ELECTRICITY SOUND, AND LIGHT

MILLIKAN AND MILLS

A SHORT UNIVERSITY COURSE IN

ELECTRICITY, SOUND, AND LIGHT

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PREFACE

This book represents primarily an attempt to secure a satisfactory articulation of the laboratory and class-room phases of instruction in physics. It is an outgrowth of the conviction that in courses of intermediate grade in colleges, universities, and engineering schools a real insight into the methods of physics, and a thorough grasp of its foundation principles are not readily gained unless theory is presented in immediate connection with such concrete laboratory problems as are calculated to give the student a sound basis for intelligent theoretical work.

Nevertheless the book is intended to be much more than a laboratory manual. It represents an attempt to present a complete logical development, from the standpoint of theory as well as experiment, of the subjects indicated in the title. It is designed to occupy a half year of daily work, two hours per day, in either the freshman, sophomore, or junior years of the college or technical-school course. In the University of Chicago about one half of this time is devoted to class discussions, lecture-table demonstrations, quizzes, and problems, and the remainder to laboratory work. The course is preferably preceded by a similar course in mechanics, molecular physics, and heat, the two courses together constituting a year's work in college physics.

The method of treatment is throughout analytical rather than descriptive, although no mathematics beyond trigonometry is presupposed. It is assumed that the student has already had a beginning course in descriptive physics in the high school or elsewhere.

Most of the apparatus required is of the stock sort found in all moderately well-equipped college laboratories. A few special pieces have been designed (Figs. 60, 99, etc.) where for one reason or another existing forms seemed ill adapted to the needs of the course. In the University of Chicago the apparatus is not, in general, used in duplicate. Nine or ten experiments are commonly kept going at once, two pupils working together. The classes are limited to twenty-five.

The authors' thanks are due to Leeds & Northrup for the cut of their post-office-box bridge (Fig. 51 *b*), to Queen & Co. for the original of their tangent galvanometer (Fig. 22), to the American Instrument Company for the original of their voltmeter (Fig. 40), and to William Gaertner & Co. for the originals of the magnetometer (Fig. 14), the voltameter (Fig. 27), the electric calorimeter (Fig. 39), the ballistic galvanometer (Fig. 60), the earth inductor (Fig. 107), the ideal dynamo (Fig. 99), and the spectrometer (Fig. 194).

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ELECTRICITY, SOUND, AND LIGHT

CHAPTER I

MAGNETIC AND ELECTRIC FIELDS OF FORCE

1. Quantity of magnetism. It is well known that under certain circumstances bars of iron and of some other metals, when suspended so as to be free to rotate about a vertical axis, turn so as to point north and south. A body which possesses the property of so doing is called a *magnet.* If the two north-seeking ends of two such magnets are brought near together, they are found to repel each other. The same is true of the two south-seeking ends. But a north-seeking and a south-seeking end are found to attract each other. On account of these opposite characteristics the north-seeking ends of magnets are called N poles, the south-seeking, S poles. The above facts may then be stated in the general law: *Magnetic poles of like kind repel one another, of unlike kind attract one another.*

Different magnets of the same length placed at a given distance from a suspended magnet are observed to exert different forces upon it. The *quantities of magnetism* in the poles, or the *pole strengths,* are then arbitrarily taken as proportional to the forces exerted. That is, the force which a given pole M exerts, at a given distance, upon some standard pole is taken as the measure of the number of units of magnetism in M. It may then be proved experimentally, by the method used in Chapter II, that the force f exerted between any two poles M and m is directly proportional to the product mM and inversely proportional to the square of the distance r between them. The algebraic statement of this experimental relation is

$$f = k\frac{mM}{r^2}, \tag{1}$$

in which k is a factor of proportionality depending upon the choice of the unit of magnetism and upon the medium through which the force acts. It has been decided to choose this unit so that k equals unity for air; that is, the equation $f = mM/r^2$, applied to air, contains the definition of unit magnetic pole. Thus if two magnets are chosen for which $m = M$, and if r is taken equal to 1 cm., then m is by definition unity if f is found to be equal to 1 dyne. In other words, *a unit magnetic pole is a pole of such strength that when placed at a distance of 1 cm. from an equal pole it repels or attracts it with a force of 1 dyne.*

