TELEPHONE LINES

AND THEIR PROPERTIES

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BY

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PREFACE TO THE SIXTH EDITION.

As the changes in telephone practice within the past two years have made necessary some changes in the text, it has been thought best to make the revision as complete as possible. Several chapters have been almost entirely rewritten, many diagrams added and the number of half-tone reproductions of photographs largely increased. An account of the latest developments in the design of long lines has been added, and a short chapter on Composite Working and Wireless Telephony.

I desire particularly to express my obligation to Dr. Pupin for revising the abstract of his paper on "Telephony over Cables and Long-Distance Air Lines."

I am glad to acknowledge, also, my indebtedness to The H. B. Camp Company, John A. Roebling's Sons Company, and The C. McIntire Company, for the use of information and cuts.

WILLIAM J. HOPKINS.

PHILADELPHIA, March, 1901.

PREFACE.

FULLY realizing the meagreness of the available literature on the subject of telephone lines, I have written the following chapters in the hope that my experience may prove of benefit to others. I have not attempted to go into the subject of line construction in any detail; but as its omission would have left the book incomplete, I have given an outline of the methods of design and construction. I hope that the applied mechanics of line construction may be fully treated in the near future by someone fully competent to do so in the light of personal experience.

The subject of exchanges has been taken up principally to round out the scope of the book; and for much of the matter under this head I am indebted to the writings of Messrs. A. S. Hibbard, F. A. Pickernell, and J. J. Carty.

In covering the ground which comes most properly under the title, the properties of telephone lines, I have endeavored, so far as possible, to avoid mathematics, and to treat the subject in a way which would prove most interesting and instructive to the general reader as well as to the student. Where it has seemed best to put in a mathematical demonstration, it has been put in a foot-note.

The results of investigations in regard to the properties of telephone lines, I have endeavored to state clearly in a general discussion. They are not susceptible of tabulation, and the most important properties it is impossible to formulate exactly.

I have treated rather fully the questions of interference with the telephone currents from outside sources, especially the troubles from electric railways; for my practice in that direction, during the last four or five years, has been considerable, and enables me to deal with that subject in the light of personal experience. This question is still of considerable importance in this country, and its treatment here may be of assistance to managers of exchanges in practical work.

It was my intention that the book should be one which would prove useful to the practical man, as well as that it should serve as a basis for a lecture course to students. I have therefore thought it best to introduce some matter in which correct elementary ideas of matter and energy are developed, so as to lead up to the most modern conception of the method of propagation of electro-magnetic disturbances.

In conclusion, I wish to express again my indebtedness to the writings of Messrs. Carty, Pickernell, and Hibbard, as well as to well-known works of Dr. Fleming, Dr. Lodge and others, and my further obligation to Mr. Carty for the results of his experiments on static induction.

WILLIAM J. HOPKINS.

PREFACE TO THE FOURTH EDITION.

SINCE the last revision of this book, the changes in practice in the matters treated are not sufficient to warrant changes in the text. There is one point, however, in regard to which it seems necessary to be somewhat explicit.

It is stated in the preface to the first edition that the book is intended both to be useful to the practical man and to serve as the basis for a lecture course to students. In the most progressive technical schools of the present day, lecture courses are provided, at an advanced period, upon special branches of engineering. These lectures are given by specialists, and each series covers, so far as circumstances allow, the practice in that particular branch, as an immediate preparation of the student for contact with active professional work. A general comprehensive training in mathematics, science, and other engineering subjects is presupposed, and no attempt is made in these courses to supply such matter, which the student has usually acquired pretty thoroughly at this stage of his education.

One special subject of this class is telephone engineering; and so far as that subject includes telephone lines and their properties, the matter must be substantially that outlined here. Transmitters and receivers, which would also belong in such a course if they had not previously received thorough consideration, will be treated in a similar manner in a little book now in preparation.

Any elementary scientific matter herein contained is intended, not to take the place of a thorough mathematical and scientific training, but as a reminder to the man who has had that training and to help the practical man who has not had it to profit by the book.

I cannot refrain from expressing my gratification at the evidences which have come to me of the usefulness of the work to those for whom it was primarily written.

WILLIAM J. HOPKINS.

PHILADELPHIA, January, 1898.

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TELEPHONE LINES

AND THEIR PROPERTIES.

CHAPTER I.

OVERHEAD CITY LINES.

WHEN, on the introduction of the telephone, it became necessary to construct lines for the transmission of its currents, the knowledge of what were the requirements for an efficient telephone line was conspicuously wanting. In regard to the properties of such a rapidly alternating current but little—in fact, practically, nothing—was known. The lines must be built, however; so by applying the small stock of knowledge which had been acquired in telegraphy, and by more or less skilful guessing, shift was made to get up something that would work, although not very well. Since that beginning rapid advances have been made in the improvement of apparatus, and no less rapid strides in the knowledge of what constitutes a good line. We are beginning to know, too, chiefly as the result of experiment, what are the characteristics of the telephone current; its magnitude, its effects on other currents and on itself, and the effects of external and internal conditions upon it; what characteristics we wish to preserve, and what we wish to alter or destroy. From this knowledge, which is still very incomplete, we can to some extent determine the proper form, dimensions, and material to make use of in building a line; and it is most necessary that the maximum efficiency of transmission should be obtained, for the most perfect apparatus can accomplish nothing if the requisite characteristics of its current are lost or destroyed.

For a successful telephone system the first requisite is efficient service; and this can be obtained only by good construction and careful inspection and maintenance. I shall therefore take up, first, the design and construction of the system.

THE SYSTEM.

The exchange, or central office, should, of course, be so situated that the total length of line to be erected shall be a minimum. It is seldom possible, however, to place the exchange in the most desirable location. The routes for the lines must be secured, and as the so-called "house-top" construction is not now considered good practice, the lines must run in streets, either on poles or under the surface. The method which has been found the best, and the most economical for maintenance, is to run trunk-lines on poles or in conduits, as far as possible. From these main trunk-lines, of which there may be three or four, branches are run off at intervals, and the individual wires are distributed from definite points. Lines designed in this manner are much easier to maintain in good order than those put up in a haphazard way. If on poles, they are not so unsightly, and they do not form the net-work overhead of which there has been so much and such well-founded complaint.

If the lines are underground, this is the only practical way to run them. The cables, containing many wires or circuits, are laid in conduits underground, the branches being led off from the main trunk-lines in the same manner as in the case of pole-lines. At the proper points the distribution of wires is made on poles, the cables being led up the poles and connected in cable-boxes to the individual wires.

In many systems, covering large areas, the subscribers may be divided to advantage into several groups. This is the case in all large cities where the distances are great, and where the communication between different groups or classes of subscribers is not very frequent. In such cases the main exchange is so placed as to serve to the best advantage the busiest districts. A sub-exchange is established for each outlying district, and is connected by a trunk-line of comparatively few wires with the main exchange.

Upon this question of branch exchanges there has been great difference of opinion. Their use may cause delay in making connections and increases the liability to make mistakes; but when a switchboard has grown beyond a moderate size, these objections are outweighed by other considerations. Modern practice appears to approve branch exchanges and their use is growing.

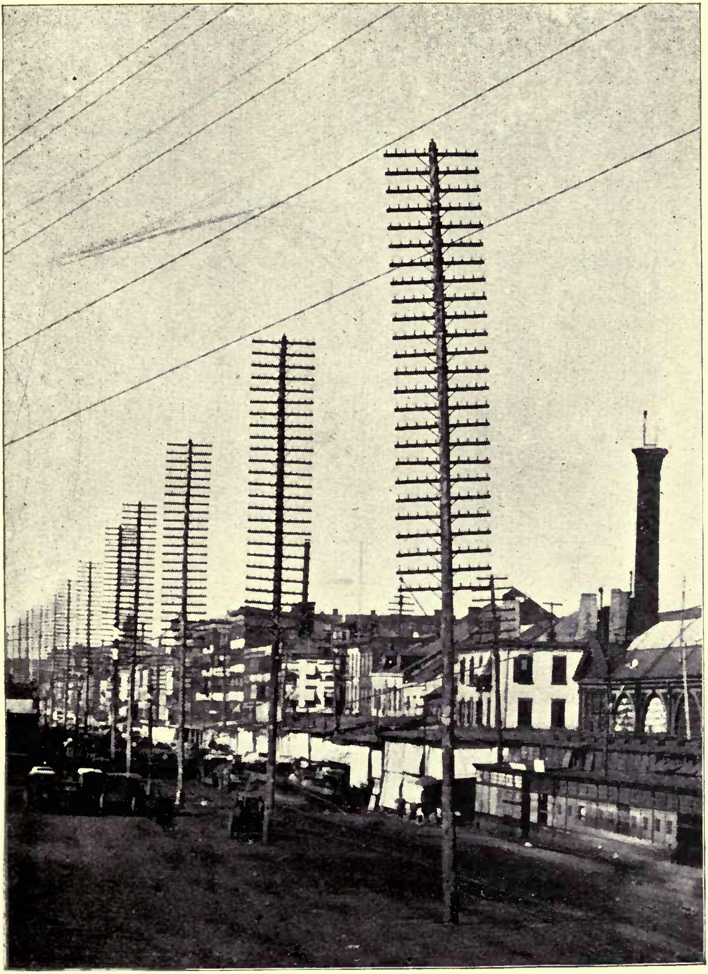
The capacity of an exchange of given size may be very considerably increased by the judicious use of "party lines." When this is done in accordance with approved modern methods, no serious objection can be made to the practice, unless, perhaps, on the score of convenience.

POLE LINES.

A pole line consists of poles set in line along the route chosen, each pole carrying one or more cross-arms and each cross-arm carrying from two to ten insulators mounted on pins. The wires are tied to the insulators and run parallel with each other from pole to pole.

A pole line may carry any number of wires, from one to fifty. Some lines carry double that number of wires, or even more; but unless forced to it by peculiar conditions, it is not wise to run more than fifty wires on one set of poles.

The poles are usually of Canada cedar, the longer poles of pine, not less than seven inches in diam-



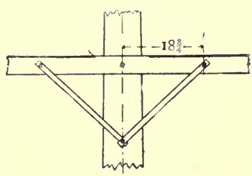
HEAVY POLE LINE CONSTRUCTION, WEST STREET, NEW YORK.

The number of wires on these poles has since been reduced by more than half, and the poles shortened accordingly.

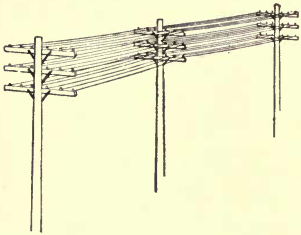
eter at the top, and for city lines they should be a little larger than that. They should be stripped and shaved, and the gains for the cross-arms cut before setting; and they should be set not less than six feet into the ground. In many cases the cross-arms may be bolted on before setting the pole. The pole is not subjected to any chemical treatment before setting; but, after setting, the poles in a city line should be given two coats of good paint, both for the looks of the line and for the preservation of the wood.

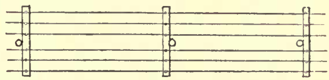
The proper height of pole depends on the conditions met with. It is generally necessary to use a rather tall pole for city work, in order that the line may be thoroughly clear of the street, and not be too much of an obstruction to the adjoining buildings.

The cross-arms should be of Norway pine, well coated with a mineral paint of good insulating properties. They are usually 4¼ by 3¼ inches, and 10 feet long; and are sent bored and painted from the factory. Cross-arms should be set 2 feet apart, on centres, and braced to the pole with iron straps, placed as shown in the figure. The best pins are of locust, 1¼ inch in diameter, and are set 12 inches on centres in the cross-arm, the two centre pins being 15 inches apart, to clear the pole.



The poles are set 130 feet apart, terminal sections 75 feet; and they are so set that on adjacent poles the cross-arms face each other, as in the figure. If they are set in this way the arms are not likely to be pulled off; but when set all facing the same way, it sometimes happens that a whole line

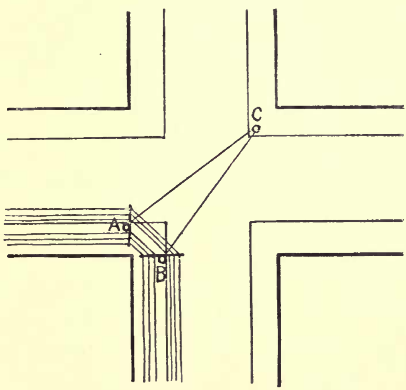




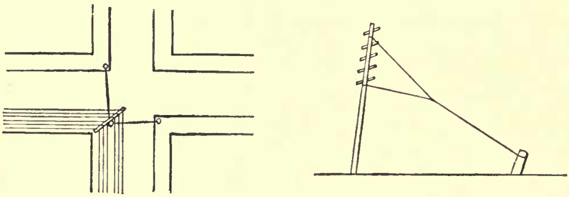
will go down at once, all the cross-arms being pulled off the poles. For if, through an excessive strain at one point, or some accidental cause, such as, perhaps, a fallen pole, a cross-arm happens to be wrenched off, the strain in the same direction is transferred to the next pole, that arm comes off, and so on, like a row of blocks, until the strain is relieved, and a considerable length of tangled wires lies upon the ground. On the other hand, if the poles are set alternately facing, and back to back, as in the figure above, it is almost impossible to pull off more than two sets of arms; and in many cases a broken pole is kept from falling, and the grounding of all its wires avoided.

It is important, both for the looks and maintenance of a line, that the tops of the poles should be as nearly as possible in line. This condition will generally be attained in cities by using poles of the same height, as the surface of the street is sufficiently level; but in country lines, as will be seen later, inequalities of the ground must be compensated for by different heights of pole.

Especial attention must be paid, also, to corner poles. Whenever possible, it is best to take off branch trunk-lines in opposite directions from the same pole, or in such directions that there shall be no resultant sidewise pull on the pole. When this is not possible, the angle at which the pole is to be set must be calculated, and the pole strongly guyed. Excessive inclination of poles is to be guarded against, however, as the strain thus caused on the pole is apt to be as great as when the angle is too small, and is more concentrated. In any case, corner poles should be of greater diameter than the line poles, and the cross-arms so set that the strain will pull them against the pole, and not away from it.



One of the best methods of turning a street corner is that shown in the diagram. In this case two poles, A and B, are used at the corner, both anchored at the corner diagonally opposite, as shown, to C. It is not necessary, in this construction, to cant the cross-arms, but it may be necessary to use what are known as "**Y** guys," to prevent the poles from bending near the top. The **Y** guy is shown below.



When a single pole is used at a corner, it should be doubly guyed. The former construction is the better one.*

There are many forms of insulator in use, none of which is altogether desirable; but for mechanical reasons the insulator should be of such form that the wire is tied near the base of the pin, thus keeping the leverage small.

WIRE.

It was at one time almost the universal custom to use galvanized iron wire for city lines. Iron wire possesses just two advantages—strength and cheapness. Electrically it is altogether undesirable, especially for telephone lines, and it is easily and quickly corroded by the acids which are always to be found in abundance in the air of cities. Hard-drawn

* For additional methods of guying, see chapter on Long Distance Lines.

copper wire is now produced possessing sufficient mechanical strength, and copper resists corrosion for a long time — we do not yet know how long, for there are now no copper lines which have been up for a sufficiently long time to suffer from this cause. For electrical reasons copper is infinitely superior to iron, and in the long run will be found to be cheaper.

Assuming, therefore, that copper wire is to be used, the size is next to be determined. It is not possible, nor would it be profitable, to calculate the exact size which should be used at any point, as in electric lighting. It is necessary to use a wire sufficiently large to give the requisite mechanical strength, and in general, for pole-lines, the larger the wire the better the line. This is not absolutely true for all cases, as there are other conditions to be considered; but in a general sense it is true. The wire which has been quite generally used, where copper has been employed at all, is 0.08 inch in diameter. It breaks at about three hundred and twenty-five pounds, and has proved to be very satisfactory wherever it has been used.

Copper wire, as has been said, resists corrosion for a long time. On exposure to the air and weather a thin, dark-greenish skin, probably a chloride, forms on the outside of the wire, and protects the inside of the wire from further action. The length of time necessary to form this skin varies, of course, according to the conditions of exposure, and the corrosion might, after long exposure under adverse conditions, penetrate to a considerable depth. I have not, however, as yet, found any as thick as $\frac{1}{1000}$ of an inch, and there is every reason to think that the length of life of a line of copper would be practically unaffected by corrosion due to exposure.

STRINGING.

In stringing the wire the best practice is to pull it up rather tight. By following this plan, with the comparatively short spans recommended, the "sag," or "dip," is very slight, and it is impossible for the wires to blow together, as they can swing but little. Moreover, the appearance of a line so constructed is much more regular and pleasing than when a long span and a large dip are employed.

When using copper wire, it is customary to put up a line with a dip greater or less according to the weather.* In cold (freezing) weather it is pulled as tight as the linemen can pull it; and in warm weather (say 65° to 80° F.) a span of one hundred and twenty-five feet is allowed a dip of about one foot at the centre.† The wire is tied to the insulator with copper wire of the same size as the line wire,

* For method of stringing wire, see chapter on long distance lines.

† This puts a rather severe strain on the wire in very cold weather, especially when loaded with snow or sleet; and the practice in this respect might be slightly modified to advantage.

but the tie wire must in some cases be annealed. The tie is shown in the diagram, each end being wrapped five times about the line wire.

Line joints in copper wire may be made in various ways, as the well-known "American" joint; but

the best and quickest, as well as the most permanent, is made by means of the "McIntire" sleeve.

In its latest form, which is now standard, this sleeve consists of a single elliptical tube, as shown in

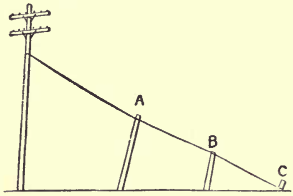
the cut. The single tube sleeve has taken the place of the double form.

The wires are passed through from opposite ends

and the tube twisted by a special clamp. No solder is used. Three and one-half turns will make this connector and its wires virtually a solid mass of copper, perfectly air-tight and mechanically fully as strong as the wire.

For guy wires, iron or steel is used on account of its strength, and the proper size for a guy wire must be determined by the strain on the pole, using a large factor of safety. When very large guy wires are used, it is better to have them stranded.

When possible it is best to run the guy wires to the base of the next pole, but it is frequently necessary to set posts for attaching the guy wires, and in such cases care must be taken that the posts are strong enough and properly set. Much annoyance has been caused by the failure of posts which were faulty or improperly set. An instance of this, which came under my own observation, is shown below.



The first post, A, was too weak, and the wire was fastened near the top. This post soon showed signs of giving way, and the post B was put in, but was also improperly set, and the guy wire AB fastened to its top. This in turn it was soon necessary to reenforce by the post C, which bore practically all the strain. This was in a city street, and is a bungling and unsightly piece of work, besides costing more than if it had been properly done in the first place.

By far the greater number of problems which arise in putting up a city pole line, are individual, and must be solved according to circumstances. Strength should never be sacrificed, and the aim should be to make the line look as well as possible. In general, the line which *is* the best will *look* the best.

CHAPTER II.

UNDERGROUND WORK.

THE tendency at present, at least in the larger cities, is entirely toward underground systems; and in these the difficulties to be met with are far greater than in the case of overhead lines. The general planning of routes has already been outlined, but instead of setting a line of poles, conduits must be provided.

Very many methods of putting wires underground have been tried. The plan of burying them permanently, without providing means for getting at them for purposes of alteration and repair, is very expensive and not admissible; and the plan of drawing the wires into permanent ducts, with man-holes at convenient distances, has been almost universally adopted. Whatever the system, the conduit must be straight, or nearly so, between man-holes, and there must be no sharp corners to abrade the cable sheath, or cause difficulty in drawing in. The man-holes are usually placed about two hundred feet apart, but a cable may continue through a man-hole without being cut.

So many systems of subway construction have been proposed that only the most prominent among them will be described. The systems may be roughly divided into three classes:

1st. Conduits of vegetable material.

2d. Conduits of metal.

3d. Conduits of silicious material.

In the first class there are the—

1 (*a*). Valentine creosoted box.

1 (*b*). Wyckoff creosoted tube.

1 (*c*). Paper or fibre conduit.

In the second class there are the—

2 (*a*). Johnstone sectional cast-iron conduit.

2 (*b*). Wrought-iron pipe in hydraulic cement.

2 (*c*). Wrought-iron pipe in asphaltic concrete.

2 (*d*). Cement-lined wrought-iron pipe.

In the third class—

3 (*a*). Dorsett.

3 (*b*). Lake conduit (terra-cotta).

3 (*c*). Camp conduit.

3 (*d*). Cement and stone conduits.

CONDUITS OF THE FIRST CLASS.

1 (*a*). *The Valentine conduit* consists of a rectangular box, divided into ducts 3 inches square, into which the cables are drawn. The box is made of yellow pine, 1 inch thick, from which the sap has been withdrawn, and which has been treated

with a dead oil of tar or creosote. The wood partitions between the ducts are treated in the same way. These boxes are made in lengths of about twelve feet, and are buried from two to three feet beneath the surface. The abutting ends are carefully adjusted and joined, and the whole outside is thoroughly coated with tar. This is the cheapest form of conduit.

1 (*b*). *The Wyckoff conduit* is very similar to the Valentine. It consists of tubular ducts bored in blocks of creosoted wood, the blocks being grooved and splined together. It is laid and the joints made in the same way as the Valentine conduit.

1 (*c*). *The paper conduit* consists of paper tubes impregnated with a compound of asphaltum, a number of these tubes being laid in a wooden box and filled about with the same compound. It is said that this compound is free from the faults of cracking and other deterioration which have proved fatal to so many similar devices; but there is no available information as to its behavior in actual service for a term of years. Severe laboratory tests on this material have given excellent results.

CONDUITS OF THE SECOND CLASS.

2 (*a*). *The Johnstone sectional cast-iron conduit* is used chiefly for electric lighting. It is made in 5 feet lengths, which are laid one above another and held

by clamp pins. The cross-section is rectangular, and each section is divided by removable partitions into several ducts. The cover is flush with the surface of the street, and hand-holes are provided for distribution to houses. This conduit is laid directly in the earth, without cement or concrete, and is efficient for electric lighting purposes.

2 (*b*). *Wrought-iron pipe in hydraulic cement.*

2 (*c*). *Wrought-iron pipe in asphaltic concrete.* This conduit consists of wrought-iron pipes of 3 inches diameter, in 20-feet lengths, the iron being nearly ¼ inch thick. The method of laying is as follows, the only difference between the two systems being in the materials used for the concrete: The bottom of the trench is first levelled to grade and the sides braced with plank. A thick layer of concrete is then put in and rammed. On this a row of pipes is laid, close together. Any desired number of pipes is used, and a second layer of concrete, thinner than the first, is rammed between and over them. Upon this is placed a second row of pipes, then concrete, and so on *ad libitum.* The concrete is laid thicker on the bottom, sides, and top, to give the whole additional strength, and over all is laid 2-inch creosoted yellow-pine plank as a protection against pickaxes in subsequent excavation.

The joints are made with sleeves having a tapering or vanishing thread, which is tight, and enables them to be laid very rapidly. The pipes are laid free from burrs and have a smooth inner surface. In some cases they are asphalted. Much of the New York subway system consists of this form of conduit.

2 (*d*). *Cement-lined wrought-iron pipe conduit.* The cement-lined pipe is made in single or multiple tubes, of from 1 to 7 or more ducts, by holding vertically a sheet-iron tube, with a smaller brass tube inside. In the space between the two tubes is poured semi-liquid cement. When this has solidified the brass tube is withdrawn. The method of laying is much the same as that last described, the pipes being in lengths of 8 feet, connected by ball-and-socket joints. A great deal of this conduit is laid in the New York subways.

CONDUITS OF THE THIRD CLASS.

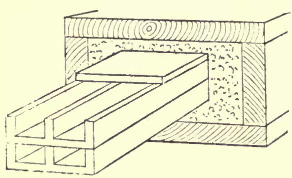
3 (*a*). *The Dorsett conduit* is one of the oldest forms. The material used is a composition of pitch, coal-tar, and gravel, which is moulded into blocks 4 feet long, having tubular openings 2½ inches or 3 inches in diameter. These blocks are butted together and joined by pouring in a mixture of pitch and tar which hardens quickly. This liquid is prevented from entering the ducts by sleeves, which are placed inside the ducts at the joints. The great fault of this conduit is that the blocks get out of align-

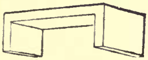
ment at the joints, leaving sharp edges in the ducts and allowing gases to leak in.

A considerable amount of this conduit has been in use in Chicago for some years, and some in New York.

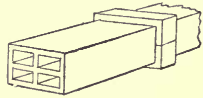
3 (*b*). *Lake conduit.* This consists of short lengths of terra-cotta pipe, of rectangular section, usually divided vertically into two ducts. Three lengths of 4 feet each are joined before the pipe is laid, the joints being made by butting the ends and wrapping them with burlap. The burlap is then thoroughly tarred, and the length of 12 feet laid directly in the ground, being joined to the abutting pipe in the same way. This conduit has given good satisfaction in several cities.

The method of laying this conduit, as used in Washington, D. C., differs somewhat from that just described, and makes a more substantial structure. The conduit itself is of terra-cotta,



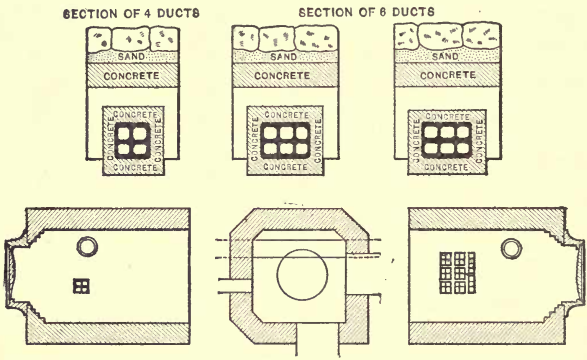


rectangular in cross-section, as shown in the illustration.



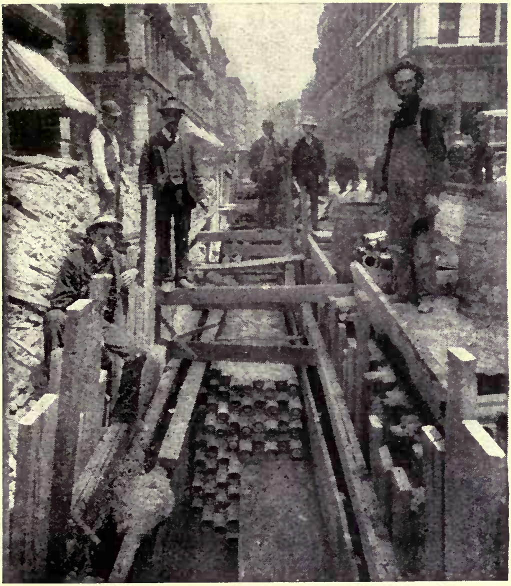
Each piece is formed with two ducts, and one is laid on another, the bottom of the upper section forming the top of the lower. Joints are made by bracket-shaped pieces which cover the abutting ends, and the whole is laid in concrete, which holds the brackets in place and affords mechanical protection to the conduit.

