is treated as a substance*: From the standpoint of Maxwell's cautionary remarks in (35.), such treatments would appear to exhibit excessive haste. Nevertheless Maxwell will devote this Article and the next to a serious examination of the two principal fluid theories. Why do this? One reason, certainly, is that fluid thinking had already become well established in scientific discourse; no student of electricity could afford to be ignorant of its precepts. But perhaps a deeper reason is that these theories tend to generate clever contrivances that have no actual basis in the phenomena, and whose artfulness merely disguises unnecessary assumptions. One such artifice is the one Maxwell mentions at the conclusion of this paragraph: the distinction between "free" and "combined" electricity. He will call attention to its spurious character in (36.6) below.