2. Quantity of electricity. It is also equally well known that when a glass rod has been rubbed with silk it attracts a pith ball, but after contact with the pith ball, repels it. Similarly, when ebonite has been rubbed with cat's fur it attracts a second pith ball, but after contact with the pith ball, repels it. Furthermore, the pith ball which has touched the rubbed glass and is repelled by it is attracted by the ebonite, while the ball which is repelled by the ebonite is attracted by the glass. On account of this behavior the pith balls are said to have been *electrified,* or to have received *charges of electricity*; and on account of the opposite characteristics of these charges the one is called *positive* and the other *negative.* These charges of electricity can be produced in other ways, but in every case it has been decided to call a charge positive when it is repelled by a glass rod which has been rubbed with silk, negative when it is repelled by an ebonite rod which has been rubbed with cat's fur. The above facts may then be stated in the general law: *Electrical charges of like sign repel one another, of unlike sign attract one another.* It need scarcely be said that in adopting these conventions and in setting up this law no assumption whatever has been made regarding the nature of electricity. It has merely been agreed to call a body *electrified,* or *charged* *with electricity,* which behaves toward pith balls or other objects as does the rubbed glass or the rubbed ebonite.

Definitions precisely similar to those used in the quantitative study of magnetism are adopted also in the quantitative study of electricity. Thus if q and Q are two electric charges the magnitudes of which are measured by the forces which they exert upon a third charge at a given distance from it, then it can be proved experimentally that

$$f \propto \frac{qQ}{r^2}.$$

As in magnetism, so in electricity, the unit of quantity is chosen so that for action between charges separated by air

$$f = \frac{qQ}{r^2}. \tag{2}$$

This equation contains, then, the definition of unit charge. In words, *unit quantity of electricity (unit charge) is defined as that quantity which placed in air at a distance of 1 cm. from an equal quantity acts upon it with a force of 1 dyne.*

3. Electrical conduction. If a charged ebonite rod is rubbed over one end of a long metal body which rests upon sealing wax or glass, a pith ball placed near the remote end of the metal body will at once be attracted to it. If the metal body is replaced by one of glass, or wood, or almost any nonmetallic solid, no effect whatever is produced upon the pith ball. In view of experiments of this sort, it is customary to divide substances into two classes, *conductors* and *insulators,* or nonconductors, according to their ability to transmit electrical charges. Thus metals and solutions of salts and acids in water are all conductors of electricity, while porcelain, rubber, mica, shellac, wood, silk, vaseline, turpentine, paraffin, and oils generally are insulators. No hard and fast line, however, can be drawn between conductors and insulators, since substances can be found of all degrees of conductivity between that of sulphur, amber, or quartz, the best insulators, and that of silver and copper, the best conductors.

4. Distinctions between electricity and magnetism. The fact of conduction constitutes one of the most essential distinctions between electricity and magnetism. Electrically charged bodies lose their charges, in part at least, as soon as they are touched by conductors, but such treatment has no influence whatever upon magnetic poles. The phenomena of magnetism therefore show nothing which is at all analogous to the phenomenon of conduction in electricity. Furthermore, all bodies, conducting or nonconducting, can be strongly electrified by friction if they are mounted upon insulating supports, but only iron, steel, nickel, and some newly discovered alloys of copper, magnesium, and aluminum, called Heussler alloys, can be appreciably magnetized. Magnetism and electricity are then to be regarded as distinct phenomena. A peculiar relationship, however, which has been found to exist between them will be discussed in Chapter III.