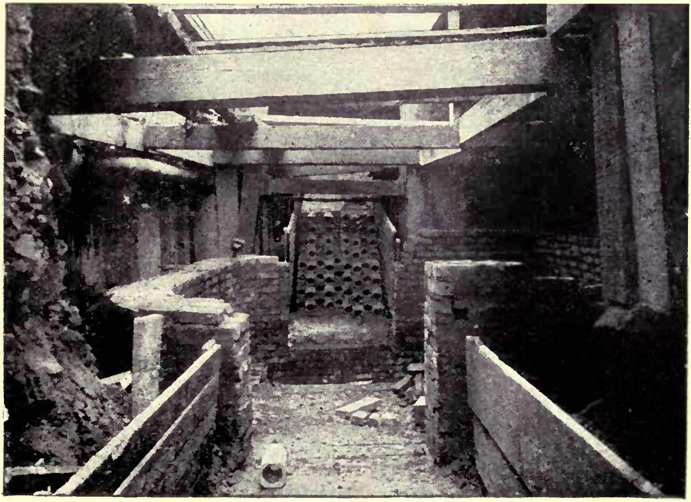
Other conduits are in use, of the same general design and construction, differing from those just described in some details.



McRoy Conduit and Manhole.

3 (*c*). *Camp Conduit.* This is, at present, perhaps, the most important conduit, as it has become the standard for many telephone companies. It is made of selected clay, vitrified by intense heat and thus rendered water-proof and chemically inert. The standard conduit is made in single duct form, each section 18 inches long, with a cylindrical opening 3 inches in diameter. The outside is 4¼ inches square, with chamfered corners. These pieces are required "to be straight both on the outside and in bore, the

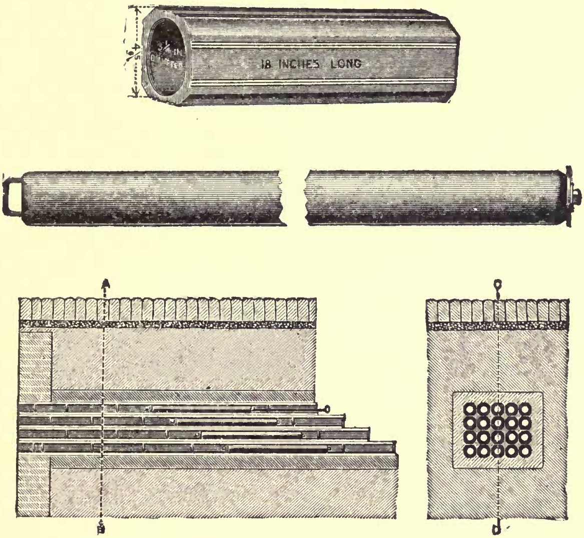




Camp Conduit, Boston.

bore to be accurately centred, fully 3 inches in diameter throughout its entire length, smooth and entirely free from lumps and projections." The bore is scraped out with a three-pronged steel scraper.

The ducts are laid in tiers, on a well-rammed bottom of 3 to 6 inches of concrete, and after the



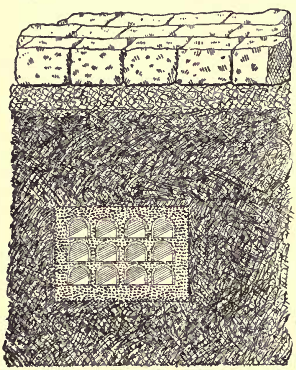
Camp Conduit, showing Single Duct Section, Mandrel, and Method of Construction.

desired number of ducts is in 3 inches of concrete is put on the top and sides. The sections are laid up like bricks in mortar or cement, breaking joints, alignment being maintained by the use of long mandrels which fit the pipe and carry a gasket at the end. These mandrels are pulled along in each duct as the work advances.

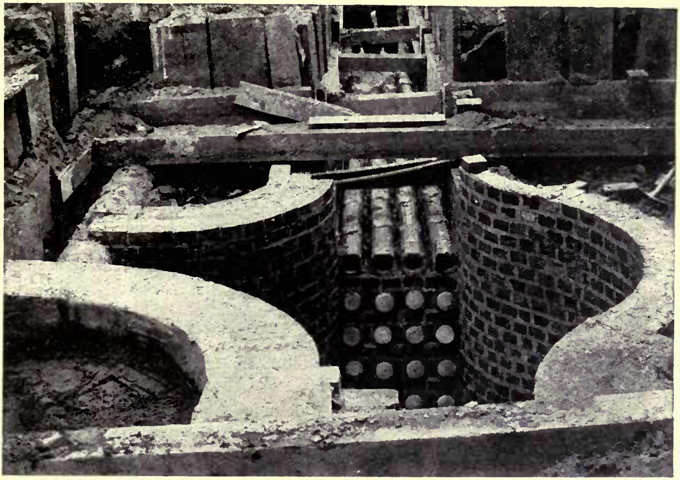
The matter of grades is carefully attended to, for in any conduit it is necessary for proper drainage that the slope should be continuous and perfect from one manhole to another.

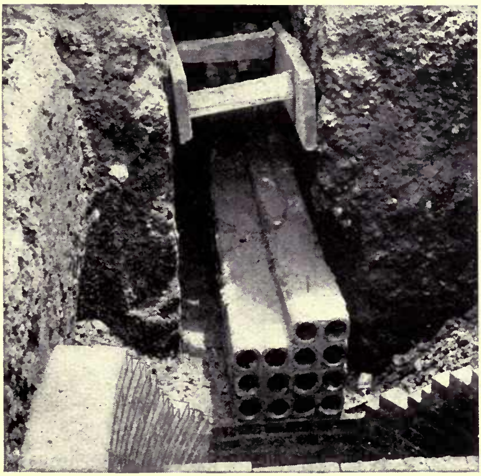
3 (*d*). *Cement and Stone Conduits.* Several methods have been proposed for the construction of conduits consisting principally or at least in part of Portland cement. Some of these methods have proven unpractical and have been abandoned, while none of this class has met the favor which has been given in turn to the iron pipe and the terra-cotta.

The *Sewall* cement arch consists of cement formed upon an arch of iron wire. These arches, when hard, are laid in the usual manner on smooth cement floors and hydraulic cement concrete is filled in between and around them, uniting with the walls of the ducts, in a few days, to form a solid mass.



In another conduit of the same class, the cement is made, under great pressure, into pipes in short lengths. These, laid in the usual manner, soon become, with the concrete bed, a solid mass of stone.





Camp Conduit Construction.

Several of the conduits described have been in favor for telephone work. The cement-lined iron pipe was much used for some years, then was gradually supplanted by the multiple-duct terra-cotta and that, in turn, by the single duct, vitrified clay.

In some underground work now in construction in Chicago, a system of tunnels is to be used, about 30 feet below the street surface; and the wires and cables for various purposes are to be strung on racks along the sides, as in the large sewers of Paris. These tunnels are 8 feet high and have a maximum width of 6 feet, the laterals, for distribution, being 3 feet in diameter. They are lined with Portland cement. Aside from the question of first cost, this is the ideal method of distribution, combining the advantages of the overhead and the usual underground systems. Unless some unforeseen difficulties arise, it may be confidently predicted that this system will be successful and economical in operation. The subways of the electric roads, which are sure to be constructed under most of our large cities within comparatively few years, may, perhaps, be profitably used in a similar way. Even if the railroad tunnel itself is unsuitable or not available, the additional cost of building a small cable tunnel at the same time, along the same route, would not be great.

CREOSOTED WOOD AND CORROSION.

The creosoted wood conduits, as they are the cheapest to put down, were the first to be used;

but their use resulted in rapid deterioration, and sometimes destruction of the lead sheath of the cables.

In making these conduits the sap is first withdrawn from the wood and its place filled with some preservative substance, usually creosote. It is necessary that this should be done thoroughly; for if a portion of the sap remains, fermentation eventually takes place, resulting in the formation, within the duct, of vegetable acids, which attack the lead of the cable-sheath and rapidly destroy it. The same result will follow if the preservative substance contains any organic acid. Improperly prepared creosote often contains sufficient acetic acid to attack lead, and acetic acid tends to form, with lead, salts which are unstable in the presence of carbonic oxide, changing into the carbonate, and thereby again setting free the acid. This again attacks the lead, and the process is repeated until the sheath of the cable is destroyed. An unlimited supply of carbonic oxide is usually at hand, from the illuminating and other gases which permeate the soil of our streets, and the conduit is seldom tight enough to exclude them.

This destructive corrosion may be recognized by the appearance of the lead. It produces a white scale, irregular pits, or a white efflorescence covering a pit in the lead, and must not be confounded with another form of corrosion which is harmless. In the latter form the lead shows a uniform hard, dark-brown coating, which protects the pipe from further action.

Even if the material of the conduit does not contain the destructive agent, it may be admitted from soil containing decaying or fermenting organic matter, and the chemical process go on, although with much less rapidity than in the first case. To provide against this, both ducts and man-holes must be gas-tight. It is probable, however, that if the wood of which the ducts are made is properly and carefully prepared, there would be no such destructive action, and the life of the conduit would be practically without limit.

ELECTROLYTIC CORROSION.

With the rapid growth of electric railways, the volume of current traversing the earth has been enormously increased during the past few years. The troublesome effects of these currents have increased also.

Whatever method is used to bond the rails or otherwise provide a return of good conductance for the railway current, it seems practically impossible to avoid occasional potential differences between the rails and the earth or between different parts of the earth along and near the railway. More or less current is therefore caused to pass between the ground and any uninsulated conductor laid in it; and injurious electrolytic action may occur at points where current in considerable quantity leaves such a conductor. The most marked action of this kind has been upon iron pipes, such as the service pipes for gas or water, especially when they are of wrought iron. Cast iron resists the action, in many cases completely, because of the non-conducting properties of the silicious coating usually formed upon the surface.

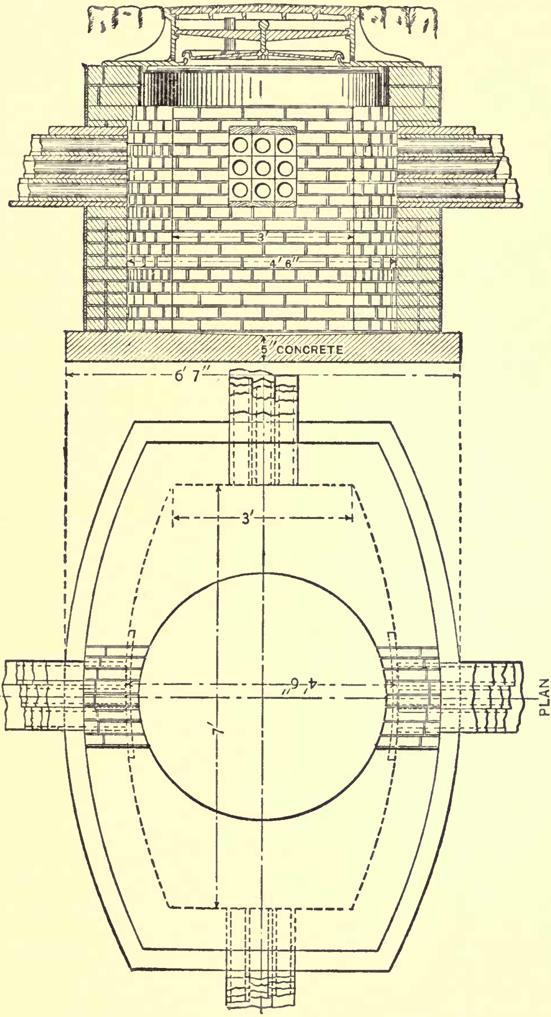
Wrought-iron conduit pipes are, of course, liable to attacks of this kind if they are in any way exposed; and the sheaths of cables have often been pitted and perforated from the same cause to such an extent as practically to destroy them. If possible, therefore, the conduits should be completely insulated from the outside; but if leaks are unavoidable, they are less injurious when evenly distributed along the length of the conduit than when concentrated at a few points.

Terra-cotta or cement conduits are not subject to this destructive action, nor do they affect the sheath of the cable chemically, as has often happened in creosoted wood ducts. They are not so strong, mechanically, as iron ducts in good condition; but they are infinitely better than corroded pipe, and when laid in concrete the conduit is strong enough.

In New York City considerable trouble has been experienced from the proximity of steam-heating pipes. The only precaution which can be employed is to avoid the steam-pipes whenever possible, and to use a suitable cable.

Evidently even with the most suitable material

Pipe Destroyed by Electrolytic Action.



A Standard Manhole.

for a conduit, if water and gases are allowed to leak in from the street, the sheath of the cable is still liable to corrosion. It is necessary, therefore, that the joints in the ducts and in the man-holes should be water- and gas-tight; and in this respect the conduits laid in concrete are best.

MAN-HOLES.

Man-holes, as the name implies, are holes or chambers in the ground, breaking the continuity of the conduit; and their purpose is to give access to the ducts for drawing in or drawing out cables, making connections, or repairing. A man-hole should be of such size that a man can work easily in it. It should be water- and gas-tight, but provision should be made for drawing off any water that may collect in it. Man-holes should be not less than six feet in diameter, and of such a depth that the ducts enter two or three feet from the bottom. The best practice at present is to build them of brick, laid up in concrete cement, with a hydraulic cement bottom. The outside of the walls is coated thoroughly with cement to prevent the entrance of gas or water. The roof is either arched or supported on iron girders. Double covers are provided, the lower one having a rubber gasket at the joint, and being so shaped, that any water coming from the strect will drain away from the joint. The lower cover is fastened down by a cross-bar and gun-metal bolt, while the street cover, weighing about three hundred and fifty pounds, is loose on its seat. A man-hole must be placed at every point where the conduit makes a sharp turn. It is usual to locate them, in the straight portion, at street crossings, or about two hundred feet apart.

The importance of keeping the man-holes, as well as the ducts, free from gas and water can hardly be exaggerated. If gases and moisture once find their way in, it is practically impossible to get them out; and the life of the cables may be very materially shortened by their presence. Moreover, the presence of illuminating gas mixed with air may be the cause of dangerous explosions. A mixture of one part gas to eight parts of air is very explosive, and there are many ways in which it may be ignited, even in conduits containing no electric-light cables. The greatest trouble in the New York subways is due to the leakage into them of gas, with which the soil of the streets is permeated. Many methods of ventilation have been tried, with but partial success, and it is now necessary to provide the man-holes with vents to allow the gas to escape and thus guard against explosions. Many explosions have been caused by the leakage of the gas through the pipes containing electric-light wires up a pole to an arc lamp. Here the gas is ignited, and the flame runs back into the duct, causing an explosion.

DRAWING IN CABLES.

In order to place the cable in the finished duct it is necessary to provide some means of pulling it in at the end. In some forms of cement conduit a small cord is put through each duct as it is laid, and the cord is left in place to be used whenever it is desired to draw a cable into the duct. A rope is then attached to the end of the cord and drawn through, the cable being in turn attached to the end of the rope and drawn in by means of it. This method, however, was found not to be a good one, as the cord rotted in the duct, and the use of so much cord involved a needless expense. It is now the practice to put the rope through by the process of "rodding," as it is called.

RODDING.

In this process a number of short rods is used, the aggregate length being sufficient to reach from one man-hole to the next. There are various forms of rods—continuous steel, spiral steel, or short lengths of wood. The best are of cane, and can be attached together by screw-and-socket joint or by a pin and slot (bayonet joint). One rod is pushed into the duct at a time, being attached to the rod ahead of it at the joint, until the other end of the duct is reached, at the next man-hole. A mandrel which just fills the duct loosely is usually placed on the end of the first rod to clear away all obstructions. A rope is then fastened to the last rod, and the whole pulled through, the rods being detached one at a time as they come out of the duct.

DRAWING IN.

When the rope has been drawn in it is attached to the end of the cable. This must be done with some care; for it is necessary that the strain should come principally upon the conductors and not upon the lead sheath. Moreover, there must be no bunches to catch and stick in the duct. A swivel should be provided in the rope, near the cable. The farther end of the rope is then passed around a windlass fastened in the pavement at the edge of the man-hole, and the cable is drawn in by turning the windlass. The reel of cable should be mounted at the edge of the first man-hole, and the cable guided into the duct by a man stationed in the man-hole, taking care that the cable sheath does not run against the edge of the opening so as to abrade or injure the covering. But one cable should be drawn into a duct, and a cable should never be drawn over others. The telephone cables now in most general use are of such a size as to most economically fill a 3-inch duct, leaving room enough for the drawing in.

TESTING AND MAKING JOINTS.

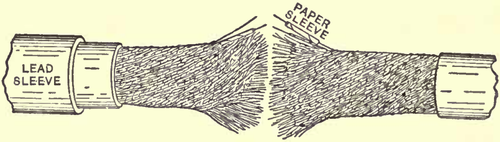
When the cable has been drawn in, it should be cut and carefully tested. If found perfect, the connections are made immediately, each joint wrapped, a lead sleeve slipped over the joint, and the whole sealed perfectly tight. This is usually done by a soldered "wiped joint." If the succeeding section is not ready to be connected, the end of the cable should be sealed up.

It was formerly the practice, in many cases, to run the cables direct from duct to duct, across the man-hole. This resulted in filling the duct with a confused mass of cables, and rendered any subsequent work in the man-hole very difficult. Cables running into a man-hole should be led from the ducts, in order, around the sides of the man-hole, supported by shelves or hooks on the wall. This leaves the centre free for work, and makes inspection or testing easy.

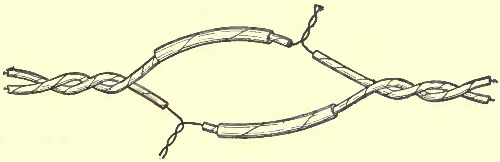
The following instructions are given by John A. Roebling's Sons Co. for the splicing of cables.

Have ready a pan and ladle for the paraffine, a portable furnace, a lead pipe somewhat larger that the outside diameter of cable and about two feet long, called the "lead sleeve." Also paper sleeves for the covering joints in conductors, and a good plumber. The paper sleeve can, with advantage, be baked in a slow oven for some time before beginning the splice. For the purpose of giving more prominence to details, the proportion of length to diameter is sacrificed in the figures. The splice should really be much longer than the drawing indicates. Heat paraffine on the furnace.

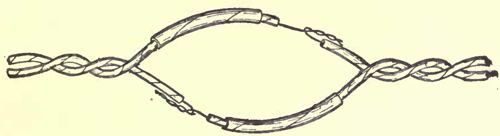
Cut back the lead nine to twelve inches from each end of cable, and if insulation is of dry paper, douse the conductors with hot paraffine to prevent paper from untwisting and exposing wires.



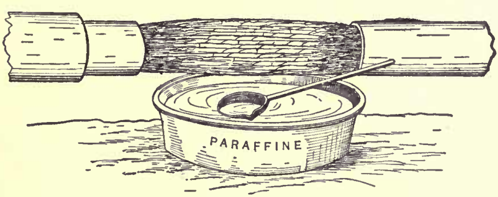
Slip lead sleeve over one of the cable ends and paper sleeves over one wire of one pair of both ends. Join the wires of a pair on one end to those of a pair on the other end.



Within the space allowed for the splice (16 to 22 inches) "break joints" as much as possible. Turn down the twist.



Cover joints with paper sleeves. When all pairs are joined, ladle hot paraffine over splice until no bubbles appear in hot liquid.



After the splice is "boiled out" serve spirally the spliced conductors with a plain strip of white cotton and again boil out with paraffine. Slip the lead sleeve over splice and finish with wiped plumbers' joints while the splice is still hot.

Do not use acid in soldering. The best flux is the grease from a tallow candle. Go to next splicing place, unseal end nearest exchange and test through splices just made (as before), to terminal in exchange. Be careful at each splice as to joining good wires to bad ones. The last work on that cable will be a connection to terminal head on pole.

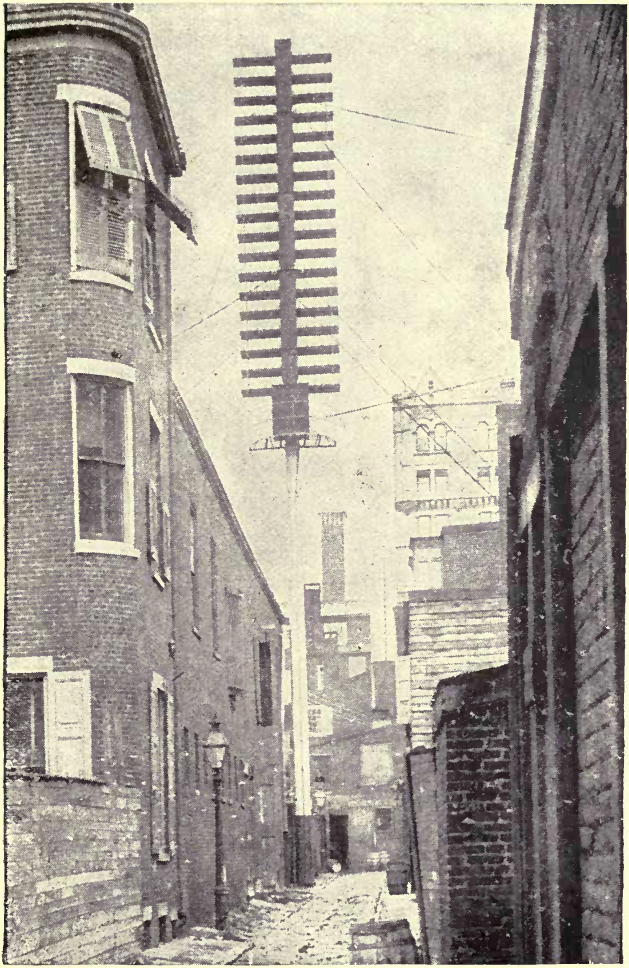
Make a test with receiver after every splice and every terminal connection. *Never leave a cable end unsealed for any length of time.*

Terminal heads out of doors should be protected by galvanized iron box.

DISTRIBUTION.

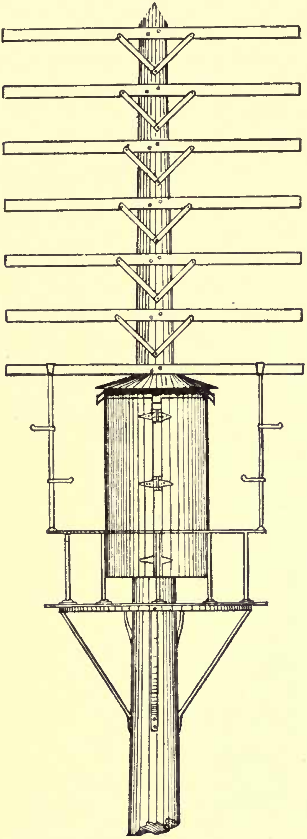
The distribution of the circuits in the conduit to individual subscribers is done from poles by short overhead lines, as it would generally be impracticable to run single underground wires, on account of the great cost. For the location of a distributing pole a point is selected which is as nearly as possible in the centre of a group of several subscribers. A cable is run from the nearest man-hole to this pole, and led up the pole, through iron pipe, to the cable-box. It is necessary to use a cable-box for two reasons: The cable must be protected from injury by lightning, and a lightning arrester must therefore be inserted in every line, between the overhead portion and the cable; and the cables now universally used for telephone work must be hermetically sealed to prevent the entrance of moisture, which would gradually destroy the insulation. Various forms of cable-box have been used; and two of those put into use by the American Telephone & Telegraph Company are shown.

The first of these, although now superseded, is still in use to some extent and is therefore described. The box is of iron, 30 inches in diameter, and en-



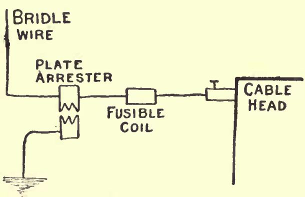
Distributing Pole, Philadelphia.
Older form, many of which are still in use.

circles the pole. It is weather-tight, with overlapping doors, and is provided with tubes for the cable and wires, which enter at the top, just under the eaves. Below the box is a circular platform, 6½ feet in diameter, surrounded by an iron railing, and firmly supported both from the cross-arm and from the pole. Access is had to this platform through a trap-door in the floor, and iron steps are provided on the supporting rods, to reach the cross-arms above. On this platform the lineman can work with ease and quickness, and the results are infinitely better than when he was obliged to cling to the pole and cross-arms for support.



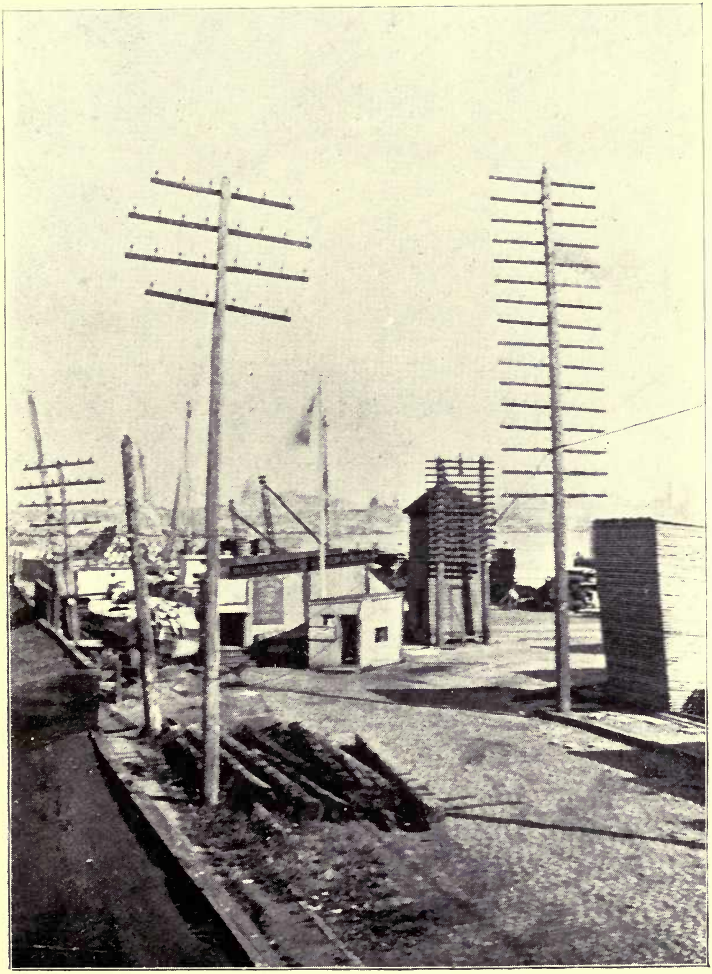
Old Standard Distributing Pole.

Inside the cable-box the connections are made from the cable to the overhead wires. The wires in the cable are connected to their respective binding-posts in the cable-terminal, the cable sheath being connected with the nozzle by a wiped joint of solder. After soldering, the conductors are boiled out with paraffine and the cover screwed down upon a rubber gasket.* The end of the cable is thus hermetically sealed. The bridle wires are covered with waterproof insulation. They should be joined to the line wires either by McIntire sleeves or by soldering; but they must not be soldered to the hard-drawn copper between supports, as the heating reduces the strength of the hard-drawn copper. The bridle wires are then led along the under side of the cross-arms and down the pole into the cable-box. Within the cable-box the bridle wire is led first to the "plate" arrester, which is connected to earth; then to the fusible coil arrester, which is connected to the proper binding-post in the cable-head. This plan admits of ready change in the



* The directions given by John A. Roebling's Sons Co. for connecting up the cable terminals sold by them are as follows:

Strip lead from end of cable and insert ends of wire into nozzle, allowing lead sheath to extend through it, and connect lead sheath to nozzle with wiped plumbers' joint; connect ends of cable wires to inside terminals by pushing into slots. The wires will stay in place until permanently fixed by solder. Use a non-corrosive soldering flux. A compound of two parts (by bulk) of chloride of zinc, twelve parts of alcohol, and ten parts of glycerine is a very good one. If conductors insulated with paper or cotton, pour in and pour out paraffine heated to about 300° until all moisture is expelled. While box and wires are still hot put on rubber gasket, and screw cover to box.



North River Cable Terminal, New York End.

arrangement of circuits when desired, by changing the cross-connections in the cable-box.

The present standard distributing pole is shown in the cut.

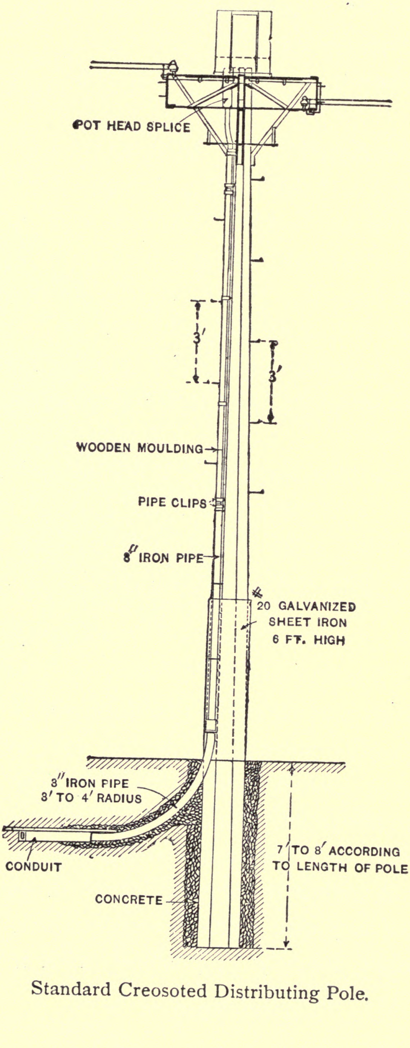
The cable sheath is cut back, as for connecting to a head, and the bridle wires joined directly to the conductors in the cable. The splice is made in the usual careful manner, using paper sleeves; the conductors are bound together tightly with twine and tape; a lead sleeve is slipped up over the splice and sealed to the cable sheath by a wiped joint; the splice is then filled, by special device, with a sealing compound.

The splice thus formed is held up under the protecting hood and the bridle wires led through arresters to the line wires, which are ended at insulators held upon the circular iron framework about the pole.

CABLES.*

The cables now used for underground telephone lines are, in this country at least, of uniform pattern, although the material of which they are made depends upon the manufacturers. The early cables used consisted simply of insulated wires grouped together and covered with a protecting sheath of metal. The wire was of any size that chanced to suit the ideas of the maker, usually very small, with a very thin

* See also chapter on Cables



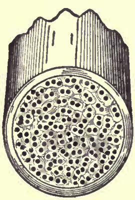
Standard Creosoted Distributing Pole.

insulation; the main object being apparently to get as many conductors as possible into the smallest possible space. Through successive stages of development the wire and its insulation both grew. The difficulties due to induction gave rise to numerous devices, "induction killers," and "anti-induction cables," none of which were practically successful. The only sure method of preventing this trouble consisted in twisting the two wires of a circuit about each other; and this method has now been universally adopted.

INSULATION.

The insulation in telephone cables now consists universally of some fibrous material such as cotton, jute, or paper. The rubber compounds have been used to some extent, but have been found, on the whole, inferior to fibre, although possessing some advantages. In a cable with rubber insulation it is not necessary to seal up the ends, as the insulation is itself waterproof, nor is a metallic sheath necessary, except for mechanical protection. But the disadvantages of a material of this nature are insurmountable, practically. The rubber is likely to deteriorate with age, and admit moisture, or it softens with heat and allows the wire to become displaced from the centre. Worst of all, its specific inductive capacity is so high that it is, on that account alone, unfit for use in telephone cables. Fibre is cheap, permanent when protected from moisture, and it cannot spread, so that permanent centring of conductors is assured.

The present requirements as to cables are the result of long experience and the co-operation of manufacturers and consumers. The greatest step in advance was the introduction of paper insulation, which just about doubled the working efficiency of a cable of given size. The standard cable is now of the following dimensions. Diameter of conductor, .035 inch; outside diameter of insulation, .125 inch; length of twist, 2¾ inches to 3¼ inches; maximum outside diameter of cable, 2¼ inches; thickness of lead sheath ⅛ inch. It has been the practice to coat the sheath with asphaltic paint, then with a braided jacket saturated with asphaltic paint, as protection against corrosion. This is of doubtful advantage, as the braided jacket is reasonably sure to rot, sooner or later, and leave the duct clogged with moisture-collecting substance.



Section of Cable.

As it was found that a sheath composed of pure lead was rapidly destroyed when placed underground, the lead was alloyed with tin, which gives very good results. The alloy is harder than lead and resists destruction very much better.* The percentage of

* See page 23 on destruction of sheath.

tin which can be successfully alloyed with lead is limited. The specifications now most generally followed, for armor, are as follows: Lead, 97 per cent.; tin, 3 per cent.

For	1¾-inch	pipe,	3.5	pounds	per	foot.
"	1½	"	"	3	"	"
"	1⅜	"	"	2.75	"	"
"	1¼	"	"	2.5	"	"
"	1⅛	"	"	2.25	"	"
"	1	"	"	2.00	"	"
"	⅞	"	"	1.75	"	"
"	¾	"	"	1.5	"	"
"	⅝	"	"	1.00	"	"

The desired number of circuits, or "pairs," as they are called, is made up into a cable, not promiscuously, but in concentric layers, each layer having a slight twist, spirally, in the direction opposite to the direction of twist of the adjacent layers. This twist of the layers gives flexibility to the cable. The conductors are of the best Lake Superior copper, and the "Conference" specifications call for a conductivity of not less than 98 per cent. of pure copper.

These dimensions have been determined from consideration of all the known conditions of transmitting efficiency, available space, and expense; and they undoubtedly give the best cable that has yet been in use.

CHAPTER III.

"LONG DISTANCE" LINES.

THE first lines connecting cities were constructed on the same plan as the telegraph lines, that is, they were of iron wire and were grounded circuits. Less attention, too, was paid to the material and method of construction than there should have been. The spans were long, the poles usually not high enough, nor strong enough, many poorly set, and with defective guying. Clearly, with such lines as these, it would be impossible to talk to any great distance, except in the most favorable weather and under the best conditions of apparatus. When, therefore, the first long distance line, a portion of the present line between Boston and New York, was projected, it was recognized that only the best that could be built would be satisfactory. The results have more than justified the large expenditure, and comparing the Boston and New York line with a City Exchange line, each with its apparatus, the former is under all conditions far superior.

The more recent trunk lines between cities, or what are commonly known as the " Long Distance " lines, erected by the American Telephone & Telegraph Co., are of the most substantial construction.

The number of wires carried on a long distance line varies from twenty, or occasionally less, up to one hundred; but the most economical and best line to build and operate is a line of fifty wires on fifty-foot poles. The cost of such a line, complete, is in the vicinity of $3,500 per mile.

POLES.

The poles are of white cedar,* or chestnut, obtained principally from Canada, and carefully selected. They must be alive and sound when cut; and although the company's specifications call for "'live, green cedar wood," it is most necessary that all wood used, whether for poles or cross-arms, should be thoroughly seasoned. If the wood is painted or set into the ground when green, with the sap in it, dry rot is sure to set in, and the pole, although presenting a fair exterior, may have entirely lost its structure and its strength. If the precaution of seasoning has been neglected in the case of any considerable number of poles, the weakest will some day fall from some cause usually insignificant, and its fall may bring down several miles of line.

* Although red cedar and white cedar are here called by their common names, it is to be understood that red cedar is really a juniper and may be referred to under that name. The name *white cedar*, as generally used by the northern lumber men, is applied principally to the *arbor vitæ;* sometimes to one of the cypresses, the true white cedar.

MATERIAL.

The best material for poles, leaving iron poles out of consideration, is red cedar; but it would be difficult, if not impossible, to obtain red cedar poles of specified dimensions in the necessary quantity. White cedar is largely used, therefore, as it can be obtained in quantity, straight and of the desired length. Chestnut, juniper, Norway pine, and long-leaf or yellow pine are used to greater or less extent, the practice depending largely upon the locality. The life of the pine poles, however, is short, and the yellow pine has also some structural disadvantages. In general when an adequate supply of poles of any suitable wood exists along or near the route, such poles are used. Cedar, chestnut, and juniper are the only woods specified by the American Telephone and Telegraph Company.

INSPECTION AND CUTTING.

The ideal method of obtaining the best poles would be for the inspector to examine the standing timber, select and mark the trees to be cut, and see that they are felled at the proper season. All timber should be cut in the winter months, from December to February, when the sap has left the trees and growth is temporarily suspended. November is not always a safe month for cutting and none should be cut after the first of March, as the sap may then, in some cases, have begun to run. Timber which contains sap when cut is likely to rot quickly and the bad condition of such a pole may remain undetected until it falls. No amount of artificial seasoning can make a pole cut when filled with sap the equal of one cut at the proper time.

An inspector for such duty as that suggested would need to be more or less skilled in forestry. Special knowledge would be needed to choose intelligently and avoid trees which may appear sound and suitable, while really diseased. For example, both cedar and juniper are liable to the attack of a fungus which destroys large portions of the interior of the trunks. It attacks only mature trees and its presence is very difficult to detect in the growing tree.

It is not usual, however, to carry the inspection so far. A general inspection of the standing timber in a district is sometimes made, but the trees are not marked and the cutting is left to the contractor. All he has to do is to meet the specifications. Even this amount of inspection is possible only when poles are to be bought in large lots. For small orders it may usually happen that no representative of the telephone company sees the poles until they are delivered along the route. The inspector can then judge only approximately of the condition of the wood and the chances of its having a reasonably long life, although it is easy to determine whether the dimensions and straightness fulfil the specifications.

The trees, when felled, should be trimmed of all branches, cut to the required length and the bark stripped off at once. It comes off most easily then, and the tree—white cedar especially—is more subject to the attacks of wood worms if the bark is left on. These worms honeycomb the interior and reduce the wood to dust. The poles, when cut and stripped, are hauled to the route of the line or to the railroad, as the case may be.

PRESERVATIVE PROCESS.

Until within a few years it has not been customary, in the United States, to subject even the butts of the poles, which are to be in the ground, to any preservative process. It has been the English practice, for many years, to creosote the butts of poles to prevent decay, and this practice is becoming less uncommon here. The difference in this respect may probably be accounted for by the difference in climate. The method of preservation most used in such cases, is described below. This process is also applied to yellow pine cross-arms.

The timber is first subjected to either live or superheated steam for a period of three to six hours, according to the condition of the timber. The temperature, during this treatment, is not allowed to exceed 250° F. The steam is then cut off and the creosoting chamber containing the timber is exhausted to a vacuum of 26 inches of mercury. During this part of the process the temperature of the chamber is maintained above the boiling point of water corresponding to the degree of vacuum obtained—not lower than 125° F. This process is continued for at least two hours—longer if necessary—until the by-product indicates that all the sap and water is removed from the timber. Dead-oil of coal tar is then admitted, at a temperature between 120° and 250° F., and forced, by pressure, into the wood until an amount has been taken up by the timber equivalent to 12 pounds to each cubic foot of wood.

DIMENSIONS.

The poles must be not less than seven inches in diameter at the top—for curves, eight inches—and of reasonable diameter at the butt.* They are squared

* Length.	*Chestnut.* Circumference, six feet from butt, not less than,	*Cedar.* Circumference, six feet from butt, not less than,	*Juniper.* Circumference, six feet from butt, not less than,
30 feet.	36 inches.	36 inches.	37 inches.
35 "	40 "	38 "	40 "
40 "	43 "	43 "	44 "
45 "	47 "	47 "	48 "
50 "	50 "	50 "	52 "
55 "	53 "		
60 "	56 "		
65 "	59 "		
70 "	62 "		
75 "	65 "		
80 "	69 "		
85 "	72 "		
90 "	75 "		

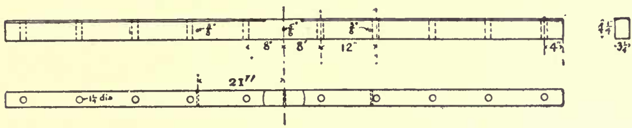
For any wood or height, circumference at top must be not less than twenty-two inches.

at both ends, and the top afterward cut to a wedge-shape. Every pole is stripped and the knots cut close, and the gains for the cross-arms cut before setting. They are subject to inspection before being accepted, and if these requirements are not complied with, and if they are not reasonably straight and of proper proportions, they are rejected.

The standard 'cross-country line now consists of thirty-five foot poles, having an ultimate capacity for four cross-arms, each carrying ten wires. These are not all put in place when the line is first built, but all four gains are cut in each pole, so that the additional cross-arms can be put on when they are needed. In actual lines, this standard height of thirty-five feet is a minimum. Obstacles are frequently met with in running lines along highways, and these obstacles must be cleared by the lines running above and not beneath, the lowest wires clearing by not less than four feet. As a matter of fact, therefore, the poles vary in height from thirty-five to one hundred feet. In consequence of the rule of the American Telephone & Telegraph Co. that their lines must run above obstructions, seventy-foot poles are not uncommon and there is a short length of line where the poles reach the great height of one hundred feet. The minimum height of pole for long distance lines was formerly fixed at forty feet; but it was found that this height, when the pole was heavily loaded, sometimes caused an excessive strain at the base.

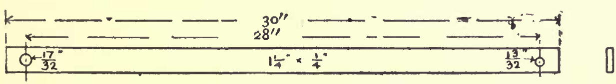
CROSS-ARMS AND PINS.

The standard cross-arm is of Norway pine, yellow pine or cypress, free from sapwood and bad knots. It is ten feet long and $3\frac{1}{4} \times 4\frac{1}{4}$ inches in section.

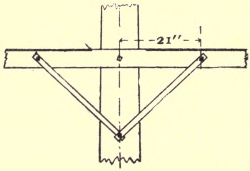


It is bored as shown in the diagram and painted with two coats of metallic paint before delivery.

The cross-arms are set twenty-four inches apart on centres, the upper arm being ten inches from the top of the pole. Each arm is fastened to the pole by a single galvanized iron bolt, and is braced to the pole with two iron straps, also galvanized. The braces are

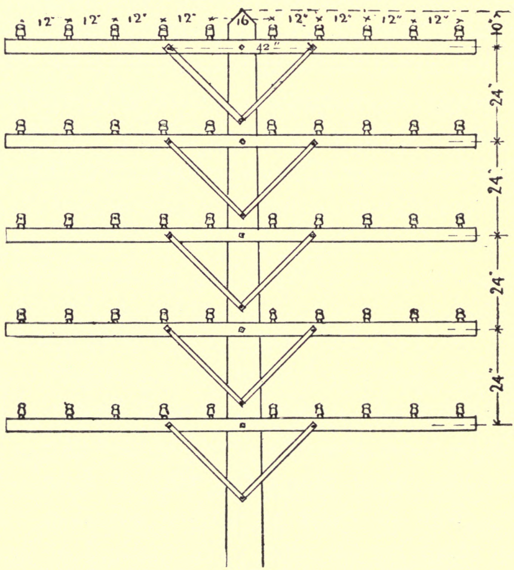


held to the pole by a fetter drive bolt, five inches long, passed through both straps and driven into the pole; and to the cross-arms by carriage bolts. All this iron work is well galvanized, and must stand the test of four dippings into sulphate of copper solution without removing the zinc. The method of bracing is shown in the diagram.



The pins are of the best locust, 1 ¼ inch in diameter. They are set twelve inches apart, except the two nearest the pole, which are set sixteen inches apart, for clearance. Each pin is held in place by a nail driven through from the side of the arm. The insulator used is that shown in a subsequent chapter. It is of white glass and rather small.

It has been the practice to provide every fortieth

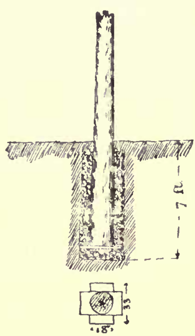


SCALE ¼" TO 1 FOOT

pole with a double set of cross-arms and insulators, on opposite sides of the pole; and every twentieth pole has the alternate cross-arms duplicated in the same way. This is for the purpose of making the transpositions.* Latterly, however, a new form of insulator, devised by Mr. Hibbard, of the American Telephone & Telegraph Co., has been used, which makes the duplication of cross-arms unnecessary. The pins for the transposition insulator are substantially the same as the standard pin, the thread, however, being cut farther down toward the base.

SETTING POLES.

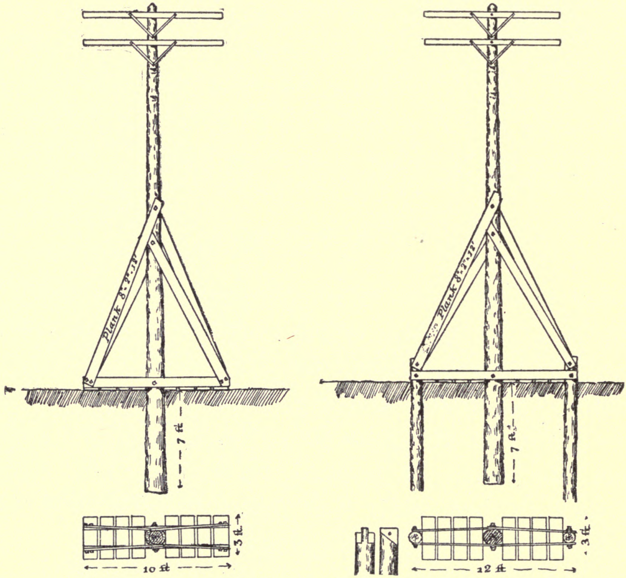
On straight lines, all poles are set into the ground six feet. On curves they are set deeper than that, usually six and one-half to seven feet. The holes are dug large enough to set the poles in easily, and the earth is tamped hard around the butt while it is slowly shoveled in. When the ground is too soft to hold the pole properly, artificial foundations are resorted to. One of the simplest methods consists in filling about the pole



with a grouting of cement, sand, and broken stone, mixed in the proportion of one part cement to two

* See page 224.

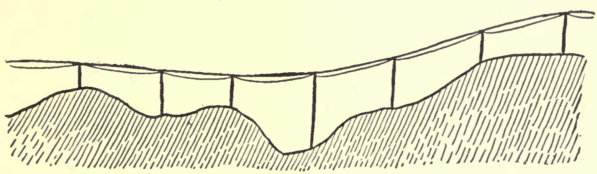
parts sand and five parts stone. A thin layer of grout should be placed in the bottom of the hole, and the butt of the pole, resting on two crossed planks, placed upon this foundation. The space is then filled in with grout.



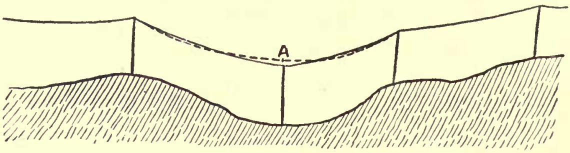
When the ground is very bad the pole may be supported by braces from a platform built of plank, piling being used when necessary. The plank braces are all fastened by standard cross-arm bolts. When piling is used, the heads of the piles should be cut to receive the ends of the braces, as shown in the detail.

On straight lines, poles are spaced one hundred and thirty feet apart, as nearly as obstructions will allow, and the cross-arms are set alternately facing each other and back to back. When the span is very long, however—say two hundred feet—the cross-arms on the poles at each end are so set that the pull on the long section will set the arms against the poles. The same practice is followed at the terminals of lines, the cross-arms on the last two poles being placed on the side away from the line; and on curves the arms must always be placed on the sides of the poles facing the middle of the curve.

The conditions met in building a 'cross-country line are in many respects different from those obtain-



ing on lines built along a railroad or in a city. In selecting poles for a 'cross-country line, and in determining what height of pole to use at a given point, the conformation of the country must be considered, and the height of pole adapted to it, so that the tops of the poles shall be as nearly even as possible. This gives an approximately even strain on all the poles. If this is not done there may be at some points an upward pull on the poles, which will result in pulling off the insulators, as at *A* in the diagram below, where the dotted line shows the position the wires would naturally assume.



Care must be taken that the poles be not given too great an inclination on curves; for in such a case, when the wires are drawn up, the tops of the poles are bent over toward the outside of the curve. This, instead of relieving the pole, as it would if the inclination were too slight, buckles it, and tends to concentrate the strain at one point, so that it is apt to break. Cedar poles, in breaking, do not split and make a long break, but are apt to snap off short; and it has been found that the points at which this break is most likely to occur are at the butt, just above the ground, and at a point just under the cross-arms. In fact, cases have been known where the pole has snapped in both places at once.

It is now considered the best practice to set all poles perpendicularly and to provide against any side strain by guying.

GUYS.

Hard drawn steel or silicon or aluminum bronze should be used for guys. Soft iron has been used for this purpose to a considerable extent; but soft iron stretches so readily that a strain is soon put upon the pole and the guy does not fulfil its purpose. Bronze wire-rope would be a very desirable material, the only objection to its use being its high cost.*

In the use of hard steel, considerable care must be exercised in making joints. It is in many cases very brittle, and a sharp bend, if made carelessly, will cause it to break off short. Care in inspection and manipulation are the only safeguards against this difficulty.

Guys should always be in the form of cable, and the steel should be thoroughly galvanized. The cable or rope should consist of not less than seven strands, each 0.109 inch in diameter. The wire should be free from flaws and scales, sand or splinters. It should withstand a pull of nearly five times its own weight per mile without breaking, and should take not less than fifteen twists in a length of six inches.

The seven strands of the rope should be laid up with a twist not more than three and one-half inches in length. This insures the necessary flexibility. An equal weight of a smaller wire, with a shorter "lay," would give a better rope, although a more expensive one.

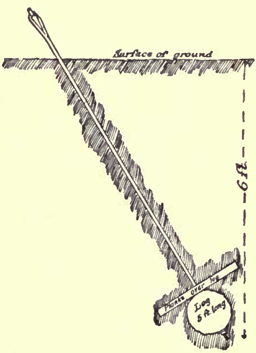
The rope is required to be furnished in coils weighing between 140 and 160 pounds.

* For the properties of bronze wire, see the next chapter.

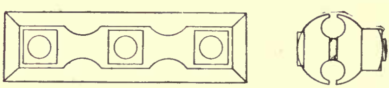
The guy rope is attached to a rod, eight feet long, having a nut and washer at its lower end. The

lower end of this rod is passed through a log which serves as an anchor.

In attaching the guy rope to the pole it is passed



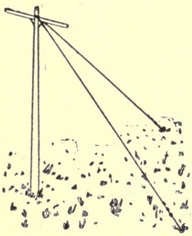
twice around the pole and fastened by means of the guy clamp, of malleable iron. This clamp has two grooves running through it, to take the rope, and is tightened by means of three bolts. The rope is held from slipping on the pole by staples driven down upon it.

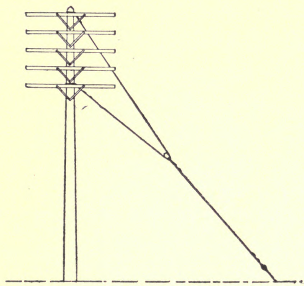


No general rule can be laid down in regard to the method of guying to be employed. The particular guy to be used in any case depends entirely upon circumstances, and must be determined specifically for each case.

The *head guy* runs from just above the upper cross-arm to the base of the next pole, or to the regular anchor guy-rod, and takes a strain in line with the wires.

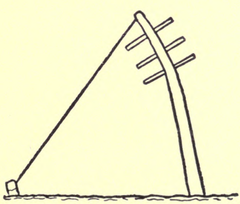
The *side-guy* runs, in the same manner, at right angles to the line, and takes the side pull. The cut shows a pole both side- and head-guyed.

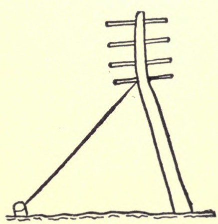




The Y-guy is a very useful form, and it is almost always advisable to use this form when the pole carries more than two or three cross-arms.

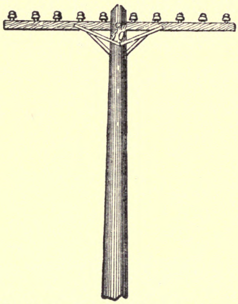
In such a case the use of a single guy is likely to



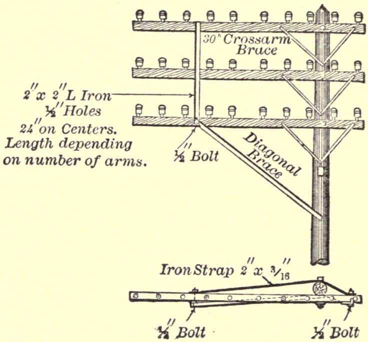


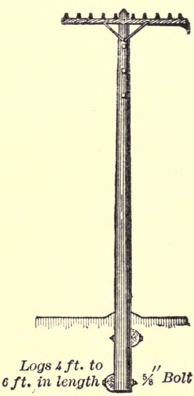
result in the bending over of the top of the pole in one or the other direction, as shown.