5. Electrostatic induction. If a positively charged body *A* (Fig. 1) is placed in the neighborhood of an uncharged body *B*, which is supplied with pith balls or strips of paper *a*, *b*, *c*, as shown in the figure, the divergence of *a* and *c* will show that the ends of *B* have received electrical charges, while the failure of *b* to diverge will show that the middle of *B* is uncharged. Further, a positively charged glass rod will be found to repel *c* and attract *a*. The experiment illustrates the fact that the mere *influence* which an electric charge exerts upon a conductor placed in its neighborhood is able to produce electrification in that conductor, the remote end receiving a charge of sign like that of the original charge, while the near end has a charge of opposite sign. If *A* is removed the charges at *a* and *b* entirely disappear, and the conductor *B* is found to be altogether uncharged, thus showing that the total amount of positive electricity which appeared at one end of *B* must have been exactly equal to the total amount of negative which appeared at the other end. *The phenomenon of the appearance of equal and opposite electrical charges in the opposite ends of a conductor placed near a charged body is known as electrostatic induction*, and a conductor in this condition is said to be *electrically polarized.*

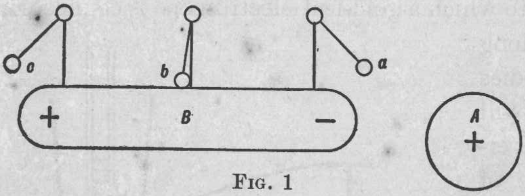

FIG. 1

6. Positive and negative electricities always appear in equal amount. That positive and negative electricities always appear in exactly equal amount, as well when the electrification is produced by friction as by induction, may be convincingly shown by attaching a piece of fur or flannel to the end of a strip of ebonite, rubbing with it the end of another similar strip, bringing the two together, without separating them, near a charged pith ball or other electroscope, then separating them and bringing each in succession near the electroscope. So long as they are together they will exhibit no electrification whatever, but when separated they will show charges of opposite sign. That these charges are exactly equal is shown by the fact that they exactly neutralized each other before the separation.

The test for the equality of the two charges may be made extremely delicate by inserting the two rubbed bodies together into a hollow metal vessel to which a gold-leaf electroscope is connected, as in Figure 2. So long as the two rubbed bodies are together the leaf will show no trace of divergence, but when one of them is removed the leaf will stand out in the position of the dotted line. When this rubbed body is replaced by the other the divergence will be of equal amount, but the charge will be of opposite sign, as can be shown by bringing a positively charged glass rod near the electroscope; for then, if the latter already had a positive charge, the divergence will be increased by the approach of the glass rod, but if it had a negative charge the divergence will be diminished.

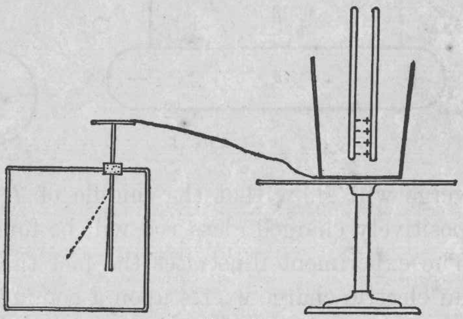

FIG. 2

7. Theories of electricity. During the nineteenth century the facts of electricity were most commonly described in terms of the so-called *two-fluid theory*. Although this theory is no longer regarded as corresponding closely to reality, and although it has perhaps never been generally accepted as anything more than a *convenient fiction*, it is so intimately related to the present nomenclature of the subject as to deserve careful attention. According to it all bodies contain equal amounts of two weightless electrical fluids, *positive electricity* and *negative electricity.* These fluids are self-repellent but mutually attractive, so that their effects completely neutralize one another in bodies in the normal condition. But if a conductor, i.e. a body in which the fluids are able to move about, is brought near a charged body, the fluid of like sign is driven to the remote end, while the fluid of unlike sign is drawn to the near end of the conductor. This furnishes the explanation of the phenomenon of induction.

In insulators the fluids are supposed not to be free to move from point to point, but friction between dissimilar substances causes electrical separation in the adjacent boundary layers of the dissimilar substances, the excess of positive which goes to one body being necessarily equal to the deficiency of positive, i.e. the excess of negative, which is left upon the other.