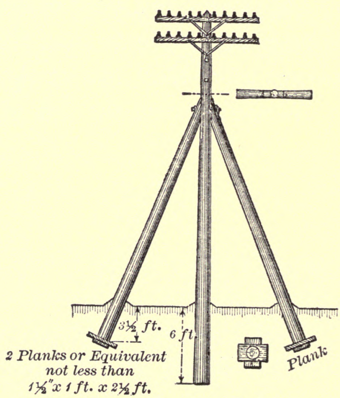
Guy stubs are used wherever it is necessary to raise

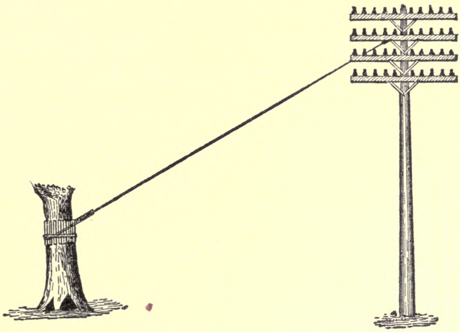


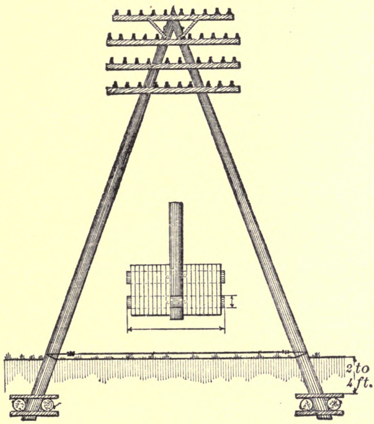
Back Brace for Cross-arms
on Corner Poles.

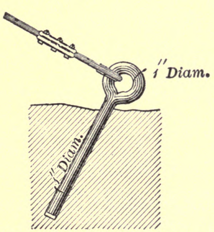




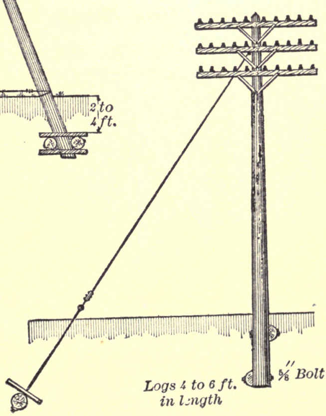




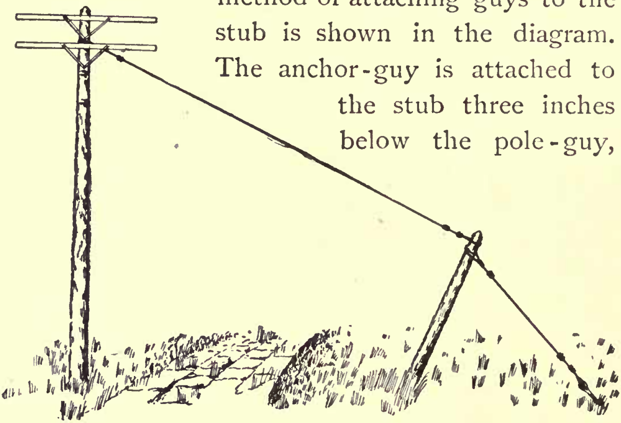




Eye Bolt for Rock Guy.

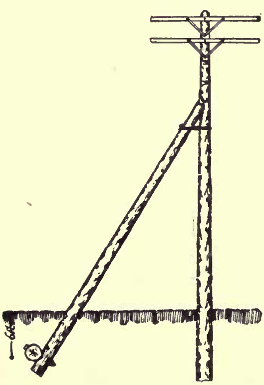


the guy to a sufficient height to clear an obstacle or to prevent the obstruction of a thoroughfare. The method of attaching guys to the stub is shown in the diagram. The anchor-guy is attached to the stub three inches below the pole-guy,



and both guys are held in place by staples, in the regular manner.

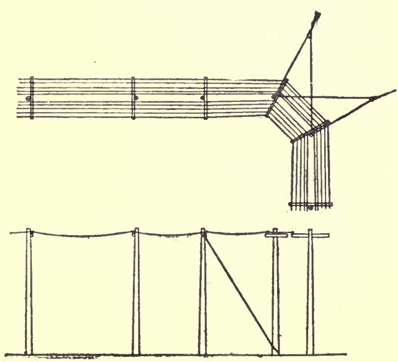
The *pole brace* is used only where it is impossible to use a guy. The brace is held to the pole by three wraps of No. 6 iron wire and by two nails at the top. The wire is prevented from slipping up on the brace by a five-inch fetter drive-bolt. The anchor is a log five feet long, buried six feet below the surface; and the brace is fastened to it by a cross-arm bolt.



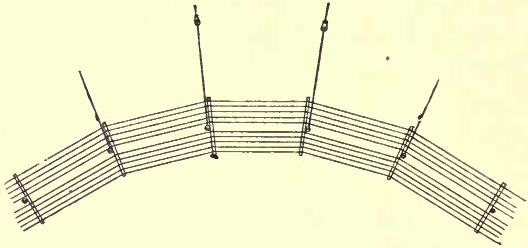
The best practice in guying is outlined below: All poles having a side strain are guyed against that strain wherever possible.

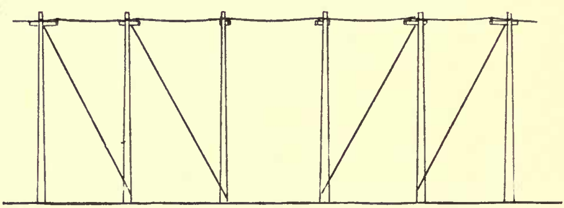
Terminal poles are head-guyed, and, if possible, side-guyed in both directions; and an additional pole is set within seventy-five feet of each terminal pole and head-guyed to it. This applies also to the entrance to a curve.

Road crossings are made at an angle of forty-five degrees, as nearly as may be, the pole at which the turn is made being head-guyed, and having also, if it can be located, a side guy to take the strain of the crossing. In every case of road-crossing the additional pole, seventy-five feet away, is head-guyed to the base of the turning pole. When neither head nor side anchor guys can be located, an additional head-guy is run from the third pole to the base of the second.



Two methods of guying at a street corner have been shown in the first chapter. Another method for a sharp turn is shown in the diagram. As with every pole terminating a straight line, the additional pole is head-guyed to the corner pole. The cross-guys are best run through dead-eyes to equalize the strain, and each corner pole is thus guyed to two anchors. It should be noted that, of each of these double guys, one part is in the direction of the pole-line and the other part is toward the centre of the curve. On every curve the side-guys should pull directly away from the centre, and sufficient head-guys should be used to take the whole strain of the line.



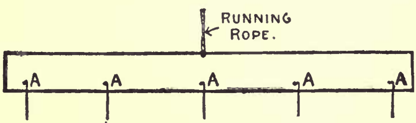


Even in straight lines, guys are placed at regular intervals. A line carrying between ten and twenty wires is double head-guyed and double side-guyed at intervals of one mile; and lines carrying more wires than that are guyed in the same manner at proportionately frequent intervals.

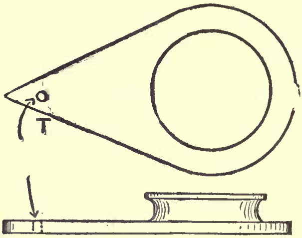
In hilly country, head-guys should be so placed as to take the downward strain due to the weight of the line.

STRINGING.

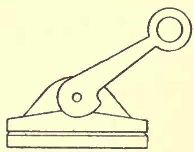
The process of stringing wire has been modified from time to time. The older method and the most modern practice are both given below. The poles for a distance of one-half to three-quarters of a mile have been set, the cross-arms and insulators are in place. A rope, called the "running rope," is then carried along over the cross-arms for the whole distance, and attached at one end to a board known as the "running board." This running board is roughly shown in the diagram. At this end of the line the reels containing the wires are mounted, and the wires, each on its separate reel, are attached to the running board at A, A, A. When the wires are all made fast to the running board in the manner described, a team of horses is hitched to the other end of the running rope, and they "walk away" with it, pulling the running board and attached wires over the cross-arms. The wires are guided in passing by linemen stationed on each pole. In stringing wires over the lower cross-arms a divided running board is used, one half passing each side of the pole.



When the wires have been drawn over, they are pulled up tight. This was formerly done by means of the "banjo." The "banjo" consists of a wooden drum fastened upon a kite-shaped board. The wire is wound around the drum, and a small double block and fall is attached at T. Each wire in turn is drawn tight, and at a given signal is tied on all the poles at once by the linemen stationed there.



An improvement on this method consists in the use of a clamp to grip the wire while it is pulled up. This clamp operates on the principle shown in the illustration.



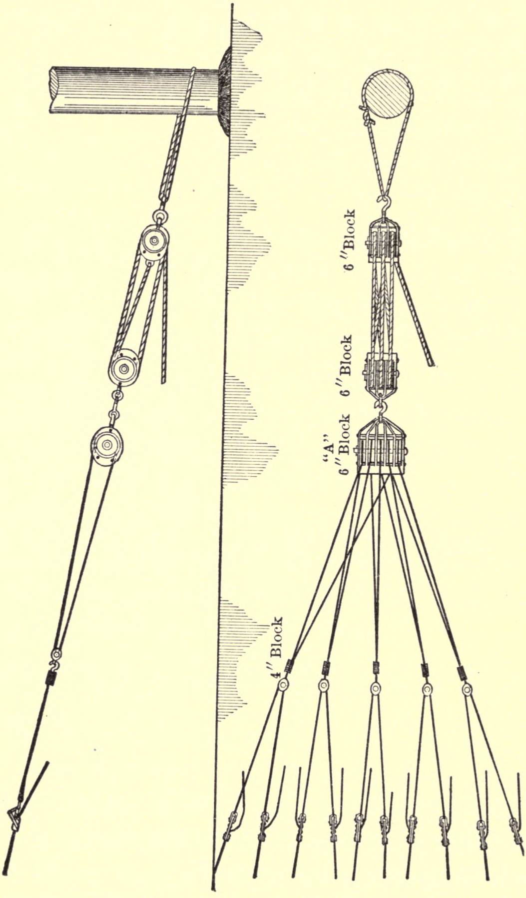
The wire is gripped between the jaws, which are so shaped as not to injure it, and the strain on the chain forces the arm more into line with the wire. This turns the cam and closes the jaws the more tightly, so that the grip on the wire increases with the pull on the chain.

All the wires on a cross-arm are pulled up at once, with the apparatus shown in the cut. This insures even pull on all the wires, which influences greatly the stability of the line.

The sag allowed No. 8 or No. 12 wire is shown by the following table.

Temp. Fahr.	Span 75 feet. Sag.	Span 100 feet. Sag.	Span 115 feet, Sag.	Span 130 feet. Sag.	Span 150 feet. Sag.	Span 200 feet. Sag.
− 30	1 inch.	2 inches.	2½ inches.	3½ inches.	4½ inches.	8 inches.
− 10	1½ "	2½ "	3 "	4 "	5 "	9 "
+ 10	1½ "	3 "	3½ "	4½ "	6 "	10½ "
+ 30	2 inches.	3 "	4 "	5½ "	7 "	12 "
+ 60	2½ "	4½ "	5½ "	7 "	9 "	15½ "
+ 80	3 "	5½ "	7 "	8½ "	11½ "	19 "
+ 100	4½ "	7 "	9 "	11 "	14 "	22½ "

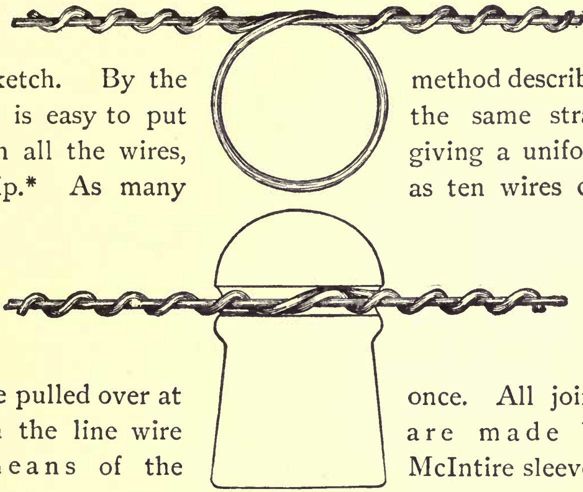
While the wire is held by the tackle, a clamp is put on it at the last pole and is fastened to the cross-arm, holding the wire until the next length beyond is pulled up and connected to it. The neglect of this precaution used to result in making kinks in the wire at each insulator. For when the tackle was taken off



Apparatus for Pulling Up Wires.

after the wire was tied, the strain would cause the tie to slip around somewhat on the glass, and a little sharp bend would be made in the line wire just back of each insulator. This weakened the wire.

The tie is made with wire of the same size and material as that used for the line, and is shown in the sketch. By the method described it is easy to put on all the wires, the same strain giving a uniform dip.* As many as ten wires can be pulled over at once. All joints in the line wire are made by means of the McIntire sleeve.

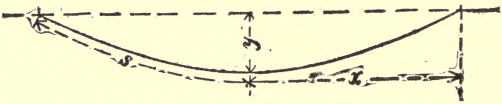


* The dip and pull for a given span can be readily calculated by the formulæ given below :

Copper wire, 174 *pounds per mile.*

$$\left.\begin{aligned}
&\text{40 poles to the mile, dip (inches)} = \frac{870}{\text{Pull (lbs.)}}\\
&\text{43 poles to the mile, dip (inches)} = \frac{756}{\text{Pull (lbs.)}}\\
&\text{45 poles to the mile, dip (inches)} = \frac{684}{\text{Pull (lbs.)}}\\
&\text{53 poles to the mile, dip (inches)} = \frac{500}{\text{Pull (lbs.)}}
\end{aligned}\right\}\text{Approximate.}$$

The location of the wires on the cross-arm is shown in the diagrams. On the straight line, all wires are placed on the inner side of the pins, ex-



x = one-half the span (in feet).
y = dip (in feet).
S = one-half the length of wire (feet).
H = horizontal pull (in pounds).
w = weight of wire per foot (in pounds).

$$y = \frac{m}{2}\left(e^{\frac{x}{m}} + e^{-\frac{x}{m}}\right) - m.$$

$$S = \frac{m}{2}\left(e^{\frac{x}{m}} - e^{-\frac{x}{m}}\right)$$

This is the equation of the Catenary, which is the curve in which the wire hangs. [Where $m = \frac{H}{w}$.]

$$\left\{\begin{array}{l} e^{\frac{x}{m}} = 1 + \frac{x}{m} + \frac{x^2}{m^2 \lfloor 2} + \ldots \\ e^{-\frac{x}{m}} = 1 - \frac{x}{m} + \frac{x^2}{m^2 \lfloor 2} - \ldots \end{array}\right\}$$

$$y = \frac{m}{2}\left(1 + \frac{x}{m} + \frac{x^2}{m^2 \lfloor 2} + \ldots + 1 - \frac{x}{m} + \frac{x^2}{m^2 \lfloor 2} - \ldots\right) - m.$$

$$y = \frac{m}{2}\left(2 + \frac{x^2}{m^2} + \ldots\right) - m.$$

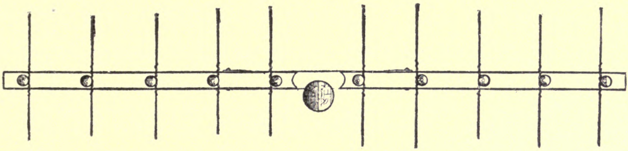
Terms of degree higher than the second may be neglected when the conditions are such as are met in practice.

$$y = \frac{x^2}{2m} = \frac{x^2 w}{2H}.$$

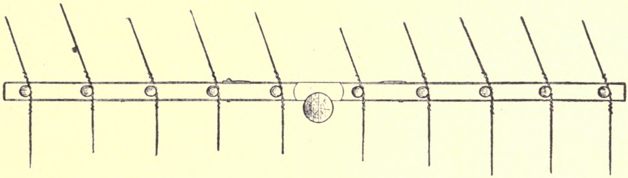
For copper wire 0.104 inch diam., weighing 174 pounds per mile :

$$y = .0165 \frac{x^2}{H};\ y \text{ (inches)} = 0.2 \frac{x^2}{H}.$$

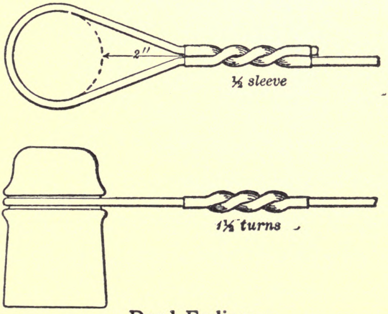
cepting the two inner wires, which are placed outside for greater clearance of the pole.



On curves, the wires are so placed that the strain forces them against the insulator, and no unusual duty is required of the tie wire.



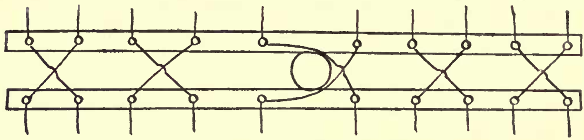
Where a wire is attached to the last insulator on the line—a "dead end," as it is called—for the purpose of connecting to a cable or to a subscriber's instrument, the attachment is made in the manner shown.



Dead Ending.

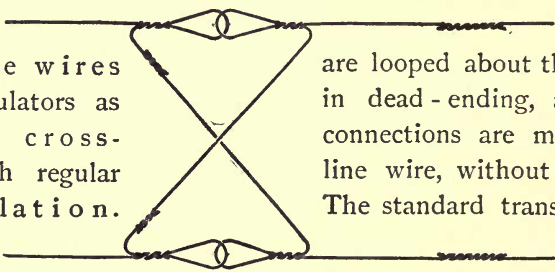
A single loop is made about the insulator, and the joint completed with a McIntire standard half-sleeve, which is given one and one-half turns.

The older method of making transpositions is shown in the diagram, which gives the simplest case.



The line wires are terminated at their insulators and the crosses made with smaller insulated copper wire, as shown.

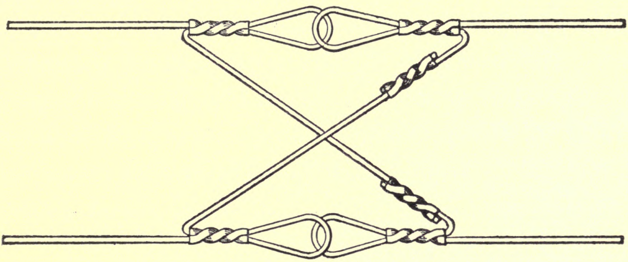
The modern practice is a great improvement on this. McIntire sleeves only are used for connections.



The wires are looped about their insulators as in dead-ending, and the cross-connections are made with regular line wire, without insulation. The standard transposition is shown above. Half-sleeves are used for the short connections.

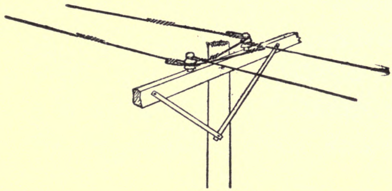
For transposition of the wires next the pole, the plan shown above will not do; for the cross-connections would pass through the pole. The plan is therefore modified, the ends being bent around outside the insulators and the connecting wires crossed behind the pole.

Both these transpositions are now made so as to avoid the break in the line wire. The wires are first pulled up at the pole ahead of the transposition. Six feet of slack is taken up, the wires on both sides being held tight by blocks and clamps. The wire is then cut, the sleeves slipped on and the transposition completed in the regular manner.



Regular Transposition.

When long distance lines enter a city, the pole lines are usually terminated near the city limits, the connections being made to underground cables in the manner already described.



connections being made to underground cables in the manner already described.

CHAPTER IV.

WIRE.

THE wire used in the construction of long distance lines is of two kinds, viz., hard-drawn copper for the lines themselves, and steel for the guys.

In the manufacture, the treatment of the metal, whether iron or copper, differs but little in the early stages of the process. The "bloom" or lump of metal taken from the furnace, is in each case about two feet long, and has a section of about sixteen square inches. The bloom of iron weighs about 135 pounds, and that of copper from 150 to 200 pounds. More than about 200 pounds cannot be advantageously handled in one piece. Having been heated in a gas furnace to the proper temperature, it is "roughed" in the first train of rolls, which reduces it to a rod about one square inch in section. It is then passed automatically through guides into the "intermediate train," which reduces it still further, with a corresponding increase in length. It is then passed into the finishing train, which rolls it alternately square and oval, and leaves it a cylindrical rod about 0. 2 inch diameter.

The finishing train of rolls is usually of the type known as the "Belgian," which has all the rolls on one shaft. This avoids gearing and its accompanying waste of power, which in such work is always great. A disadvantage attaches to this method, however, which in some measure compensates for its advantages. A greater length of wire is necessarily exposed between the passes than where the rolls are successive and connected by gears, and consequently the "scaling" is greater with the Belgian rolls than in the older method.

The wire left by the finishing train is drawn down through dies to the required size, the dies for the larger sizes being of chilled iron, and for the smaller of crucible steel. The iron dies, when slightly worn, are reamed out to the next larger size. The steel dies are hammered on the face, thus contracting the hole, and then reamed back to the same size.

Another method of wire-making, which has not yet been very extensively used, is to roll the rods cold between successive flat rolls so placed as to give the wire a polygonal cross-section. By a proper adjustment of the rolls, however, the sides of the bounding polygon are made so many, and each so short, that the wire is practically cylindrical. Although the breaking strength of such wire is about the same as that of uninjured hard-drawn copper, it is more homogeneous in structure, and less liable to loss of strength from an injury to its surface than the hard-drawn wire, which loses very greatly in strength if scratched or nicked. It is characteristic of the hard-drawn wire, also, that if bent slowly at a sharp angle a point is soon reached at which the strength of the outer skin is exceeded, and the wire suddenly gives way. This appears not to be the case with the cold rolled wire, which presents an approximately uniform resistance to bending through any angle. This wire is very free from splinters.

The hard-drawn copper wire now used is 0.104 inch in diameter.* Tests of this wire are made by the manufacturers, and in addition the wire is tested by the telephone companies before acceptance, as it must test in accordance with these specifications.

Gauge Number.	Diameter of Wire in Inches.			Weight per Mile in Pounds.		Tensile Strength.		Ductility.	
	Required.	Maximum.	Minimum.	Maximum.	Minimum.	Pounds per Square inch. Minimum.	Min. Breaking Weight for Required Diameter.	Per cent. Elongation in 5 ft. Minimum.	Minimum Number of Twists in 6 inches.
14. N. B. S. G.	.0800	.0805	.0795	103.9	101.3	65,600	330	.94	44
12. N. B. S. G.	.1040	.1047	.1033	175.7	171.1	64,600	549	1.00	40
8. B. W. G...	.1650	.1660	.1640	441.7	431.1	62,100	1,328	1.14	30

Minimum conductivity, 96 per cent. of that of pure copper.

The finished wire is made up into rolls, or coils, each consisting of about three-fourths of a mile of wire, drawn in one continuous length and without factory joints. A wire inspector, appointed by the telephone company, visits the factory as each lot of wire is completed, and carefully examines these coils, making sure that the wire is free from rough places

* Wire 0.165 inch diameter is in use for the longest lines.

and splinters.* If the wire is imperfect in this respect, or does not come up to the requirements named above, the lot is rejected. The coils are then pulled over, and from each coil that the inspector designates, a sample length is cut, about forty feet in length, to be tested for its mechanical and electrical properties. It is usual to take a specimen from one coil out of every ten, and on each specimen three sets of measurements are made, viz.: the maximum load (usually called breaking-weight), weight, and conductivity. From these measurements all the other properties of the wire are obtained by calculation.

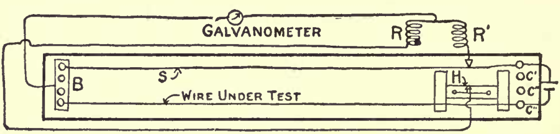
In the test for breaking-weight a length of about five feet is clamped at the ends, and the strain on the wire slowly increased to the breaking-point, the measurements being made by weights. The elongation of the wire before breaking is also obtained from this test in the following way: An initial strain of fifty pounds is put on the wire, to straighten it out, and the length of the wire carefully measured. The wire is then broken, as described, and the distance between the end clamps again measured. The difference between the two measurements is the amount of elongation. In practice this measurement is made automatically, so that all error arising from the play of the clamps is eliminated, and the distance between clamps is known at any instant.

* It is not safe to handle wire which is full of splinters, as they tear the hands of the lineman, and the copper is poisonous.

The strength of the wire for torsion is measured by twisting a length of six inches and counting the number of turns before the wire breaks. These tests are made by power on machines especially constructed for the purpose, and can be performed very accurately and rapidly.

The diameter of the wire is obtained from a knowledge of the specific gravity, by weighing a given length. The length used is, for convenience, generally 17.6 feet, or $\frac{1}{300}$ of a mile, and this measurement gives also the weight per mile.

The method of testing for conductivity and resistance per mile is not new and is well known, but the apparatus * now used for this purpose is not well known, and is so simple as to merit description.



S is a standard wire, whose conductivity has been carefully determined, once for all, and is exactly 17.6 feet long between contacts. This standard wire is left in position permanently, and never disturbed. *B* is a heavy bar of metal into which are set a number of massive binding posts, with corresponding posts in brass blocks at *C C′ C″*, etc. The blocks *C C′ C″* etc., are provided with plug connections with a metal bar in connection with a battery. *H* is a

* Devised by Mr. A. C. White, of the Amer. Bell Tel. Co.

strip of wood, and has fastened permanently upon it a metal scale graduated in distances (feet and tenths, etc.) from the edge of the binding posts on *B*. *H* can be moved vertically between guides and is provided with a horizontally sliding contact having a pointer which moves over the graduated scale. *R* and *R'* are resistances, in this case about 1,000 ohms each, and equal.

The wires whose conductivities are to be measured are drawn tight between the binding posts, *C C' C''*, etc., and the posts in *B*. Each is in turn plugged into connection with the battery, *H* moved under the wire, and the sliding contact adjusted until no deflection is obtained on the galvanometer. The reading of the scale is then taken, and from that and the weight of the wire its conductivity can be calculated. In practice, tables or curves are used, rendering the operation short and simple.* As the

* The necessary formulæ for this calculation and for the construction of the curves and tables referred to are given below :

To determine the conductivity of the standard wire (or any wire),

r = resistance in B. A. ohms of 17.60 feet or $\frac{1}{300}$ mile, corrected to a temperature of 20° C. or 68° F.

w = weight of 17.60 feet of wire in grammes.

d = diameter of wire in mills (thousandths of an inch).

For copper wire,

Conductivity $= \frac{4.463}{wr}$. If r is in legal ohms, constant = 4.414.

$$d = 6.433\sqrt{w}.$$

For any wire,

Conductivity $= \frac{184.2}{d^2 r}$. If r is in legal ohms, constant = 182.2.

$d = 77.64\sqrt{\frac{w}{W_0}}$. When W_0 = weight of 1 cubic inch in grammes.

If any other than the B. A. ohm or the "legal" ohm is used, the apparatus is arranged, the resistances at the adjustable contacts affect only the coils R and R', which are wound of high resistance. The error due to resistance at these contacts, therefore, is practically eliminated.

Hard-drawn copper wire 0.104 inch in diameter should have a breaking strength of not less than 540 pounds, and should elongate more than one per cent. of its length before breaking. The number of twists in six inches varies much in different specimens, but there seems to be no reason why a wire six inches long should not take at least forty twists before breaking.

The conductivity of hard-drawn copper should be 97 per cent. of that of pure copper, or very nearly as high. Indeed, some has been tested that had a conductivity of 98 per cent. or more. One characteristic of hard-drawn wire appears to be that most of the strength is in the outside, so that especially great

proper constants can be easily found in each case by the use of the ratio between the new standard and either of those given above.

To determine diameter, conductivity, resistance per mile, and weight per mile of copper wire from measurements of weight and comparison with standard wire (Thomson Bridge method):

K = conductivity of standard wire at 20° C. or 68° F.

w = weight of 17.60 feet of standard wire in grammes.

r = resistance of 17.60 feet of standard wire at 20° C. or 68° F.

L = length of wire under test which balances standard wire.

W = weight of 17.60 feet of wire under test.

$$\text{Conductivity} = \frac{Kw}{17.60} \cdot \frac{L}{W}. \qquad \text{Resistance per mile} = \frac{5280r}{L}.$$

$$\text{Weight, in pounds per mile} = 0.6614\,W.$$

$$\text{Diameter (in mills)} = 6.433\sqrt{W}.$$

care needs to be exercised that the wire is not nicked in any way. A nicked wire, even if the injury be apparently very slight, will break with a much smaller strain, and have a much less elongation than when uninjured. The difference is out of all proportion to the extent of the injury.

It has been customary, in obtaining the tensile strength and elongation of iron and steel wire, to use lengths of not more than one or two feet. A greater length would give more accurately the average values, and there appears to be no good reason why a length of five feet should not be used, as in the case of copper. The tensile strength of iron and steel ranges from 70,000 pounds to 100,000 pounds per square inch; and the elongation, in the short lengths tested, is from 12 per cent. to 20 per cent. All iron and steel wire should be well galvanized.

Within the last few years much attention has been devoted to the manufacture of silicon-bronze and aluminium-bronze wires. The properties of bronze wire depend entirely upon the proportion of silicon or of aluminium used in making the alloy, and upon the care exercised in smelting and drawing. As the proportion of aluminium or of silicon is increased, the tensile strength becomes greater, but the conductivity and ductility are diminished. It is now possible to produce a bronze wire having exceptionally high mechanical properties. Some silicon-bronze wire now on the market has a tensile strength as high as 80,000 pounds per square inch, and is capable of standing about 80 twists in a length of six inches before breaking. An aluminium-bronze wire recently tested by the author had a tensile strength of 110,000 pounds per square inch, which is as high as that of the best steel, but the ductility was not so great as that of the silicon-bronze wire just mentioned. The conductivity of bronze wire cannot be expected, under the most favorable conditions, to much exceed 40 per cent. of that of pure copper; and for that reason bronze is far inferior to copper as a material for line wire. Its high tensile strength, however, and its freedom from corrosion make it eminently suitable for guy-wires in many cases. The only objection to its use for this purpose is a commercial one, namely, its high cost, which is at present about six times that of iron; but it is a question whether the increase in first cost would not be fully balanced by the saving in repairs and renewals.

The deterioration of iron or steel wire depends largely upon its location. It is most rapid in cities or near the sea-coast. In large cities, especially, where the atmosphere is filled with smoke and corrosive vapors, the life of an iron or steel wire is very short. Under the action of these vapors, the coating of zinc is slowly eaten away; and as soon as this coating has been entirely removed from any spot, the wire rapidly disappears. Many cases have been known in which the life of an iron wire in a city has been less than two years; and in one case which came under the observation of the author an iron wire, originally galvanized, was found to be, at several points, nothing but a mass of rust within less than a year after stringing.

The life of copper wire under similar circumstances is as yet undetermined. Copper is practically unaffected by the gases and vapors of a city atmosphere, and even where it is exposed to the action of the winds blowing directly off the salt water, the action is so slight as not to produce any appreciable effect. Tests have been made on hard-drawn copper wire which had been in service for ten years, and it was found to be apparently as strong as when first put up. As it is exposed to the weather a thin coating of chloride or carbonate forms on the surface of the wire and protects it from further action.

Silicon-bronze and aluminium-bronze possess the same characteristics as copper in regard to deterioration, being even less liable to corrosion. So far as chemical change is concerned, therefore, the life of a copper or bronze wire is practically without limit.

CHAPTER V.

INSULATORS.

Many forms of insulator have been tried, and many different materials used.

Glass is almost universally used in America, and gives excellent results in most cases. The tendency has been to make the glass insulator for telephone use as small and light as possible; and the insulator now in most common use seems ridiculously small in comparison with the immense earthenware or porcelain arrangements commonly used in England on telegraph lines. The difference in climate will, however, account for the difference in size and material, and our lines in America will usually test fully as high as most English lines. Moreover, it is not necessary or desirable to keep the insulation of telephone lines as high as it could be made.

Glass has several disadvantages as an insulating material, and these have contributed largely to make its use as an insulator uncommon in England, where the air is generally overcharged with moisture. It is very hygroscopic, readily condensing moisture, and retaining a thin film of water on its surface, and is especially brittle, more so than earthenware or good porcelain. Blown glass is better in every respect than cast or ground glass for insulators, as the surface of blown glass is less hygroscopic than a surface formed in contact with a mould, or by grinding. Nevertheless, cast glass insulators are almost universally used in this country, as they are very much cheaper than blown glass, and give a sufficiently good insulation. One of the greatest advantages of glass insulators is their transparency, for cocoons are much less apt to be made under them than under opaque bodies, such as porcelain and stoneware.

Ebonite has been used to some extent for insulators, and gives very good results when used in unexposed places. As it quickly roughens on exposure to the weather, it is not a good material for line insulation.

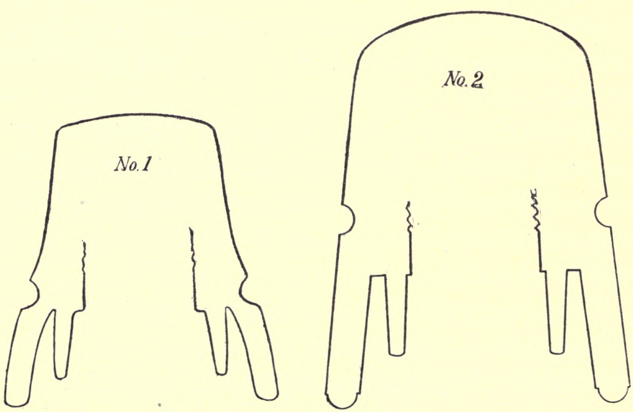
Brown stoneware is an excellent material for this purpose, as it is strong, cheap, and durable. The glaze seldom or never cracks, and its color makes it inconspicuous. The surface is not, however, equal to that of porcelain.

Thoroughly vitrified porcelain makes the best insulator, and is largely used in England and on the Continent. The surface resists the formation of a continuous film of moisture, and is easily washed by rain. Good porcelain is tougher than glass, but its opacity is a disadvantage, as the dark cavities under the bells favor the formation of cocoons and spider's webs and the accumulation of dirt. Porcelain is much more expensive than glass, and this is one of the greatest reasons for its infrequent use in this country.

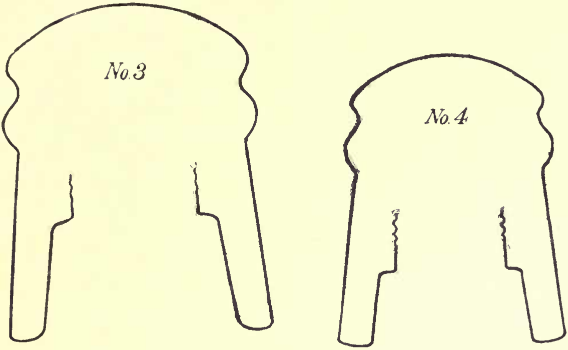
Baked wood, impregnated with a non-conducting compound, has been used with some success in dry climates, but cannot be recommended for general use.

An extended test was made a few years ago on several forms of glass insulator in common use, taking observations of weather conditions and measurements of insulation.

For this purpose four of the most typical forms of insulator were selected and fifty of each, mounted



in the usual way, were so placed as to be fully exposed to the weather. Regular signal service instruments were used to determine the relative humidity, temperature, etc., and were set as near as possible to the insulators. The insulation measurements were made on a very delicate galvanometer, and the arrangement was such that the leakage in the appa-



ratus from the galvanometer to the insulators under test was at all times practically *nil.* Short tests on porcelain knobs showed them to be so totally unfit for insulators that the tests were soon abandoned.

Referring to the diagrams, No. 1 and No. 2 are double petticoat insulators, differing chiefly in size. No. 2 has been used much by the Western Union Telegraph Co. on its telegraph lines. No. 3 is a large, single petticoat insulator, also used by the Western Union Co., and No. 4 is the pony single petticoat, in very general use on the long distance lines of the American Telephone & Telegraph Co. No. 1 has never been in practical use.

The test covered a period of four and one half months of summer weather, and measurements were made on an average about once a day. The weather conditions were of course varied, about

50	per cent.	of the	observations	being in	clear weather.
20	"	"	"	"	fair weather.
18	"	"	"	"	cloudy weather.
12	"	"	"	"	fog or rain.

Many observations would have been made during rain, but if the rain is falling in any considerable quantity the insulation falls so rapidly and is so variable that no just comparison of the different types could be made under such conditions.

Easterly winds, in the test, were those blowing directly from the salt water, and were therefore always heavily laden with moisture and often accompanied by fog or mist. As would be expected in such a case, the insulation was almost always lower when such winds prevailed than when the wind was from the land. No definite relation could be noted between the velocity of wind and the relative humidity or dew-point; but it was found that with a given direction of wind the insulation was approximately inversely proportional to the relative humidity.

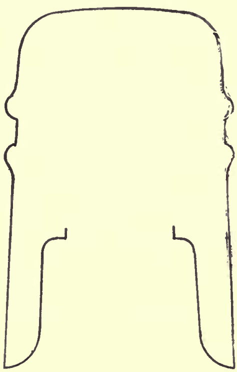
The insulation after rain, when sufficient time had elapsed for the insulators to dry, was usually somewhat higher than before, owing, doubtless, to the washing off of the dust and smoke which had collected on them. No marked loss of insulation could be observed, however, just before a rain.

Contrary to the general opinion that the more open double petticoat form dries more rapidly than the close single petticoat, it was not found that the insulation rose any more rapidly after rain in one case than in the other, although when rain begins to fall the insulation of the double petticoat insulators falls much the more rapidly. Moreover the double petticoat forms lose their insulation to a much greater extent than the single petticoat.

During fine weather the large sizes of each form gave practically identical results, and the double petticoat insulators each showed higher insulation than the single petticoat of each size. In such weather any one of the four would have a sufficiently high insulation, and it is only during bad weather that the difference becomes important. In bad weather, that is, during and after rain or fog, the single petticoat makes a better showing than the double petticoat form.

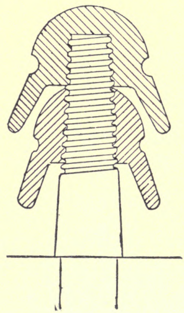
The question of form alone can be properly treated, however, only when the consideration of size has been eliminated; and for this purpose the factor $\frac{\text{mean diameter}}{\text{conducting length}}$ must be determined for each insulator and the results be reduced by its use to a unit size. As it is the resistance of the film of moisture which is measured, this is equivalent to reducing the measured resistances to a unit length and cross-section of conducting film. When this was done the single petticoat form was found to be far supe rior to the double petticoat under all conditions of weather.

From the information obtained in this test it would not be difficult to design an insulator which would embody the best characteristics of the known forms and which at the same time would be of about the same weight as the smaller insulators. This insulator should be made of porcelain; but if made of glass it would probably show better results than any of the other small, light insulators. The main points aimed at should be a great length of conducting surface with a minimum diameter; for the tests showed that it was more important to have a long petticoat than to have the spaces underneath open for the purpose of rapid drying.



Sufficient strength should be provided for by having the wire tied well down near the base of the pin, so that very little strain would come on the material of the insulator itself.

Mr. Hibbard's transposition insulator, already referred to, is simple in design, consisting, originally, of two single-petticoat pony insulators, one over the other, the lower one having its top knocked out. The present design is shown in the figure. This device accomplishes the purpose, so far as transposition is concerned; but it is mechanically not the best arrangement, as it brings the strain high up on the pin, which has to be still further weakened by cutting out more of the wood, in order to extend the thread lower down. This insulator, however, in its present form, has been in use on the long distance lines for some years. It has given no trouble, but has, on the contrary, been found very satisfactory; so that we must conclude that its strength is sufficient for the purpose.

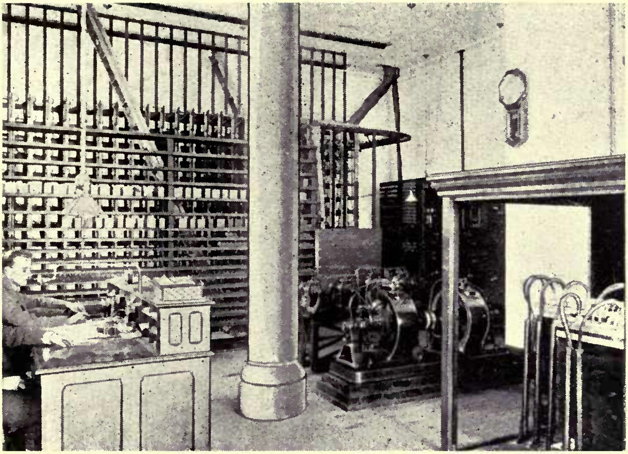


CHAPTER VI.

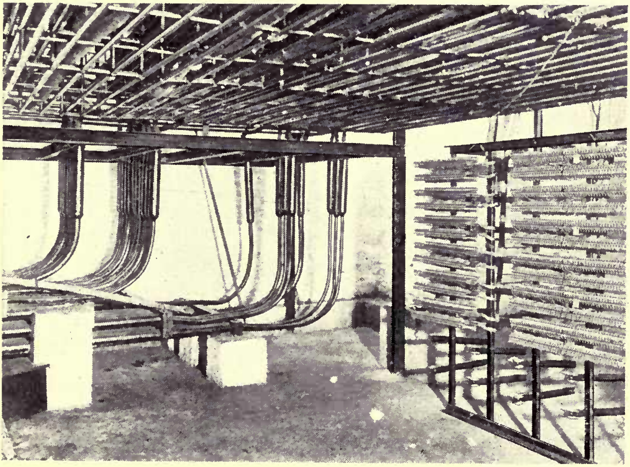
EXCHANGES.

THE number of methods of constructing and arranging exchanges or central offices is almost as great as the number of exchanges themselves. In the early days of telephony the requirements for a well-equipped exchange were not known, and each office was designed in accordance with the ideas of its manager or superintendent. Very generally the top floor of some building was obtained, designed for some other and totally different purpose, and was adapted as it best might be for the purposes of a telephone exchange. With the growth of the business the wants and necessities have become pretty well known, and all exchanges have been more or less altered and improved in their arrangements; but still too many of them are altogether faulty and inadequate.

The office building should first of all be fire-proof. This is a condition very difficult to attain; but it can be very nearly approached. Brick is the most reliable material for resisting fire, and the partitions should be made fire-walls of brick so far as possible. Whenever it is necessary to provide unbroken shafts



Power Plant, Bedford Exchange, Brooklyn.



Cable Vault and Distributing Racks.

throughout the height of the building, they should be built of brick, and the necessary doors made of wood tinned on both sides. Iron doors should not be used.

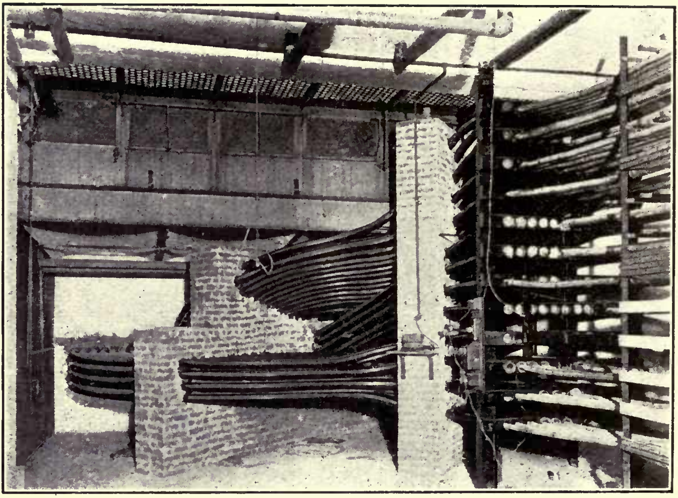
The building should be designed especially for the occupation of the operating switch-board and its necessary adjuncts. The operating office should be on the top floor. A brick shaft of suitable dimensions should be provided, leading from the basement to the top floor, and through this shaft the underground cables should be led to a room set apart for the terminals, distributing and testing purposes.

"Near to this should be a battery and power-room of ample dimensions, providing for the generators, motors, main and testing batteries, with the necessary water connections and other appurtenances. The form of the operating-room itself would, of course, depend largely upon local conditions. One of the chief requisites should be the anticipated ultimate capacity of the exchange. In general, if it is necessary to deflect the board from a straight line, it is better to have the operators work from the inside of a circle than around the outside, the arrangement being such that all operators are at once within view of the chief operator. The office should be free from elevator shafts or other obstructions, and should not be made a passageway for employees in reaching the roof or any other part of the building."

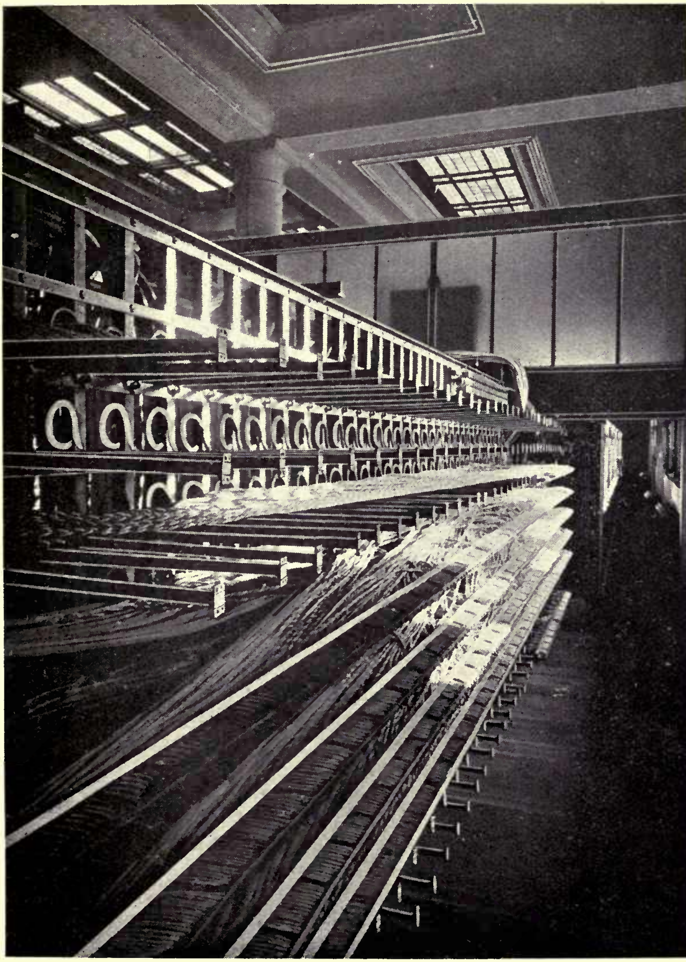
As all wires will enter the exchanges eventually by underground ducts, these ducts should be provided of ample capacity. The ducts open into the building *low down* in the basement, and provision should be made for drawing off any water they may contain, and for carrying off any gases that may collect in them. These gases are often explosive, and should not be allowed to enter the building.

Where the cables enter the building they should be available for handling, and it should be possible to get at any one cable in the duct without disturbing the others. For this purpose, it is now recommended that the cables, after leaving the ducts, be arranged symmetrically, in vertical lines, supported separately on hooks on the walls of the building, or on lines of posts erected for the purpose. This arrangement should extend to the terminal room, and the same plan should be followed at every point where it is necessary to handle the cables. It greatly facilitates testing, changes, or repairs. Where this arrangement has not been made "it is even now becoming very difficult to do the work of drawing in and wholly impossible to do the work of drawing out specific cables without interrupting the whole system. This is apparently caused, first, by the very limited area of the underground manholes, and second, by the failure to provide a comprehensive system, by means of which every one of the underground ducts may be utilized as desired."

The terminal or distributing room should be as near the operating office as possible, and here the cables should be headed and connected to fusible



Cable Vault and Distributing Rack, Main Exchange, Brooklyn.



Intermediate Rack, Main Exchange, Brooklyn.

arresters which will burn out with a current of half an ampère. These office terminal boxes should be so sealed up as to be water- and moisture-proof, to prevent deterioration of the insulation of the cable.

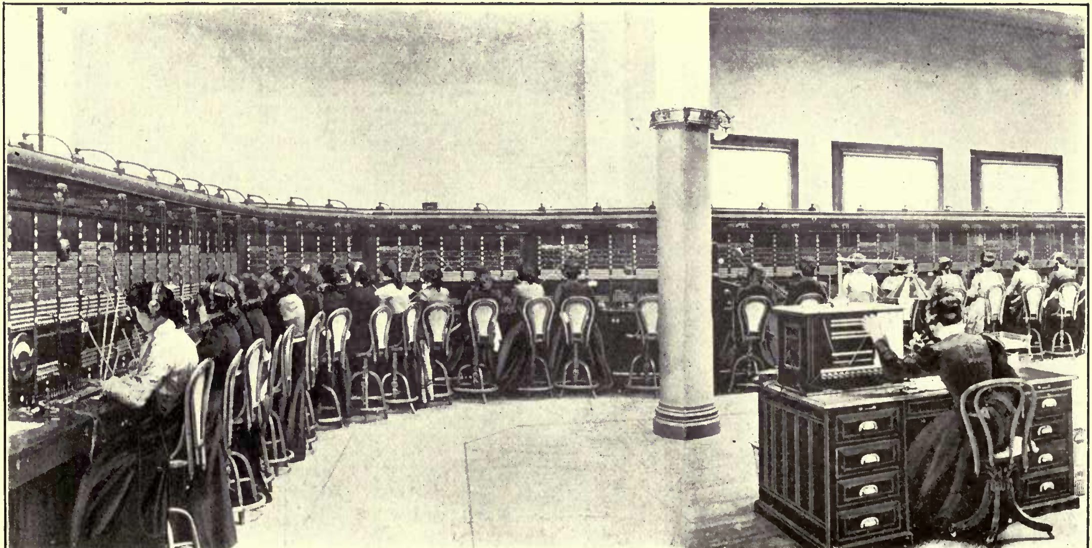
From the fusible arresters the circuit should be led by office cables, composed of twisted pairs, to the distributing board. This distributing board is to facilitate the arrangement of the operating board, and to make changes possible in the operating board without changing the connections throughout the line, or *vice versa*. The wires from the cable heads are led to binding posts, from the opposite ends of which other wires are led to the operating board. It is thus possible to connect any outside circuit into any set of jacks without disturbing the connections at the cable head. This distributing board should be made in such form that wires may be led at any time from any point on the line terminals to any desired number on the switchboard terminals, it being so arranged that even when fully occupied all distributing wires are available for handling as desired. The distributing wires should be covered with waterproof insulation and the connections soldered.

"It is especially recommended that the cable heads be mounted on a fireproof fixture, and that the distributing board be made fireproof."

"When arranged in this manner the circuits are available for testing purposes at the fusible arresters, where they may be tested out through the underground cables, or in through the distributing and operating switchboards. When an office is so arranged it is of advantage, therefore, that the testing should be done in this terminal and distributing room, and that this room should be accessible without passing through the operating room. The terminal and testing room should be in charge of the chief inspector, by whom all circuits would be tested, and who would have charge of the general trouble work of the exchange. There should be supplied for his use a telephone outfit with connections to the office manager or chief operator; circuits through the operating board; a circuit to the generator and power tables, and also to plugs available at the cable-heads, by means of which line or office tests may be made. He should have, also, a Morse outfit with relay and key, with a battery circuit included, and be supplied with a galvanometer outfit and a Wheatstone bridge. While it is not recommended that at every exchange office there should be kept additional and more delicate instruments for making insulation resistance and capacity tests, it is expected that in each company these appliances are available, and they may be connected for such tests through this chief inspector's apparatus." *

Much of the past and present poor condition of lines is due to the lack of just such information as these insulation and capacity tests would give, and in an exchange of any considerable size, or one using much underground cable, the apparatus for these tests should be permanently set up and frequently used.

* The quoted passages in this chapter are from a paper by Messrs. Carty, Pickernell, and Hibbard, entitled "A New Era in Telephony."

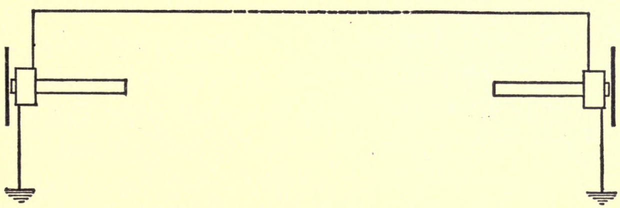


Part of the Operating Room, Main Exchange, Brooklyn.

CHAPTER VII.

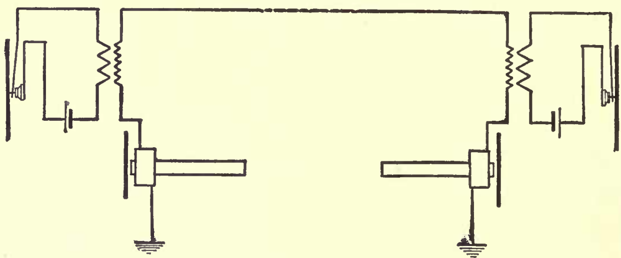
SWITCHBOARDS.

It seems a long stride from the simple circuit connecting one telephone with another to the complicated arrangement of circuits in the modern switchboard. In fact, this long gap is filled with a great number of short steps and the development from the simple circuit has been continuous—so continuous and so rapid that it has hardly been possible at any time



Circuit for Magneto-Telephones, Grounded.

to regard the existing practice as in any degree established or permanent. The details of one scheme of connections have scarcely been worked out before some other scheme was devised which was preferred and adopted. In consequence of this, it has happened more than once that a switchboard which, when contracted for, represented the latest and best practice, has been superseded and become obsolete before it was finished. It is obviously not practicable to keep abreast of the latest developments in a branch of an art which is subject to such continual changes. Switchboards, both in the general scheme of circuits and in the design of details, continue still



Complete Circuit, grounded, using Microphone Transmitters.

one of the most fruitful fields for inventors, and each week sees a very considerable list of patents granted. There will be treated here, therefore, only the few most important types.