The modern modification of the two-fluid hypothesis is that which has been developed within the last decade by Drude and Riecke in Germany. It is identical with the older two-fluid theory, save that it replaces the weightless and continuous electrical fluids by equal numbers of positive and negative corpuscles, or *electrons*, which are assumed to be constituents of the atoms of all substances, but which, in the case of conductors, are continually becoming detached from the atoms; so that at a given instant there are always present free positive and free negative corpuscles which are able to move through the conductor in opposite directions under the influence of any outside electrical force. Conductors differ from insulators only in that the atoms of the latter do not lose their corpuscles to any appreciable extent.

The old-time rival of the two-fluid theory was the so-called *one-fluid theory*, originally due to Benjamin Franklin. It differed from the two-fluid theory only in regarding a positive charge as indicating an *excess*, a negative charge, a *deficiency* in a certain normal amount of one single, all-pervading electrical fluid, viz. positive electricity, which was self-repellent but strongly attracted by ordinary matter. In order to account for the mutual repulsions of negatively charged bodies, it was found necessary to assume that the particles of ordinary matter, when dissociated from electricity, repelled one another.

A modern modification of the one-fluid theory has recently come into prominence through the combined work of several physicists in high standing, notably Lord Kelvin and J. J. Thomson. According to this theory a certain amount of positive electricity is supposed to constitute the nucleus of the atom of every substance. About the center of this positive charge are grouped a number of very minute negatively charged corpuscles, or electrons, the mass of each of which is approximately $\frac{1}{2000}$ of that of the hydrogen atom. The sum of the negative charges of these electrons is supposed to be just equal to the positive charge of the atom, so that in its normal condition the whole atom is neutral or uncharged. But in the jostlings of the molecules of a conductor electrons are continually becoming detached from the atoms, moving about freely between the molecules, and then reëntering other atoms which have lost electrons. Therefore, at any given instant, there are always present in any conductor a large number of free negative electrons and an exactly equal number of atoms which have lost electrons, and which are therefore positively charged. Such a conductor would, as a whole, show no charge either of positive or of negative electricity. But the presence near it of a body charged, for example, negatively would cause the negatively charged electrons to stream away to the remote end, leaving behind them the positively charged atoms, which, in solids, are not supposed to be free to move appreciably from their positions. In the presence of a positively charged body, on the other hand, the electrons would be attracted to the near end, while the remote end would be left with the immovable positive atoms.

The only advantage of this theory over that which assumes the existence of two types of corpuscles is that, while there is much direct experimental evidence for the existence of negative corpuscles of about $\frac{1}{2000}$ the mass of the hydrogen atom, no direct evidence whatever for the existence of such positively charged corpuscles has as yet been brought to light. In general, wherever positively charged bodies appear they are found to be of atomic size. The negative corpuscles, on the other hand, are sometimes found as constituents of atoms, sometimes as independent detached bodies.

It will be seen that this last theory is like Franklin's in that it assumes but one *movable* kind of electrical matter, i.e. one *electrical fluid,* while it is unlike it in making this fluid negative instead of positive, and also in making it consist of discrete particles. It is like the two-fluid theory, however, in postulating the existence of two distinct entities called respectively positive and negative electricity. The positive electricity, however, plays quite the same rôle which in the old one-fluid theory was assigned to ordinary matter.

8. Fields of force. A *field of force* is simply a region in which force exists. It may be a magnetic, electrical, or gravitational field which is under consideration. The *strength of field* at any point in such a region is the number of units of force which unit quantity (be it mass, pole strength, or charge) experiences at the point considered. Thus the strength of field at a point 1 cm. distant from a unit pole (conceived as concentrated at a point) is unity. *Unit field is, then, a field in which unit quantity experiences 1 dyne of force.* For example, the strength of magnetic field at a given point in space is ten units if unit pole experiences 10 dynes of force when placed at this point.

The *direction* of a gravitational field at any point is defined as the direction in which a small quantity of matter would tend to move if placed in the field at the point considered. The direction of a magnetic field is defined as the direction in which an isolated *N* pole would move. The direction of an electric field is defined as the direction in which an isolated positive charge of electricity would move.