THE WILLIAMS BOARD.

The Williams board, one of the best of the old, simple boards, was a direct development from the simple telegraph switchboard, with strips crossing each other, each connected to a subscriber's line. These strips, separated by an air gap, could be connected together at will; and with the addition of annunciator drops and a row of exposed spring jacks, the arrangement made a very convenient and useful board for a few subscribers.

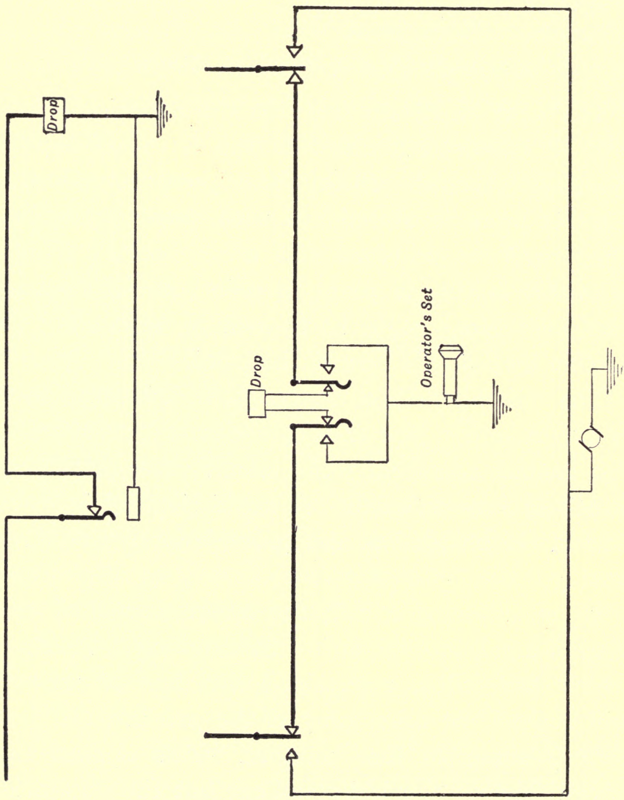
"STANDARD SINGLE-WIRE" SWITCHBOARD.

The next important step was the adoption of the type of board exemplified in the Standard Single Wire Switchboard. In this board, the design of the parts is more in accordance with present practice. The board was provided with a number of cord circuits terminating in plugs, in pairs; and the operator's instrument could be thrown in or out of connection by a simple turn of the hand.

The subscriber's line, always grounded, terminated in a light spring jack resting against a contact point, this contact completing the circuit through the annunciator drop to earth. A metal ring, let into the face of the board, was also grounded and served for testing.

Upon receiving a call, the operator pushed one plug of a pair into the jack corresponding to the drop which had fallen, ascertained the number wanted and pushed the other plug of the pair into the jack corresponding to that number. This opened the circuit beyond the jacks and cut out the annunciators. It was necessary, therefore, to provide a signal —the "clearing-out drop"—by which the subscribers could give notice when they had finished talking.

The motion of a cam cut the operator's instru-



Standard Single Wire Switchboard.

ments in or out, and on each side of this cam, or "listening in" key, was a calling key. Inspection of the diagram will show that it was possible to call either subscriber without disturbing the other.

In this system the subscribers were divided into groups of a convenient number, each group being given into the charge of one operator. In the exchange, each section of switchboard, providing for one group of subscribers and under the control of one operator, was connected, by a comparatively few trunk lines, with every other section of board in the operating room. When any subscriber wished to talk with a subscriber in another group than his own, the operator having his section in charge had to communicate in some way with the operator having the second section, and the connection was made over one of the trunk wires connecting the two sections. This communication between operators was done sometimes by talking across the room, sometimes by sending slips of paper across by messenger, and sometimes by means of annunciator drops on the trunk wires. The inconveniences of any of these methods are obvious, and the time consumed in making the connection was generally much greater by this system than by the multiple system. Consequently the "grouping" system is now retained only in a greatly modified form and for special service, as in the "express" board.

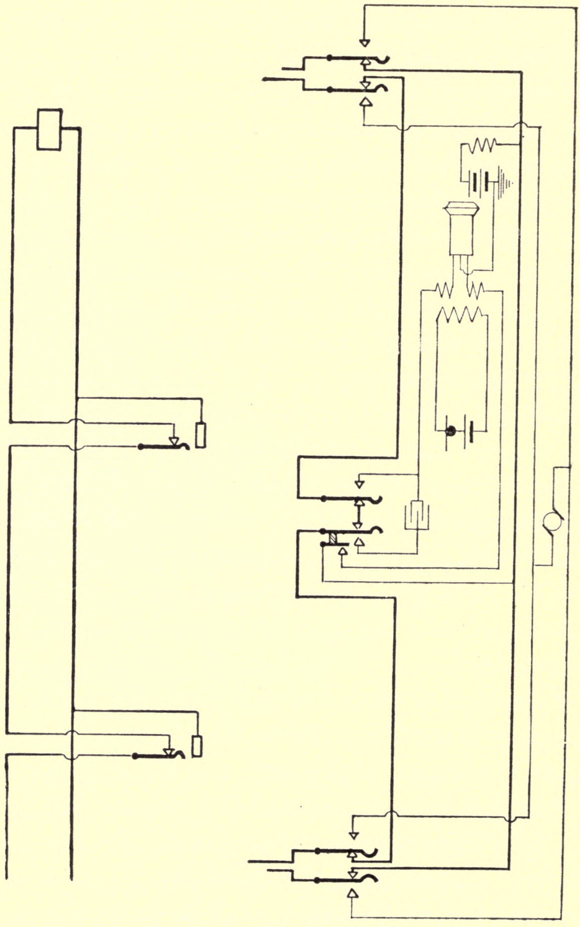
THE "MULTIPLE" SWITCHBOARD.

The multiple board is a development from the earlier boards and aimed to facilitate the operations of connecting, thus saving time and lightening the labors of the operator, while doing away with the noise and confusion necessarily attendant upon the older methods. In an operating room of the present day, where the multiple system is used, and the discipline is good, there is almost absolute silence, even although as many as five thousand subscribers may be served.

The fundamental idea in the multiple system is that every line connected with the exchange is within reach of every operator, so that a subscriber calling may be connected with any other subscriber without the necessity of using trunk wires in the office. The whole operation takes place in front of the operator receiving the call, and is all performed by her. Beyond this, the old arrangement of assigning to each operator a number of subscribers, whose calls she alone receives, is necessarily adhered to. The grouping of subscribers is planned on the basis of the number of calls of each per day, so that the work may be fairly averaged up among the operators, and no one shall have more calls than can be properly answered.

In the modern boards the connecting jacks are placed in groups of one hundred each, numbered, and conveniently divided so as to assist the eye in finding the required number easily. The board is divided into sections, and a jack for every line in the exchange is placed in each section. Each operator thus has before her all the lines in the exchange. The subscriber's lines enter from the distributing board in the terminal room, and each line loops into the proper jack in each section, passing through all the sections in series. From the last section the line should be carried to a second distributing board back of the switchboard, and from this point led to the proper annunciator drop. The use of this second distributing board makes it possible to properly assign the subscribers among the operators, and to change the make up of the group if it is found desirable or necessary to do so. By the arrangement described it will be seen that the line connects with the annunciator last, and in the older form of multiple board the annunciator was cut out of circuit when a connection was made.

Examination of the diagram will show that when any plug is pushed home in a jack, the contact between the sleeve of the jack and the ring throws a battery into connection with the ring and the potential of all the rings on that line is raised in consequence. If, therefore, the tip of any plug is touched to a ring on that line, a click is produced in the operator's telephone, signifying that the line is in use at some other section. This is the "busy" test.



Series-multiple Switchboard.

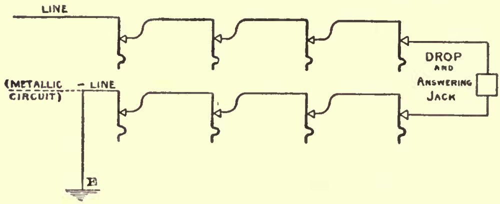
The operation of receiving calls and making the desired connections, can be traced out on the diagram.

The number of circuits terminating at each section of the board will largely depend upon the average daily use of the telephones in the exchange. Broadly, however, it may be stated that one operator will handle 100 lines, if not burdened with the making of tickets, or the handling of incoming local trunk wires. It is usual to provide three operator's outfits for each section of board, although it is only in the very largest exchanges that three operators to a section are necessary. In smaller boards the number of jacks is such that all are within easy reach of one operator.

METALLIC CIRCUIT BOARDS.

Several arrangements have been adopted for metallic circuit switchboards. In one of these arrangements the jacks come into one side of the line, in series, the drop is last and the rings come into the other side of the line. The drop is thus cut out whenever a connection is made, and for making connections a cord is provided, double, with a plug at each end. In this board, however, a leg was left open beyond the jack in use. The arrangement was accordingly modified by adopting double cords with twin plugs and causing each side of the line to pass through jacks, thus insuring good rubbing contact for each side of the line in addition to balancing the circuit.

In a metallic circuit multiple board the wires leading from the distributing board must be twisted in pairs, to avoid cross-talk; and indeed this should be done also in the case of the multiple board for

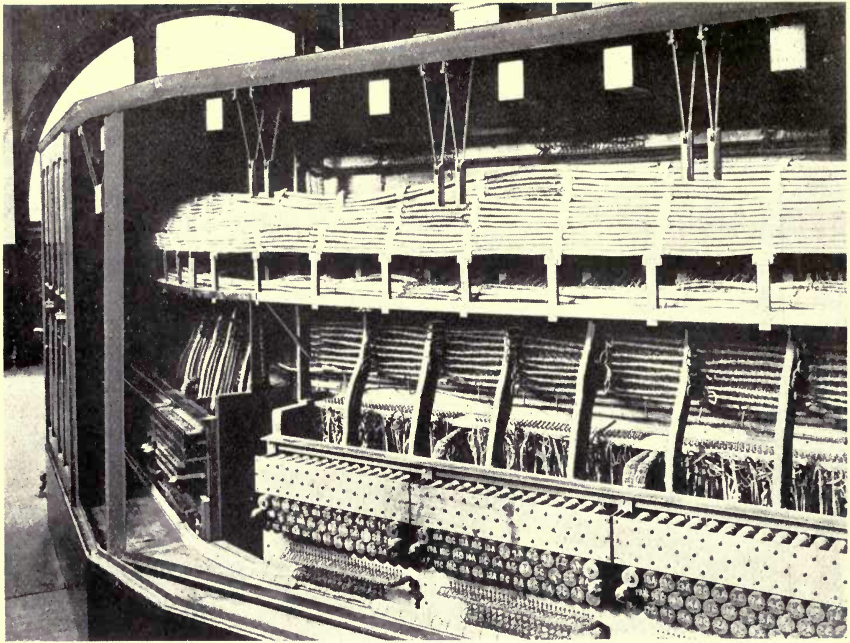


Multiple Board Adapted for Metallic Circuits. (Twin Plugs and Double Cords.)

grounded circuits. Both wires of the pair should be used, the second wire never being left open, but grounded at the farther end of the pair, even if this should be at the end of a long cable. In this way cross-talk and other disturbances, both in the board and outside of it, are completely avoided, or very much diminished.

The board should be placed far enough from the wall to leave room behind it for inspection, changes, and repairs; and it should be in a straight line if possible. When the board is too large to admit of this arrangement, the operators work on the inside of the curve, the outside being toward the wall.

In exchanges using grounded circuits and where



BACK OF SWITCHBOARD, BEDFORD EXCHANGE, BROOKLYN.

the long-distance lines enter, it is necessary to provide some means of connecting the metallic circuits with the grounded circuits without losing any of the advantages of the metallic circuits, as would be the case were the connections made direct. The metallic circuit must be complete, and the balance between its sides preserved, to get the full benefit of it. This connection is made, therefore, by means of repeating coils, which are a special form of induction coil. The metallic circuit is completed through one circuit of the repeating coil, the other circuit of the coil being connected to the grounded circuit. There is no direct connection, and the talking is done by induction in the coil. These repeating coils are in daily use in almost every exchange connecting with the long-distance service.

BRANCH TERMINAL MULTIPLE OR "BRIDGING" BOARD.

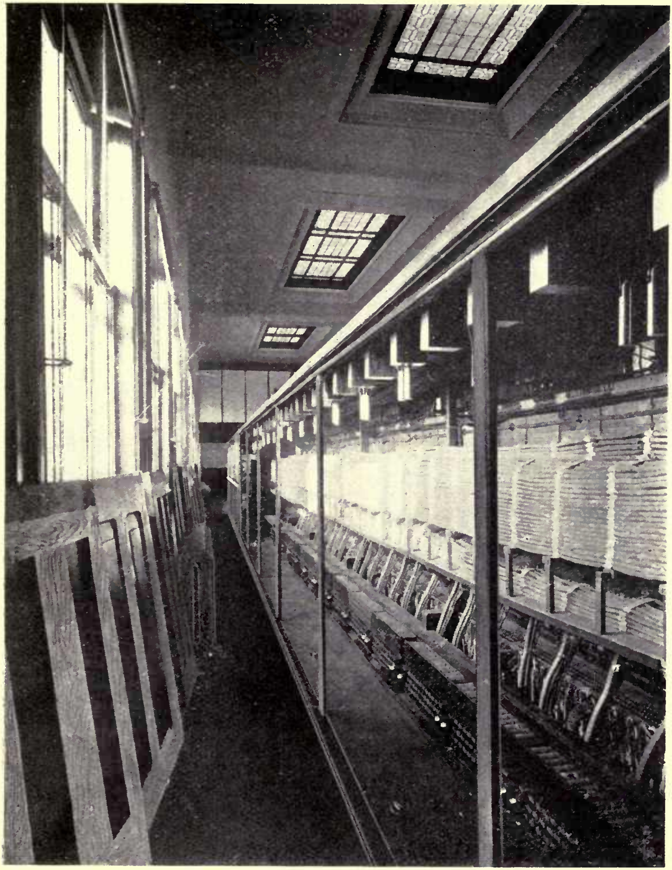
In the next important step in advance the series arrangement of jacks was discarded entirely and they were bridged across the circuit. This remedied many troubles at once. There was, at the same time, improvement in many details. The drops are all self-restoring, the line drop being automatically reset by the insertion of the plug and the clearing-out drop by the movement of the listening key. This is accomplished by winding the coils in two parts, one of which acts to release the drop, the other to set it again. The arrangement of circuits is shown in the diagram.

Each subscriber's circuit consists, in the board, of three wires in addition to the common ground; and each jack contains three springs and two rings. Two of the springs, however, are solely for the purpose of resetting the drop, a ring on the plug connecting them together and completing a battery circuit through the resetting coil.

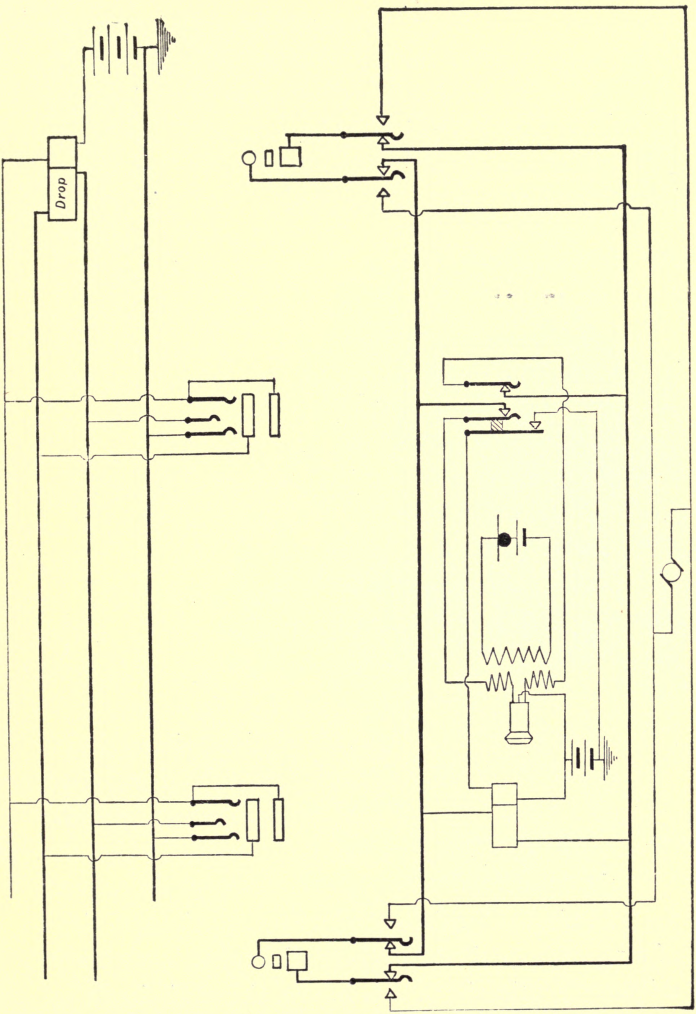
In the cord circuit, the clearing-out drop is permanently bridged across. The circuit of its resetting coil is normally open; but when the operator's telephone is connected across the line, to listen in, a short battery circuit is closed through the resetting coil and the drop is reset. The coil of the operator's receiver is divided and permanently grounded at the middle point. This ground, therefore, does not destroy the balance of the line. The procedure in receiving calls and making connections will be clear from the diagram.

THE COMMON BATTERY OR "RELAY" SWITCHBOARD.

The final step in the evolution of the modern switchboard has involved a somewhat radical change in method. At present, however [1901], there appears to be no probability that this method will, in turn, be superseded in the near future. On the contrary, the system is gaining in favor, and relay switch-



Back of Relay Switchboard, Main Exchange, Brooklyn.



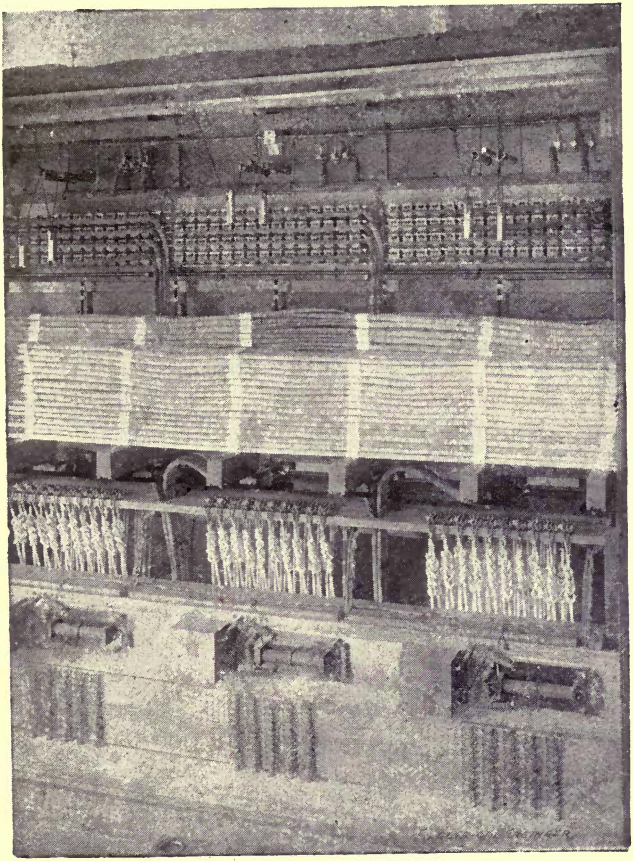
Branch-terminal Multiple Switchboard. ("Bridging" Board.)

boards are being installed as rapidly as exchanges can make provision for them.

Several common battery systems have been devised, in all of which the main feature is the concentration of the battery at the exchange. The system in most general use is that due primarily to Mr. H. V. Hayes of the American Bell Telephone Company. The signals, which, in present practice, are luminous —small glow lamps—are all automatic in their operation. The scheme of the connections is shown in the diagram, with alternative positions of the subscriber's receiver.

When the subscriber removes his receiver from the hook, a battery at the exchange actuates a relay which closes the circuit of his signal lamp and another relay, and lights the large supervisory lamp. One supervisory lamp serves for a considerable number of line signal lamps and is a check upon the operation of the board, remaining lighted so long as any calls in its dependent circuits remain unanswered, and aiding in the detection of burned-out signal lamps. Upon the insertion of the plug, the double relay operates, opening the circuits beyond, releases the armatures of the first two and extinguishes the lamps.

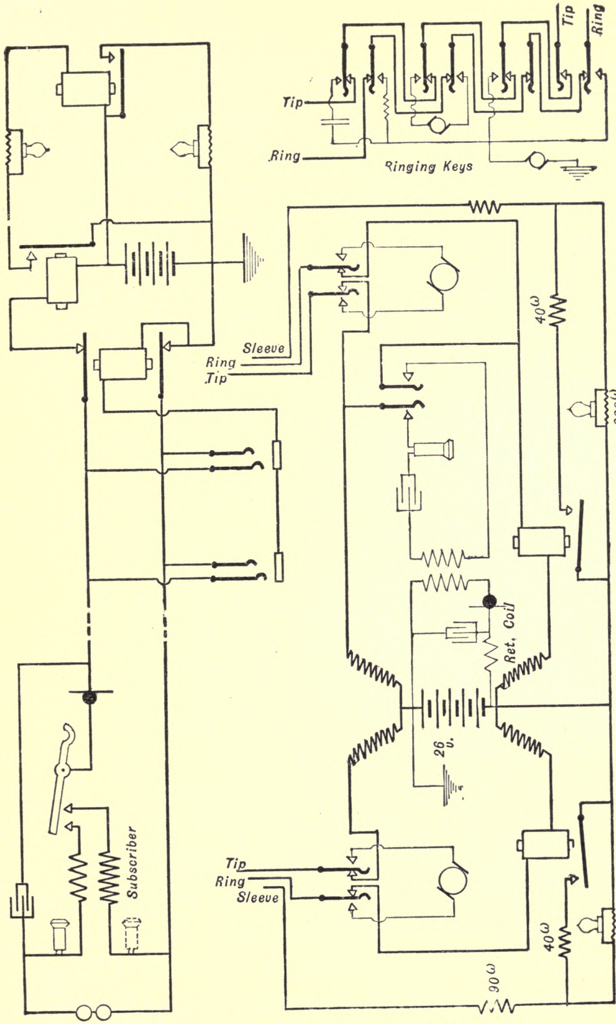
In the cord circuit, the common battery—in present practice about 26 volts—works through the two sides of a repeating coil and operates the subscriber's transmitter. While the line is in use, the cord circuit relays are closed; but when the subscriber hangs up



SWITCHBOARD AT BROAD STREET EXCHANGE, NEW YORK.

Rear View, showing connections to Drops, Line Cables, Cords and Induction Coils.

This is a bridging board, in which the jacks and annunciators are all connected in multiple or "bridged" across the circuit.



Common Battery or " Relay " Switchboard.

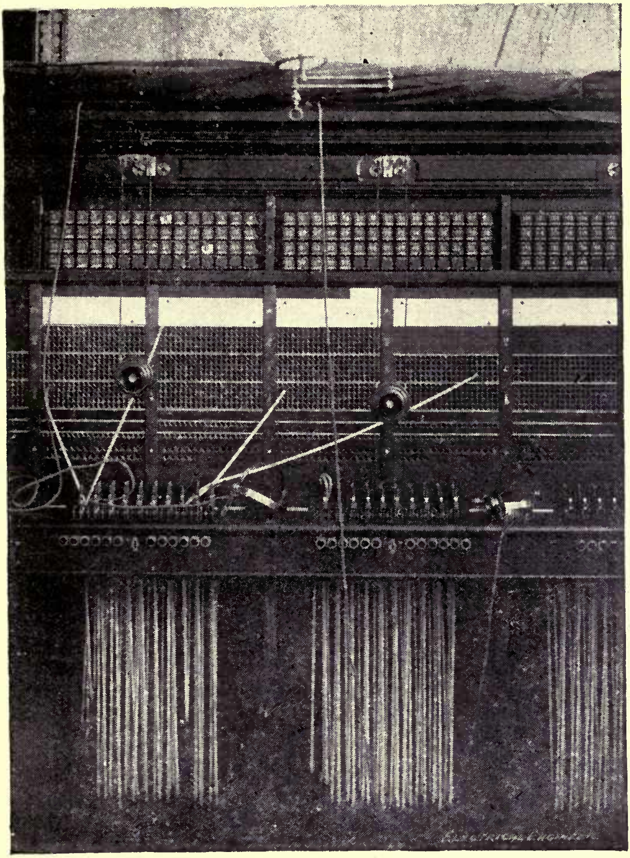
his telephone, the armature is released and the clearing out signal is lighted.

In all the most modern work there is evident a strong tendency toward making all the operations automatic. This tendency is especially marked in the devices provided for the purpose of lightening the new duties which have devolved upon switchboard operators since the extensive introduction of toll lines and the measured rate. It is conceivable that the principle of automatic operation may be extended until a much greater portion of the operator's work takes care of itself than is the case at present; but it does not seem at all probable that large exchanges can ever be operated automatically, in the strict sense of the term, with commercial success.

PARTY LINES.

Party lines are now freely used in every exchange of any size, and a great deal of attention has been given, during the past few years, to the development of this branch of the service. Several selective signal systems have been devised, in which any desired one of the subscribers on a line may be called without signalling the others, all the instruments except those in use being automatically locked.

One of the latest of these is due to J. A. Barrett. The selective signalling is accomplished by the use of suitably wound polarized bells and various combi-



Switchboard at Broad Street Exchange, New York

Front View, showing Drops, Line Jacks, Answering Jacks, Plugs, Cords, and Operator's instruments.

The indicator drops are all self-restoring. The line drop is restored by an electro-magnet energized by the insertion of the operator's plug into the answering jack. The clearing-out drop is restored similarly by the depression of the listening key.

nations of the two wires of a metallic circuit, with an auxiliary earth circuit.

THE LAW SYSTEM.

The Law system may now be considered nearly if not quite obsolete. It differs from the earlier systems described chiefly in its arrangements for calling. Formerly no generators were used; but in the central office was provided a large battery of perhaps from thirty to fifty "Law" Leclanché cells. This battery, used in connection with a circuit-breaker and induction coil, furnished the power for calling up subscribers from the central office. The subscriber has no such means of calling the exchange, but there is a second wire in connection with his apparatus, always connected to the receiver of the operator at the exchange. Over this calling wire the subscriber communicates with the operator, receiving his answer by a system of bell signals; and when the desired connection is made, he switches back upon his talking wire and converses as in any other system. The calling wires are common to many subscribers, fifty to one hundred being connected to each call wire. The subscribers' lines, or talking wires, are normally open at the switchboard, and the operator cannot talk to the subscribers. Otherwise, this system, in its connections, resembles the better-known systems.