A *line of force* in any one of these fields is the direction in which a free mass, a free *N* pole, or a free *positive* charge would move if it had no inertia. It is convenient and customary, however, to conceive of as many *lines* drawn across any square centimeter taken at right angles to the direction of the force as the field possesses units of strength at the point considered. The line of force then becomes the unit of field intensity or strength; that is, in a gravitational field *a line* means a field strength such that a force of 1 dyne acts on every gram placed in it. Thus, since the earth's field strength at the surface is 980 dynes, it is customary to consider 980 lines of gravitational force as piercing each square centimeter of the earth's surface. In magnetic fields, in connection with which the convention is most commonly used, a line means a field strength such that a force of 1 dyne acts on each unit pole. It has received the special name of a *gauss.* In electrical fields the more usual term is *tube of force,* and the conception is that as many tubes of force cross any square centimeter at right angles to the direction of the field as there are units in the field strength at that point.

With these conventions it is evident that a uniform field is represented by a system of parallel lines of force, and conversely, that where the lines of force are parallel, the field has everywhere the same strength. A convergent system of lines represents a field of increasing strength; a divergent system of lines represents a field of decreasing strength. It need scarcely be said that a line of force has no objective reality. The representation of fields of force by lines is a matter of convenience only.

9. Gravitational potential. The term "potential" was first used in connection with gravitational forces. Potential is a characteristic of a point in space, not, in general, of a body. It may be looked upon merely as an abbreviation for the expression "the potential energy of unit mass at the point considered." Thus at a point *a* above the surface of the earth (Fig. 3) a gram of mass possesses a certain potential energy with reference to a point *b* on the surface of the earth. This potential energy is the amount of work that the gram of mass can do in falling to the earth. Since the term "potential" is merely an abbreviation for the potential energy of unit mass, it is evident that potential is measured in energy or work units. The potential of a point is unity when it requires one erg of work to bring unit mass from the point which is taken as the zero of potential up to the point considered. The potential energy of unit mass at the point *a* (see Fig. 3) is greater if the point *c*, below the

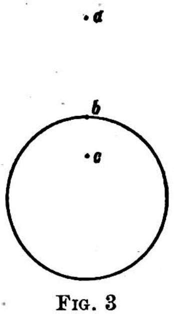

FIG. 3

surface of the earth, is taken as the point of reference instead of the point b. Thus it is evident that some point must be chosen arbitrarily from which to reckon the potential of other points.

A point which is infinitely distant from all attracting or repelling bodies is taken as the point from which *absolute potential* is reckoned, i.e. such a point is taken as the *absolute zero* of potential. The absolute potential, then, of any point in the universe is the number of ergs of work which must be done (by some outside agent) to bring unit mass from this absolute zero up to the point considered.

In general, we are more concerned with the difference in potential (usually written P.D.) between two points than with the absolute potentials of the points. The P.D. between two points is then defined as the amount of work which the external agent must do in order to carry the unit mass from the point of the lower to that of the higher potential; or, what amounts to the same thing, the P.D. is the amount of work which the acting force does in carrying unit mass from the point of higher to that of lower potential.

Now the force of gravitation is always an attractive, never a repellent, force. For all points which are at a finite distance from any astronomical body the work which the external agent must do in bringing unit mass from an infinite distance to any point is therefore less than nothing. That is, the work is done not by, but against, the action of the external agent. From the definition of absolute potential, as given above, it is evident that the gravitational potential of all points within a finite distance of any astronomical body must be negative.

10. Magnetic potential. The above definitions hold almost without change for magnetic forces, save that it is necessary to specify whether the unit quantity is an N pole or an S pole. *The magnetic potential of a point is defined as the amount of work which an external agent must do against the existing magnetic field in order to bring a unit N pole from infinity up to the point considered.* Thus the potential in the immediate neighborhood of an N pole is evidently positive, because the unit N pole is repelled, and hence the external agent must do work in order to bring up the pole from infinity. It is equally evident that the potential in the immediate neighborhood of an S pole is negative.