CHAPTER VIII.

THE PROPAGATION OF ENERGY.

MANY theories have been advanced as to the structure of matter, but the one which most satisfactorily fulfils all conditions, and the one now generally accepted, is that known as the "atomic theory."

According to this theory, the smallest possible particle into which any substance, however complex, can be divided by the most perfect mechanical means is the molecule. The molecule of any substance can in turn be divided, by means other than mechanical, into its constituent elemental parts; and each of these infinitesimal parts is called an atom. The molecule of wood, for instance, is the smallest particle which can exist and still retain the properties of wood; but it can be divided into several constituent elemental atoms, chiefly carbon, hydrogen, and oxygen, which had combined in certain definite proportions to form the molecule of wood.

The molecules of a substance are separated from each other by spaces which are considerable in comparison with the size of the molecules; and the molecules are at all times moving about through these spaces. It is this motion of the molecules which constitutes heat, and which gives rise to the sensation of heat when a body is touched. The degree of heat, or the temperature, depends on the violence of movement of the molecules, and the quantity of heat in any body is the total amount of the motions of its constituent molecules.*

By the hypothesis just developed most of the phenomena taking place within bodies can be satisfactorily explained—such as heat (in part), sound, chemical combination. There still remain, however, other phenomena involving action at a distance, such as light, gravitation, electro-static and electro-magnetic induction, and to explain these it is necessary to make another assumption. This other assumption was first made to account for the phenomenon of light, and was found to account very satisfactorily for all the observed phenomena. It is not necessary, however, to make any third assumption to account for the phenomena of electric induction, for the hypothesis we are about to develop will serve to explain the induction phenomena as well as those of light, as we shall see. Our second assumption is this: That throughout all space—the space between the molecules of all bodies as well as the space between the stars and planets—there exists a fluid which we

* "Motion," must, of course, in this connection, be understood to include the movements of the constituent parts of the molecule among themselves as well as the movements of the molecule as a whole, both of translation and of rotation.

call the "luminiferous ether." The ether is a fluid of almost perfect elasticity and of very small mass—that is, it has very slight inertia, although it must possess inertia to some extent, otherwise the phenomena referred to could not be satisfactorily explained. By "perfect elasticity" we mean that when a certain bulk of it is deformed—that is, compressed—into a smaller space by the application of some stress, if the stress is removed it will return exactly to its original volume.

WAVES.

It is thoroughly established by experiment that all action between two points not adjacent takes place by means of vibrations propagated in the medium existing between the point of origin of the disturbance and the second point. That is, the disturbance at the first point does not cause an action at the distant point without intervening mechanism, but it is propagated from one point to another in the medium as a vibration which travels in the form of waves, outward in all directions from the starting-point. Thus, if an explosion takes place at some point in the open air, the sound is not immediately heard by a person standing at some distant point, but it is propagated outward in all directions from the point of disturbance by means of vibrations in the air, until some portion of the outermost wave reaches the observer, and he hears the sound, much weakened by distance. Let us consider this phenomenon more in detail. The explosion itself does not produce sound. It causes the particles of air immediately adjacent to be suddenly pushed outward in all directions. These particles hit against the particles next adjacent and cause them to move suddenly outward, the first particles returning along the path on which they came, and so on; each particle of air moving backward and forward over a certain distance, greater or less according to the violence of the original disturbance, and communicating a similar, but lessened, motion to each particle in the next outer layer. The outer edge of the disturbance thus moves regularly along until it reaches the observer. Then the striking of the particles of air against the mechanism of the ear excites the sensation of sound.

In the case of the vibrations producing sound, each particle moves backward and forward in a line with the propagation of the disturbance. There will thus be produced conditions such that at some points the particles are crowded more closely together than usual and at some other points they are more widely separated than usual. The distance between the condensations is called a wave-length; and upon the wave-length depends the pitch of the sound heard. The distance over which each particle moves back and forth is called the amplitude of the vibration, and upon the amplitude depends the loudness of the resulting sound. The waves produced by the crowding together and drawing apart of the particles,—the condensations and rarefactions of the medium—travel along with a velocity which is always the same for the same medium under the same or like conditions.

We have so far considered only those vibrations producing sound, in which the motion of the particle is in a line with the propagation of the disturbance. But we may have vibrations in paths which cross the line of propagation of the disturbance. Let us consider the familiar phenomenon of dropping a stone into still water. Everyone knows that in such a case the ripples will travel out in circles from the centre of disturbance, diminishing in height as they recede. The height at the starting-point depends on the violence of the disturbance. In this case the particle of water vibrates up and down, *across* the line of propagation of the wave. The length of the path of each particle, or the height of the wave, is the amplitude of vibration, and the distance between succeeding crests or succeeding troughs is a wave-length.

It is entirely conceivable that there might be vibrations in which the particle moved in a circular or oval path about the line of propagation of the wave. The characteristics of the wave would remain the same so far as velocity is concerned, although its form would be different from those that we have considered.

Let us now take up again the case of the explosion cited above, and trace the energy through its several transformations. The energy first exists in the explosive, as the potential energy of chemical combination. How it got into the explosive, and what transformations it went through before that need not concern us. When the chemical combination takes place, by the firing of the detonator, or by other means, the atoms in the materials of the explosive, which is a *mixture*, form new combinations with each other, and the resulting substances—compounds—are different from the substances which existed in the mixture. One of the products is a gas. Now the molecules of a substance in the state of gas are much more widely separated and more free to move among themselves than in the solid state. The molecular motions are, in fact, much more extended. The molecules of the gas, then, strike violently against the surrounding molecules of air, and the vibration thus produced travels outward in all directions from the origin, in the form of waves, in ever-widening spheres. Some of these vibrations are of such wave-length that the sensation of sound is produced. The vibrations communicated by the explosion to the surrounding ether give rise to the sensations of light and heat. The potential energy of the explosive has now been transformed into kinetic energy in the surrounding medium. If there were no other condition but distance to be considered, the total energy passing through any one of these spherical surfaces per second would be equal to that passing through any other such surface; and the intensity of the disturbance at any point would be exactly inversely proportional to the square of its distance from the centre. To make this point clearer, let us take a soap-bubble, for example. When the bubble is of a small size, the film is of considerable thickness. As we blow the bubble larger, the same amount of matter must be distributed over a larger surface. If we consider, then, a small area on the small bubble, say one square millimetre, the thickness of the film on that square millimetre, as the bubble increases in size, will decrease and will be inversely proportional to the total surface of the bubble, which is the same as saying that the thickness of the film at any point is inversely proportional to the square of the radius of the bubble. It is not to be understood that this is an exact analogy, by any means, to the case of the propagation of vibrations, but it may help to a clear conception of the particular point we are considering. Let us now return to tracing the transformations of energy in the case of the explosion. The portion of energy transformed into heat-waves heats the air and is eventually returned to the earth as heat. The light-waves do the same, being finally transformed into waves of dark heat in some body against which they strike, and eventually return to the earth; and the same thing happens, in a different way, to the sound-waves. For the particles of air, in vibrating by one another, and hitting each other, generate heat-waves by friction, and this energy also eventually returns to the earth. In the earth this energy of heat is finally transformed, by chemical action, into some form of potential energy, as in a vegetable growth, or it is radiated out into space to some other body, there to undergo other transformations.

We have seen, in tracing the energy of our explosion through its various transformations, that there appears to be more than one kind of vibration. The vibration producing sound is the vibration of particles in the line of propagation of the disturbance, while the vibrations producing light and heat are *across* the line of propagation—a transverse vibration —and exist in the ether. The difference between light-waves and heat-waves in the ether is, in fact, simply a difference of wave-length; and our not seeing the heat-waves as light is due solely to the imperfection of our organs of sensation. These facts have been amply proved by experiment, but we shall have to accept them here as facts, without proof.

Up to this point we have not considered the propagation of electric disturbances at all. We have seen that the vibrations in the ether, so far as we have investigated them, are really of but one kind, giving rise to the sensations of light or heat according as the waves are short or long. What is the nature of the vibration by which electrical disturbances are transmitted through the ether? Theory, confirmed by recent experiment, shows us that electro-magnetic disturbances are transmitted through the ether by the same kind of vibrations that give rise to light and heat; and that the velocity of propagation of electro-magnetic disturbances is sensibly the same as that of light. This is not yet conclusively proved by experiment, but its truth seems very probable, and it is what we would logically expect to be the case.

When a particle in an elastic substance is displaced from its point of rest, the force urging it back to that point is proportional to its displacement. When the acceleration is proportional to the displacement the particle vibrates harmonically, and the velocity of propagation of the wave is constant for a given substance and given conditions. If the wave of electro-magnetic disturbance is a vibration of the same kind as the light-producing vibrations, and in the same medium, we should expect the velocity of propagation to be the same. If this is found to be the case, we shall then have vibrations of a definite kind in the ether, running through the whole range of wave-lengths, but all propagated with the same velocity. The excessively short waves will be the ultra-violet, which are too short to be distinguished by the eye as light, but which can be detected by the sensitive photographic film; the longer waves give rise to the sensations of light of the different colors known to us, running through the spectrum until the infra-red rays are reached to which the eye does not respond. These waves make themselves most manifest as radiant heat, although all the light rays have the same heating properties, less marked as the wave is shorter. The length of the waves of electro-magnetic disturbance depends on the size of the body whose "electro-static charge" is disturbed; and theory shows us that the oscillations of an electric charge on a body of atomic dimensions would give rise to waves of the length of light-waves. We have not space to follow out this theory in detail, but it seems probable that light-waves are, in fact, electro-magnetic disturbances propagated through the ether and due to the electric oscillations set up in the atomic charge. *

The length of the wave of electro-magnetic disturbance may be anywhere in the whole range of ether wave-lengths, from the ultra-violet to waves many hundred miles in length.

According to the best established theory of electric action the charge on a body is the displacement of electricity outward from that body into the dielectric. This displacement, *while it is taking place*, is an electric current. As the dielectric must, how-

* For accounts of experiments in this direction and detailed demonstration of this and similar matters the reader is referred to Dr. Fleming's Alternate Current Transformers, Maxwell's Electricity and Magnetism, Life of James Clerk Maxwell, by Campbell and Garnett, and the account of Dr. Hertz's experiments.

ever, be considered as a body which permits such action to but a limited extent, its elastic limit is soon reached and a state of strain is established. When the impressed force is removed, or its sign reversed, the strain is relieved. No satisfactory hypothesis has ever yet been advanced as to just what electricity is, or whether there is actually any such thing. We feel some repugnance to admitting that an electric current is the actual movement of material particles, although the known phenomena can be explained on such an hypothesis.* We must, therefore, be content to let that question remain in abeyance for the present, and deal merely with what we may fairly say has been found out as to the propagation of electro-magnetic disturbances, the origin and laws of electric currents and the propagation of energy.

From the extensive and complete experiments of Dr. Hertz, already referred to, he concluded that the velocity of propagation through the air of electro-magnetic disturbance is greater than the velocity of propagation through a wire. He found that the waves of electro-magnetic disturbance were reflected from conducting surfaces and refracted by prisms of dielectric substance.

We know now, from experiment, that the waves of light, dark heat, and electro-magnetic disturbance are all forms of radiant energy propagated through the

* See Maxwell's Theory of Molecular Vortices, in Life of J. Clerk Maxwell.

ether with a velocity which it is most probable is the same for all. All these waves can be reflected, refracted, and dispersed, and they are probably identical, the class of phenomena produced by them depending upon their length alone. It may not be anticipating very much to prophesy that means will be found to render these forms directly interconvertible.

In the light of our new knowledge we see that we must in great measure reconstruct our ideas as to the origin and method of propagation of electric currents. We must, in considering such phenomena, direct our attention as much to what is taking place in the space *outside* a conductor as to what is taking place *in* it. We must not look upon an electric current as necessarily something in motion in the conductor, but we must rather consider that all space is filled with energy, which can be transferred from point to point. The conductor and other portions of the circuit merely seem to *direct* the energy to particular points, where it is transformed so as to produce desired effects and to furnish a place where energy can be dissipated. The energy does not reside in the wire, for we find the whole space about the conducting wires the seat of electro-magnetic energy. Let us consider the case of a battery with its poles connected by a wire. The potential energy of chemical combination causes energy to be radiated out along certain lines, whose position the presence of the wire helps to determine, the medium through which the energy is propagated being the ether. Energy is constantly flowing in upon the wire on all sides, and is there transformed into heat or light and again radiated out.

A consideration of the phenomena in connection with the transference of energy has led to the formulation, by Professor Poynting, of the law in regard to it, as follows: "At any point in the magnetic field of conductors conveying currents the energy moves perpendicularly to the plane containing the lines of electric force and the lines of magnetic force, and the amount crossing a unit of area of this plane per second is equal to the product of the intensities of the two forces multiplied by the sine of the angle between them and divided by 4π."

That is, if $E =$ electric force, or force on a very small body charged with a unit quantity of positive electricity, and $H =$ magnetic force, or force on a small unit north pole, and if $\theta =$ the angle between the directions of these forces, then the

$$\text{flow of energy per second} = \frac{E\,H \sin\theta}{4\pi}$$

and is perpendicular to the planes containing E and H.

Let us investigate the case of a telephone circuit and see if we can trace the energy. The potential energy of chemical combination in the battery is transformed into kinetic energy and radiated outward from the conducting circuit through the ether in the form of a strain of some sort until the surface of the enclosing conductor is reached. It enters this and immediately begins to be transformed, the amount crossing successive layers decreasing until, when the centre is reached, it has all been transformed. A part is transformed into dark heat radiations, and sent out again, and a part then exists as tubes of magnetic force surrounding the wire. The action of the transmitter consists in alternately inserting into the space enclosed by the circuit and withdrawing from it a number of lines of magnetic induction. The action of an induction coil is precisely similar to that of a dynamo, the variation in the number of lines of induction enclosed by the armature (the secondary) being effected by the variation of the existing current instead of by mechanical movement. The change in the number of lines of magnetic induction enclosed by the secondary causes an electro-magnetic disturbance to be propagated through the ether in the space enclosed by the secondary circuit. This radiant energy, when it reaches the bounding wire, enters it and is again transformed, as in the primary circuit, partly into radiant heat and partly into tubes of magnetic force surrounding the wire. By suitable arrangements of parts we are now able to transform the energy of the magnetic field into the kinetic energy of mechanical movement of the diaphragm of the receiver, thence into energy of sound-producing waves in air. Part of this is dissipated as dark heat in the air, and part continues as energy of mechanical vibration in our organs of hearing, finally to be dissipated as heat. The exact path followed by the energy throughout its transformations in the circuits could be found by plotting the directions of the lines of electric force and the lines of magnetic force at each point, and making the line of propagation of energy perpendicular to both; and the rate of flow of energy through any surface could be found if we knew the magnitudes of these forces, E and H.

When energy is transferred from a point of transformation to a second point, at which it is again transformed, *work* is done by the first point on the second. A systematic application of this principle to any difficult questions arising in practice, will generally serve to clear them up more quickly and easily than it can be done in any other way. For example, we may wish to know whether the phenomena taking place in one body will be affected by the presence of some other body. The point to be investigated, then, is whether the first body does *work* on the second body; that is, whether any of the energy radiated out from the first is transformed in the second. If that is found to be the case, then we know the phenomena in the first body are affected by the presence of the second body. It is important to grasp this idea thoroughly. It can generally be applied without the use of mathematics.

Sir William Thomson has originated a theory according to which all matter is made up of almost infinitely small vortices of perfect fluid, each rotating about a hollow central space. These vortices may be of the open filament form, having two ends, or of the ring form, in which the opposite ends of the same hollow vortex are joined together. The ring form is the most stable, and the straight form cannot exist with free ends. The ends must abut on something. The rotation is a necessary condition of their existence as matter. [Material vortices of the ring form and comparatively very great dimensions, are seen in the familiar "smoke rings."]

The mathematical laws of vortices have been investigated and it has been found that such phenomena as the attraction of gravitation, electrostatic charge, and other so-called "action at a distance," can be accounted for on this hypothesis. Chemical combination can also be explained. There is, however, no experimental proof of the truth of this theory, which we must take as pure theory, yet to be corroborated. The vortex theory does not clash at all with the atomic theory, but goes considerably farther, in that it explains the structure of the atoms of ordinary matter and of the ether.

The atom is indivisible, not because of its absolute hardness, but because it slips away from the knife.

The vortex theory is complete in itself, and the proof of the untruth of any portion of it would be the overthrow of the whole.

Assuming the truth of such a theory, according to which all matter is made up of the same elemental substance, new and simple conceptions could be formed of electrical resistance, potential, and such phenomena.

CHAPTER IX.

THE TELEPHONE CURRENT.

In the transmission of speech by undulatory currents of electricity there are three fundamental and distinct operations.

The waves of sound produce waves of electric current; the current waves are transmitted over the line; and at the receiving ends the undulations of current are made to produce sound-waves. In perfect telephone transmission, were such a thing possible, the sound-waves at the receiving end would be exact reproductions of the sound-waves at the transmitting end. This it is obviously impossible to accomplish. The amplitude of the waves, or the loudness of sound, will be diminished by an amount due to losses on the line and in transformation, and by work done on the conductors themselves. The work done on the line is wasted in producing heat. But the amount of heat is so slight as not to be measureable, although the effect of this work in changing the shape and amplitude of the current waves may be very considerable.

As it is our aim to make the sound at the receiving end as nearly as possible an exact reproduction of the sound at the transmitting end, it is necessary that the apparatus for transforming sound-waves into electric waves, and *vice versa*, should be such as to cause the least possible change in form and amplitude; and in addition to this, it is necessary that the line should be so constructed that the current waves may be propagated with the minimum alteration. That is, the work done by the current in the line itself must be made as small as possible. We must therefore consider what are the characteristics of the telephone current; which of these characteristics are affected by the several properties of the line; what particular characteristics it is most essential to preserve, and what we can best afford to lose. For it is impossible to avoid losses of all kinds, and some of these losses must necessarily be considerable.

The sound of the human voice is produced by the vibration of a thin elastic membrane at the top of the windpipe. The air from the lungs, passing through a slit in this membrane, sets it into vibration, and as the tension on the membrane is varied, its rate of vibration changes accordingly, thus varying the pitch of the fundamental, and its many accompanying overtones. With the aid of the mouth the fundamental tone and the overtones are mixed together in different proportions, and in this way the different vowel sounds are produced. It is especially in the way of the reproduction of the overtones that our difficulties lie.

PITCH, CHARACTER, AND CLEARNESS.

The pitch of the sound depends upon the period or frequency of vibrations of the fundamental note, and would be the same were all the overtones destroyed. Nor is the pitch at all dependent on the form of the wave. The form of the wave determines the quality or character; and the resultant wave produced by the voice, including all the overtones, is generally of a very complex form. It is by the quality or character that we are able to recognize individual sounds. Clearness depends upon the preservation of the form of the wave, and loudness upon the amplitude of the vibrations. To recognize and understand spoken sounds it is not necessary that they should be loud. The faintest speech is readily understood if only it is clear; and clearness, or the preservation of character—that is, the preservation of all the overtones in their original relations to the fundamental—is therefore the main point to be kept in view. In the transmission of sound-waves through air there is no confusion of waves due simply to distance. There is, therefore, no loss of clearness, and in that respect the problem solves itself. In the transmission of speech by electricity there are, as we shall see, many other conditions to be considered, and the problem of preserving all the vibrations in their original inter-relations becomes very difficult.

PROPERTIES OF ALL LINES.

In transmitting sound by electricity, the transmitted current is necessarily alternating in character. Even in those cases in which the vibrations are impressed upon a steady current, the operative or sound-producing portion of the resultant current is alternating, and obeys the same laws as the simple alternating current; and we shall therefore consider, in this connection, the alternating current alone.

According to the older views in regard to electric currents, the changes in electric force which determine these currents are propagated through conductors only. We have seen in the last chapter, however, that changes in electric force are propagated through the ether. These changes are impressed upon conductors from the outside, and determine the so-called flow of current within the conductors. When the flow of current is continuous and steady, of course no changes of electric force are taking place; and the views which have been held in regard to steady currents lead to practically accurate results, although starting, perhaps, from erroneous premises.

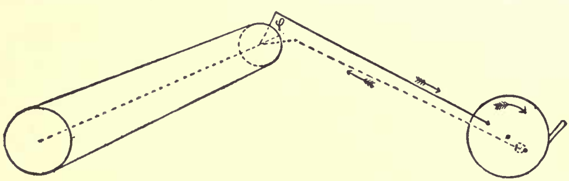
In dealing with variable or alternating currents, if we start with the correct premises as to the impress of electro-motive forces, the changes in currents and resistance no longer seem to take place according to arbitrary and empirical laws. As an electro-motive force is impressed upon a conductor from the outside, the distance to which it will penetrate the conductor depends upon its duration and upon the nature of the conductor. Therefore, with a given impressed electro-motive force, the amount of current flowing in any infinitesimal shell of a conductor will depend upon the nature of the conductor and the distance of the shell from its circumference. If the impressed electro-motive force is of sufficiently short duration, the current flowing in any such shell will differ in quantity from that flowing in any other such shell ; for the electro-motive force at any distance from the circumference is, in that case, less than the total impressed electro-motive force at the circumference, and different from that at any other point. If we calculate, from a knowledge of the rate of change of the impressed electro-motive force and the properties of the conductor, the electro-motive force at points within the conductor, the alternating current will be found to follow Ohm's law as accurately as that law is followed in the case of steady currents. In fact, the steady current is only an extreme case of the alternating current. The intensity, within a conductor, of an externally impressed electro-motive force is found to vary according to the same laws as the changes of temperature in a conductor of heat.*

* A very clear idea of the action of variable or periodic changes of impressed electro-motive force may be obtained in the following way : Take a glass tube of large diameter, fill it with a liquid having in suspension some particles or powder, and close the ends with glass.

INCREASED RESISTANCE FOR HIGH PERIODS, AND EFFECT UPON TELEPHONE CURRENT.

From the laws of distribution of alternating currents in conductors, as we have followed it above, we see that the vibrations of low frequency will penetrate a conductor more deeply than those of higher frequency. Hence the vibrations of low frequency, being distributed more widely, will meet with less effective resistance to their passage than those of a high frequency. Therefore, in a wave made up of vibrations of several periods, the vibrations corre-

If, then, the tube be turned through a given angle, back and forth about its axis, the amount of disturbance of the liquid will be seen to diminish from the circumference to the centre. The frequency of vibration of the tube and the nature of the liquid used, determine the distance of penetration of the disturbance, and the angle through which the tube is turned corresponds to the intensity of the impressed electro-motive force.



SIR WILLIAM THOMSON'S FORMULA.

σ = specific resistance in square centimetres per second.
[For copper, $\sigma = 1610$.]

a = radius of the wire.

$R(S)$ = value of $\frac{\sigma l}{\pi a^2}$ (resistance, in C. G. S. units, of length l, for steady currents.)

sponding to the sounds of higher pitch will be reduced in amplitude to a greater extent than the sounds of lower pitch; and the tendency, in transmitting speech by electricity through conductors, will be to obliterate, to some slight extent, the overtones. This is the effect of resistance alone; and here we see the first difficulty in the way of preserving the original inter-relations of the vibrations of different periods. This effect of resistance undoubtedly exists; but there is no reason to suppose that simple resistance changes the relative positions of the fundamental and superposed waves, and the detrimental effects, due to causes which we shall presently consider, are relatively so great, that the effect of resistance, except as causing a general reduction of loudness, is not noticeable.

$R(N)$ = effective resistance (impedance) of length l for alternating current of N periods per second.

$c(N)$ = current density at distance r from axis at time t.

$C(N)$ = current density in axis at time t.

$$c(N) = C(N) \cdot (ber\, q \cos \vartheta - bei\, q \sin \vartheta).$$

$$q = 2\pi r \sqrt{\frac{2N}{\sigma}}. \qquad \vartheta = 2\pi N t.$$

$$ber\, q = 1 - \frac{q^4}{2^2 \cdot 4^2} + \frac{q^8}{2^2 \cdot 4^2 \cdot 6^2 \cdot 8^2} - \dots$$

$$bei\, q = \frac{q^2}{2^2} - \frac{q^6}{2^2 \cdot 4^2 \cdot 6^2} + \dots$$

When $r = a$, $p = q$.

$$\frac{R(N)}{R(S)} = \frac{1}{2} p \cdot \frac{ber\, p \cdot bei'\, p - bei\, p \cdot ber'\, p}{(ber'\, p)^2 + (bei'\, p)^2}.$$

Accents denote differential co-efficients. In cable, where the distance between wires is not great in comparison with the diameter of wire, this formula does not hold strictly.

Some experiments in this direction were tried by the author, which go far to prove that the sharpness of the wave is not impaired by simple resistance, and that sound may be transmitted electrically through immensely high resistance, provided no other hurtful factors are introduced.

In these experiments sound was transmitted, perfectly sharp and clear, through a resistance measuring three megohms. This resistance consisted of a pencil mark upon paper, and possessed therefore, practically, no self-induction. As a source of sound, both a tuning-fork and the voice were used; and it was abundantly proved by further experiment that the observed effect was due to real transmission, and not to electrostatic action. Smaller resistances were also tried; and there is scarcely room for doubt that speech can be clearly transmitted and readily understood through several hundred thousand ohms of simple resistance * without self-induction.

* In order to avoid confusion of terms, the effective resistance, or apparent resistance, offered by a conductor to the passage of a current of a given period is called its *impedance* for that period. The term *conductance*, meaning the reciprocal of the resistance $\left(\frac{1}{R}\right)$, will also be used. *Conductivity* has heretofore had two meanings: first, the same as *conductance;* second, the ability of any given conductor to conduct electric currents, as compared with some standard material, such as pure copper.

Resistance, as used hereafter, will mean only what it has usually meant—the obstruction offered by a conductor to the passage of a steady current; *conductance* is the reciprocal of the resistance; *impedance* is the obstruction offered to the passage of the current under

SELF-INDUCTION.

In order to consider understandingly the effects of self-induction we must investigate the actions which take place when a current flows in a wire. When a current is flowing in a wire, there exist always, in the space about the wire, rings or loops of magnetic induction. When the current increases, these rings or loops of induction are expanded, fresh loops being "shed off," so to speak, from the wire; and when the current decreases, the loops of induction are contracted in upon the wire, and vanish at the centre. If, therefore, an alternating current is flowing in the wire, the rings contract to the centre, one after another, then expand from the centre with the direction reversed. We may consider, in a sense, that at the centre they are turned inside out, and expanded again.

As stated by Faraday, "If the magnetic induction through any circuit be varied by any means, an electro-motive force is set up in that circuit proportional at any instant to the rate of change of the magnetic induction at that instant." *

consideration; and *conductivity* is the ability, as compared with that of a standard material, to conduct steady currents.