11. Electrical potential. Similarly, the electrical potential of a point is the amount of work required to bring unit positive charge from infinity up to the point considered. Points in the neighborhood of a positive charge have therefore a positive potential; those in the neighborhood of a negative charge have a negative potential. These definitions apply as completely in the study of so-called current electricity as in that of static electricity. *Under all circumstances the term P.D. means the amount of work required to carry unit positive charge between the two points considered.*

12. Equipotential surfaces. An equipotential surface is the locus of a system of points all of which have the same potential. Thus the gravitational equipotential surfaces about the earth are approximately spherical surfaces concentric with it, because the amount of work required to bring unit mass to within a certain distance of the center of the earth is the same, no matter from what side the earth is approached.

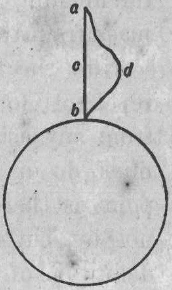

Fig. 4

Now it can be shown that *the direction of the field of force at any point is perpendicular to the equipotential surface passing through that point.* In order to prove this statement it is first necessary to show that the work done in carrying a body between any two points is independent of the path chosen. If a body is carried from b to a over the path bda (Fig. 4) a certain amount of work w is done upon it. Now suppose the work of the path bda is less than that of the path bca. Then when the body returns to b over the path acb it will give up a certain amount of energy w', i.e. it will do a certain amount of work w'. As a net result of the operation we have expended an amount of work w and have received back a larger amount of work w', and yet have brought everything back to the initial condition. We have therefore created an amount of energy $w'-w$. But according to the doctrine of the conservation of energy this is impossible. Hence w' cannot be greater than w. By reversing the operation it can be proved that w cannot be greater than w'. That is, the work of the path bda is equal to that of any other path bca.

Now let *nop* (Fig. 5) represent any equipotential surface. By the definition of such a surface the work required to move a unit body from any arbitrary zero, say *m*, over the distance *mn* is the same as that required to move it over the distance *mo*. But by the proposition just proved the work of the path *mn* is equal to the work of the path *mo* plus *on*. Hence the work corresponding to the path *on* must be zero. If it requires no work to move a body over an equipotential surface, the existing force can have no component along that surface, i.e. *the force must be everywhere normal to an equipotential surface.*

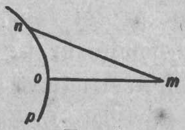

FIG. 5

13. Potential of a conductor in electrical equilibrium. That the electrical potentials of all points on or within a conductor in the static condition must be the same follows at once from the fact of conductivity. For as soon as a conductor *ab* (Fig. 6) is brought into the field of a positively charged body *c* the negative electricity within *ab* at once moves toward *b* and a positive charge appears at *a* until further movement of negative toward *b* is checked by the action of the negative accumulated at *b* and the positive accumulated at *a*. It is obvious, then, that *there can be electrical equilibrium within a conductor only when all electrical forces within the conductor have been reduced to zero.* No electrical force, then, can exist within a conductor in the static condition; hence no work can be required to move unit charge from one point to another within the conductor. It follows that *all points within or upon a conductor in the static condition must have the same potential.* The above reasoning holds as well for hollow as for solid conductors, provided no insulated charged bodies exist within the hollow portion.

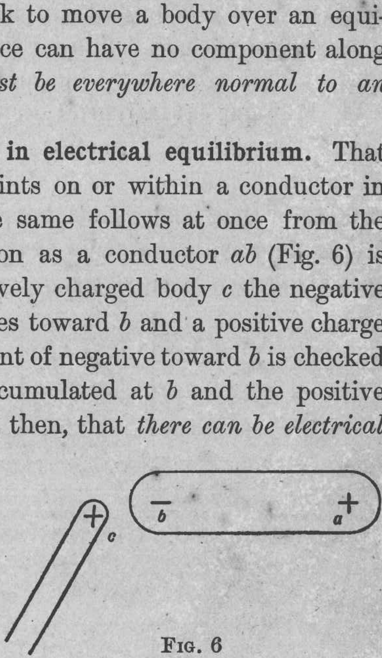

FIG. 6

The experimental verification of these conclusions was first made by Faraday, who covered a large box with tin foil and went inside with very delicate electroscopes. These remained wholly unaffected even when powerful electrical disturbances took place