* If N is the number of lines of induction passing through a circuit, any small movement for time dt, which changes N by dN, will start in motion a quantity dq. If R is the resistance of the circuit, $\frac{dN}{R} = dq$.

This electro-motive force of induction is opposed in direction to the electro-motive force impressed on the circuit. The current, in increasing, causes more lines of magnetic induction to be inserted in its circuit, and thus creates, *during the period of increase*, an electro-motive force equal, at any instant, to its own rate of increase, and opposed in direction to the electro-motive force which is impelling the current.

Any circuit traversed by a current encloses within the space bounded by the conductor a certain number of lines of induction, the number depending upon the strength of the current; and if we assume the circuit to be wholly removed from all other currents and magnets, the total inductance (number of lines of induction) through the circuit, for a unit current flowing in it, is called the *co-efficient of self-induction.*

The lines of induction through any circuit in which current is flowing, are always closed upon themselves, and form rings or loops. The exact form of the loop depends upon what is going on in the space outside the circuit, and upon the magnetic

If E is the average electro-motive force during the movement, and C the average current during dt, $C\,dt = dq$.

Substituting, $$C\,dt = \frac{dN}{R}.$$

By Ohm's law, $$C R = E.$$

$$\therefore E\,dt = dN.$$

$$\frac{dN}{dt} = E.$$

properties of the medium through which it passes; but every loop of induction must surround the current which caused its existence. If, then, we imagine a second circuit placed near the first, some of these loops, in passing around through space, will be threaded through the area enclosed by the second circuit. Hence, if any change takes place in the current flowing in the first circuit, it will cause contraction or expansion of the loops of induction, and therefore a change in the number of lines of induction passing through the second circuit. This will give rise to an electro-motive force of induction in the second circuit, opposed in direction to the electro-motive force in the first circuit, and equal to the rate of change in the number of lines of induction passing through the second; and this will give rise to a current in the second circuit. This phenomenon is called mutual induction.

If, now, we go a step farther, and imagine that an electro-motive force is originally impressed on the first circuit, and another electro-motive force is impressed on the second circuit, this condition of affairs will exist: Let us call the first and second circuits A and B, respectively. The circuit A will have its system of loops of induction, some of which pass through the circuit B, and the circuit B will have its system of loops of induction, some of which pass through the circuit A. There will then be a bundle of loops of induction which are linked with both A and B; and the number of lines of induction so linked will depend on the current flowing in each circuit, and the position of one circuit with respect to the other. If we assume the two circuits to be wholly removed from all other currents and magnetic material, and unit current passing in each, the number of loops of induction linked with both circuits is the *co-efficient of mutual induction* for those circuits in their given relative positions.*

Evidently, the co-efficient of mutual induction will change with every change in the relative positions of the two circuits. If one circuit is in the plane containing a loop of induction due to the other circuit, then no lines belonging to the A system will pass through B, and no lines of the B system will pass through A. In this case the co-efficient of mutual induction is zero, and a change in the current in one circuit will have no effect upon the other.

We thus see how we can represent the effect of one current upon another, by constructing the system of lines of induction due to each, and seeing what lines pass through both circuits. If we add a third circuit, C, with its system of lines of induction, some

* We use the terms "lines of induction" and "loops of induction" merely as a help to the imagination in forming conceptions of the state of things we are considering. It must not be understood that they are actual lines; but, by speaking of the number of lines through a given surface, we are able to see a clear and actual image of the intensity of the inductance through that surface. In a similar sense we speak of lines of force of any other kind.

of the lines of the C system will pass through A and some through B; some of the lines of the B system will pass through A and some through C; and some of the lines of the A system will pass through B and some through C. We have therefore a new relation depending upon the positions of A, B, and C with respect to each other, and upon the current flowing in each circuit. In the same way, we could make up a resultant system of as many circuits as we chose. Let us assume that we have a large number of such circuits, all alike in form and dimensions, but a considerable distance apart. Then the number of lines of induction of one system, which is linked with each of the other circuits, will be very small. If we now move the circuits into new positions, nearer together, the number of lines linking the different circuits together will be increased. We may thus approach the circuits nearer and nearer, the strength of the links continually increasing, until the different circuits come together and form one circuit, the conductor having a cross-sectional area equal to the sum of the cross-sectional areas of the elemental circuits of which it is composed, and the current flowing in it being equal to the sum of the elemental currents. Evidently, in this case, all the lines of each elemental system will be linked with every other system, and we see, therefore, that the self-induction of a circuit may be regarded as the mutual induction of its elements upon each other. This condition is very nearly, if not quite, attained in practice in induction coils having the primary and secondary wound side by side throughout, as in some forms of repeating coils.

The subject of induction becomes much complicated when the medium through which the lines of magnetic induction pass is of magnetic material; but, as we shall consider the case of circuits of copper only, and shall not deal with apparatus in which magnetic material is used, that portion of the subject need be considered here but very briefly.

In circuits consisting entirely of non-magnetic material, and surrounded by material of constant magnetic permeability, the inductance (the number of lines of induction passing through the circuit) is a constant depending only on the form and the size of the circuit. If, however, the medium through which the lines of magnetic induction pass is wholly or in part of magnetic material, the inductance is no longer constant. The value of the inductance in this case depends largely on the magnetic history of the material, and will be different for different directions of the magnetizing force—that is, it will depend on whether the magnetization is increasing or diminishing. With a periodic electro-motive force, the coefficient of induction will not only be variable, but will have two values for a given value of current.

If we magnetize a piece of iron to what is called saturation, and then demagnetize it by a gradual withdrawal of the magnetizing force, the value of the magnetization for a given value of the magnetizing force is greater during the withdrawal of the force than during its increase; and if the piece of iron is carried through a complete cycle of magnetization, from any degree of magnetization to any other degree, and then back to the starting-point again, it is found that the curve representing the increase of magnetization encloses, with the curve representing its decrease, an area which represents work done upon the iron. The curve of decrease lags behind the curve of increase, and this lagging behind is called *magnetic hysteresis.* Energy is actually expended in performing the cycle of magnetization, and this energy is dissipated as heat in the iron. This is something quite apart from the production of heat by eddy currents, and would take place in iron so perfectly divided that eddy currents could not occur. It is due to a sort of magnetic friction—a resistance of the molecules to change of arrangement, and is diminished by mechanical vibration.

There is also a magnetic lag due to the fact that time is required for a given magnetizing force to produce its effect. This is most noticeable in the softest iron and under feeble magnetizing forces.

The electro-motive force impressed on any circuit, then, may be resolved into two portions, one of which serves to overcome the opposing electro-motive force of induction, and the remainder drives the current. That is,

Impressed electro-motive force = effective electro-motive force + counter electro-motive force of induction.

The effective electro-motive force and the counter electro-motive force differ by a quarter of a period, and the effective electro-motive force is in the same phase as the current. The mathematical investigation of the flow of simple periodic currents,* shows us that the phase of the current is retarded behind that of the impressed electro-motive force by an angle ϑ, such that

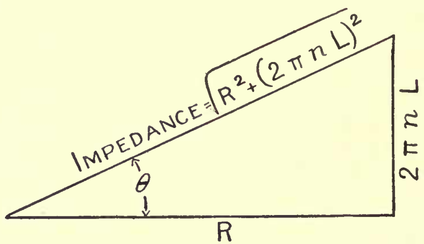
$$\tan \vartheta = 2\pi\, n \frac{L}{R},$$

where n is the number of vibrations per second, L is the co-efficient of self-induction, and R the resistance. We see also that the maximum value of the current would be obtained by dividing the maximum electro-motive force by $\sqrt{R^2 + (2\pi\, n\, L)^2}$; and that the form of the current curve has not been changed from the simple harmonic, or sine curve, by its retardation of phase.

The quantity $\sqrt{R^2 + (2\pi\, n\, L)^2}$ is the impedance, and, as we shall see, in dealing with the properties of telephone lines it is the impedance and the angle of

* See Fleming, Alt. Current Transformers, p. 115 *et seq.*

lag, ϑ, which concern us immediately. As the current $= \frac{E}{\text{Impedance}}$, impedance takes the same place, for alternating currents, that the resistance has for steady currents. The impedance can therefore be measured in ohms. Having obtained the impedance in ohms and R, in ohms, and knowing n, in seconds, we can obtain the self-induction, in "secohms," and the value of ϑ.* The relations can be illustrated by the figure below.



As the resultant curve representing the waves of spoken sound is made up of a fundamental sine curve with the sine curves of the different overtones superposed upon it, the effect of self-induction, in retarding the phase of each component curve, is the same

* The practical unit of self-induction is 99777×10^4 centimetres; it is not exactly the earth's quadrant, in consequence of the legal ohm not being exactly the intended or true ohm. $r\,C + L\frac{dc}{dt} = E$, where r is in ohms, C in ampères, and E in volts. L must therefore be expressed in terms of a unit which is 99777×10^4 cm., or about 6,200 miles.

as if each of the component sets of vibrations were taken by itself. Self-induction, then, causes an apparent increase of resistance—an actual increase of impedance—and a retardation of phase. That is, the waves are, in effect, held back through a certain portion of a cycle. The amount of this retardation depends upon the period of the alternations and the nature and form of the circuit. For a simple vibration, therefore, consisting of waves of one period only, this effect would be entirely immaterial; for the waves would be simply shifted in position, their form remaining unchanged, and the effect at the receiving end would be precisely the same as though no change had taken place. Or, if the retardation of phase in any given circuit were the same for all periods and amplitudes, the practical effect would be *nil.* Unfortunately, however, this is not the case. The waves which we wish to transmit are very complex, consisting of simple harmonic waves of all frequencies, from about two hundred per second up to fifteen hundred per second, or perhaps even higher; and the phase of waves of high frequencies is retarded more than the phase of waves of low frequencies. This will evidently result in the displacement of the overtone waves with regard to the fundamental and to each other; and the resultant wave at the receiving end will be different in form from the wave at the transmitting end.

We have necessarily, then, so far as we have considered the transmission of speech by electric currents, two harmful effects :

1. The overtone waves of shorter period are reduced in amplitude to a greater extent than are the waves of longer period ; and

2. The waves of different periods are displaced with regard to each other, those of the shorter periods being retarded to the greater extent.

The first effect is, as we have seen, usually not noticeable ; but the second effect is often considerable, producing confusion of the component waves among themselves, and hence indistinctness of speech.

There is one other property possessed by every material circuit, which has an effect upon an alternating current flowing in that circuit. That is electrostatic capacity.

The subject of the transmission of alternating currents over lines having capacity, and the phenomena produced by the existence of capacity, has been very ably treated by Mr. Thomas H. Blakesley, according to geometrical methods.* Without going into the demonstrations, either geometrical or mathematical, we may consider the results and conclusions reached.

If a simple periodic current is flowing in a circuit having a condenser bridged across at some one point, the variation in the supply of the condenser will evi-

* For the full treatment and development of the subject the reader is referred to Mr. Blakesley's book, "Alternating Currents of Electricity."

dently be harmonic. As the maximum difference of potential in the condenser occurs when the current is passing the zero point, however, the curve of potential differences in the condenser, although similar to the curve of current, will be retarded in phase by one-quarter period behind the phase of effective electro-motive force. The value of the current between the condenser and the source of electro-motive force is augmented, and its value beyond the condenser decreased. With a *simple* harmonic current, indeed, the quantities concerned may be so adjusted that the effect of self-induction is annulled. This fact seems to be of slight assistance, as the telephone current is made up of components of widely differing periods. If, however, the adjustment be made for the highest important overtone, the balance for the lower tones will be even more complete. A method for doing this will be described.

If, now, we insert several condensers at intervals along the line, the effects will be twofold. The current in the sections nearer the source will be increased, and in the more distant sections it will be diminished. We shall find, also, a continual delay in the phase of the current as we recede from the generating source. Thus the current in each section is slightly less than in the section next preceding, and slightly later in reaching the same phase, so that the current in each section differs from that in every other section in both respects. Even with a *simple* periodic current, therefore, there will be a continual decay in passing through a long line or cable having capacity. Self-induction, if the conductor has capacity also, does not necessarily diminish the strength of the current, but may, up to a certain point, be actually beneficial. If the line has no capacity, however, self-induction always diminishes the current.

Any wire or cable may be looked upon as a conductor having capacity, distributed more or less uniformly along its length, not concentrated at any definite points; and in such a case we see, from our consideration of the subject thus far, that at no two points in its length will the current be the same in value or in phase, even when the current is simply periodic. When the resultant periodic current is made up of many simple currents, of different periods, the effects are much more disastrous. For the amount of falling off in current depends upon the period, being greater as the period is smaller. Thus the component waves will have their relative values changed, and will be displaced with regard to each other and to the fundamental, as in the case of self-induction. We can see, too, that if the circuit is divided between any two points, the arms having different values for capacity and inductance, the wave will be still further confused.

In actual lines it is probable that the effects of capacity greatly preponderate over those of self-induction; while in all apparatus the effects of self-induction are the greater.

In any line, as the waves recede from the generating source, the energy appears to be gradually dissipated. It is communicated to the medium surrounding the wire, existing there partly as energy of the magnetic field and partly as electrical energy; and the process of propagation consists in the transformation from magnetic into electrical energy and *vice versa*.

During the progress of the wave from the transmitting end, the current is attenuated, the higher frequencies to a greater extent than the lower, as has been pointed out in the preceding pages. This is regulated by the amount of inductance and capacity possessed by the line, and will be diminished by increasing the inductance of the line, to a certain definite extent. This fact has long been known, but the practical difficulty has been to construct a line in which this balance has been obtained for all important current frequencies, without introducing the inductance in such a form that it causes reflections and aggravates the trouble.

A method which seems likely to accomplish this very desirable end is due to Dr. M. I. Pupin. Inductances of suitable definite values are inserted in the line at regular intervals which are certain exact fractions of the wave-length of the highest important overtone. Compensation is thus obtained for that particular frequency and the attenuation reduced to sufficiently small value. For the lower tones, the approximation to a perfect line will be still greater.

CROSS-TALK.

We have, so far, considered only the effects due to the flow of an alternating current in a circuit wholly removed from all other conductors. Let us now investigate the effects upon the current of the proximity of other conductors.

When an alternating current traverses a conductor, the conductor is given static charges of alternately opposite sign. Let us assume that it is first charged positively. Then displacement currents are produced from neighboring conductors into the dielectric, and a corresponding negative charge on these conductors results. When the next reversal of the current occurs, the negative charge in the surrounding conductors is reversed also; and this reversal of charges on surrounding conductors is caused by the current twice in every complete vibration. In the case of the telephone current, therefore, the complete reversal of charges on surrounding bodies is caused from four hundred to one thousand times a second, and the induced charge is varied in amount by the overtone waves, in some cases as often as three thousand times a second. The performance of this work by the current causes in general a considerable loss of sharpness of the waves of the telephone current, the tendency being to reduce the amplitude of all the component waves, thus "smoothing off" the current wave and changing the character as well as lessening the volume.

In these surrounding conductors the changes in static charge just described will evidently result in the production of a current corresponding to the inducing current, but less in amplitude. And if such a wire forms part of a second telephone circuit, the speech transmitted over the first circuit will be overheard in the telephones of the second circuit, but fainter. This phenomenon, which has always been common and very marked, is called "cross-talk." In the earlier days of telephony, and in fact up to a comparatively recent time, it was generally supposed that the phenomenon of "cross-talk" was due to electro-magnetic induction, that is, to mutual induction, as we have already developed it. The effects of electro-magnetic induction and of electro-static induction are in this respect the same; and whether the phenomenon is due to the one or to the other is determined by the strength of the inducing current and the physical relations of the circuits. It has now become generally recognized that, with the usual relations of circuits to each other and the usual strength of the telephone current, the effects of mutual induction are very feeble—in fact inappreciable—and cross-talk is due to electro-static induction alone; although in induction coils and such apparatus, electro-magnetic induction is the chief and only important cause.

Some very interesting experiments on this point have been performed by Mr. J. J. Carty, and were described by him in a paper read before the New York Electric Club in November, 1889. These experiments show conclusively that cross-talk on telephone lines is due to electro-static induction alone; and I give Mr. Carty's own description of the experiments, only emphasizing the fact that the volume of cross-talk depends upon the specific inductive capacity of the insulation, as well as upon the distance apart of the conductors. This would not be the case were the effect due to electro-magnetic induction.

" While a study of the strange noises heard in the telephone might be of interest, I shall in this paper limit myself to the consideration of 'cross-talk,' and to the action which takes place when wires are bunched in cables. In the simple case of inductive 'cross-talk' first cited, in which telephone wires are strung parallel on the same cross-arm, the presence of 'cross-talk' is said to be due to dynamic or current induction ; that is, if a current commences to flow in one of the wires from north to south, it will at that instant cause an induced current to flow in the other wire in the opposite direction, from south to north. As the telephone current is constantly changing its direction and strength, this explanation seems to apply and is the one given in the text-books.

"This is the kind of induction referred to in the law of Lenz, and applies to induction coils and to parallel wires when the current is of sufficient strength. I shall speak of this hereafter as electro-magnetic induction. To-night I shall describe some experiments which seem to prove that the induction between telephone wires is due to electro-static rather than to electro-magnetic action.

"I will first show a case of electro-static induction * between telephone wires, in which there is a neutral point at the centre of the secondary wire, at which point there is no induction, while at the ends marked inductive effects are noticeable.

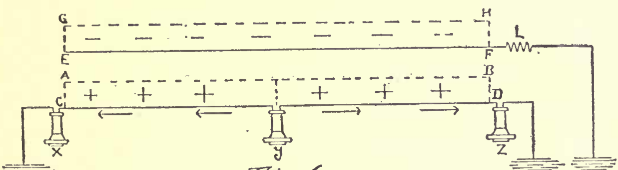


Fig. 1.

"In Fig. 1, E F and C D are two well-insulated parallel telephone wires, each 200 feet long and placed one-eighth of an inch apart. E F is open at one end and connected to ground at the other through a Blake transmitter, L, in the ordinary

* In explaining an experiment of Mr. Culley before the Society of Telegraph Engineers in 1875, Mr. Preece pointed out that in a certain telegraph line, subjected to induction from a neighboring telegraph line, there was a neutral point. I can find, however, no reference to this in Mr. Preece's book on "The Telephone," and its practical application to telephone induction seems to have been lost sight of.

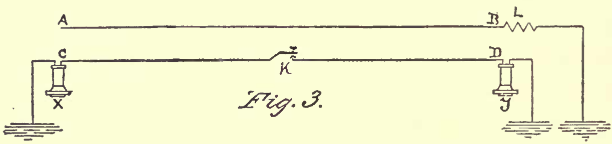
manner. In front of the Blake transmitter I place a vibrating tuning-fork, which acts on the transmitter in the same manner as the voice, and which produces impulses on the line E F of the same strength as voice currents. At the centre of the line C D we have the telephone Y, and at the extreme ends the telephones X and Z. With the tuning-fork at L in operation, tones are heard at X and Z, but the middle telephone, Y, is silent. A study of the changes of potential produced in the wire E F by the transmitter, will give us an explanation of this phenomenon. As is well known, the telephone current is an alternating one, and the potential of the line E F varies constantly and is changed from positive to negative many times per second. The wire E F, being open at E, would be at the same potential throughout. It is assumed that at a given instant, the height of potential at F would be represented by the dotted line F H; then the potential at E would be represented by the dotted line E G, and the total charge on E F would be represented by the rectangle E G H F. We will assume that this charge is of the minus sign. The existence of this charge on E F presupposes the presence of a charge of opposite sign on C D, which would be represented by the rectangle A C D B.

"Now suppose the potential on E F becomes zero, owing to the operation of the transmitter, then the whole charge on E F gets to earth at the grounded end of E F, but the charge on C D has two paths to earth, one at C and the other at D. This results in two currents, as shown by the arrows, one flowing to earth through the telephone X, and producing sound at X, and the other flowing to earth through the telephone Z, and producing sound at Z. No current flows through the telephone Y, and consequently no sound is produced therein. Again, changing the potential of E F causes a corresponding set of currents, but in opposite directions to those first described, meeting in the centre and producing no sound in the centre telephone, but causing the end telephones to give out sounds the same as in the first instance. Inasmuch as the line E F is opened at one end, and therefore has almost an infinite resistance, it is clear that this phenomenon is purely an electro-static one.

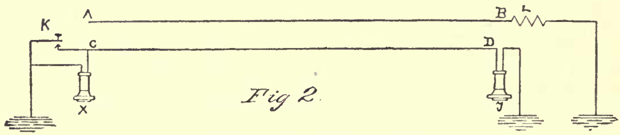
"In this and the succeeding experiments I have not attempted to give the exact shape of the induced charge, as it would unnecessarily complicate the subject and would not in any way affect the result. As a matter of fact the dotted line A B should slope off from the centre toward the ends.

"With the line E F grounded through an ordinary subscriber's line and instrument, the effect is the same as when the line is open, and the neutral point is still found. This is because the telephone current, even when flowing in a closed circuit, is so weak that it is not capable of producing a magnetic field of sufficient strength to affect the neighboring wire, or the magnetic effect is so small that it is obliterated by the movement of the static charge. For convenience in some of the succeeding experiments, the disturbing wire will be shown open at one end.

"If there is no current flowing at the neutral point, opening the wire at that point should have no effect on the telephones located at the ends. In Fig. 3 A B is the disturbing wire with the transmitter, L,



arranged as before; K is a key located at the neutral point of C D. With the transmitter, L, in operation, no change is produced in the tones heard at the telephones X and Y by opening and closing the key, K. If this induction were electro-magnetic, opening the line C D would prevent current from flowing in any part of the circuit. In Fig. 2 we have another proof of the electro-static nature of telephone induc-



tion. A B is the usual disturbing wire with its transmitter, L. C D is the secondary wire with the telephones X and Y, located at the ends, as in the previous experiment. By means of the key, K, the telephone X may be cut in and out of the circuit. With the key open, the usual tones are heard at X and Y. Now, if the induced current flowing in the circuit C D is due to electro-magnetic induction, upon short-circuiting the telephone X, and thereby reducing the resistance of the circuit C D, the strength of the induced current should be increased and the tone at the telephone Y should be correspondingly louder. But this is not the case, as on closing the key the sound at Y, instead of being increased, entirely disappears. This is because the charge on the wire C D finds an easy path to earth through the key, and such a small portion of the charge goes to earth through the telephone Y that no audible effect is produced therein.

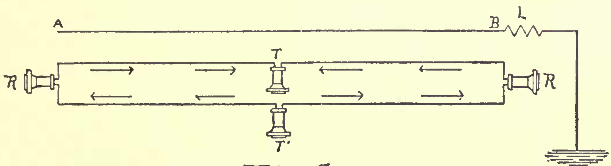


Fig. 4.

"Fig. 4 shows the disturbing wire, A B, arranged as before, but the secondary wire, instead of being put to earth at both ends, has its circuit completed by a second wire placed outside of the field of A B. With this arrangement, neutral points are found at T and T[1], while the usual disturbances are heard at telephones R and R', located at the ends. In this case a movement of the static charge takes place in the metallic circuit, causing at one moment a set of currents starting from T' in both directions through the end telephones and meeting at T, and at the next instant the reverse takes place.

"I will now show some of the effects of electro-magnetic induction, at the same time suppressing electro-static induction.

"In Fig. 5, A B is the disturbing wire as before,

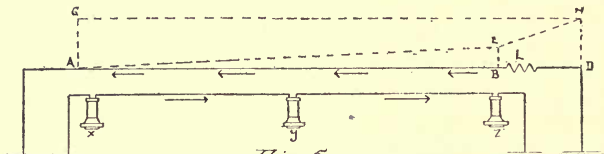


Fig. 5.

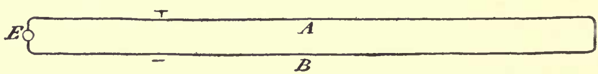
but grounded through a short thick wire at A. Instead of placing the tuning-fork in front of the transmitter, L, and acting on it through the air, producing delicate currents like voice currents, an automatic circuit breaker and five cells of Leclanche battery were connected in the primary circuit of the transmitter, thus producing in the line A B alternating currents of great strength. The secondary wire containing the telephones X, Y, and Z is of the same length and at the same distance from the disturbing wire, as in the previous experiments. With the circuit breaker at L in operation, loud musical tones are heard at X, Y, and Z, and the tone is the same in all three telephones, the neutral point in this case having disappeared. This is a true case of electro-magnetic induction, because short-circuiting the telephone Y increases the sound in the remaining telephones, and leaving the short circuit on Y, and short-circuiting the telephone X still further increases the sound at Z. This latter experiment furnishes a most striking contrast to the result obtained in Fig. 2, where by short-circuiting the telephone X the sound was completely removed from the telephone at the other end of the line.

"Another proof that this is electro-magnetic induction is found in the fact that if the line be opened at Y, the sound disappears from all the telephones. If the line A B were opened at A, the potential along the line would be constant, and the charge which A B would take would be represented by the rectangle A G H D ; but when the line is grounded at A through a low resistance, there is, of course, a fall of potential along A B ; the principal drop, however, occurring in the secondary coil of the transmitter L, the line B E representing the height of potential at the terminal of the coil, and the electro-static effect which the line A B would have is represented by the triangle A E B. This triangle, although exaggerated in the diagram, is still much smaller than the rectangle A G H D, and explains the absence of electro-static induction between the wires ; while the powerful current generated in L, and the comparatively low resistance through which it has to flow, account fully for the electro-magnetic effects observed.

"I have made a large number of laboratory experiments and observations on actual telephone lines, all of which point strongly to the conclusion that electro-magnetic induction does not exist in telephone lines outside of the telephone and transmitter. This view of the subject, applied to the theory of transpositions of metallic circuits and to the action of wires in cables, gives the only satisfactory explanation of observed phenomena." *

From this view of the cause of "cross-talk" we can form much more accurate ideas as to the actual condition of things on a telephone circuit.

When a neighboring conductor forms a part of the primary telephone circuit, the harmful effects of induction, both internal and external to the circuit, are very much reduced. In this case the positive charge



sent out in one direction, and the negative charge in the other direction, assist each other. The work which must be done in the direct reversal of charges upon A and B by the impressed electro-motive force at E, is lessened by an amount due to the electro-

* Another series of experiments by Mr. Carty on the same subject was described in a paper read before the American Institute of Electrical Engineers in March, 1891. This is given in full in Appendix B.

static induction from A to B and *vice versa.* The induced static charges on other bodies at a greater distance, being the resultant charge due to both conductors, are in general very slight, and the loss of sharpness from static induction upon external conductors is usually, in the case of metallic circuits, inappreciable.

Let us now recapitulate, briefly, the characteristics of spoken sound and of the telephone current. The properties of spoken sound are :

1. Loudness, or volume.
2. Clearness.
3. Quality.

It is, of course, desirable that the sound received should be of a good volume. But speech, however loud, is utterly unintelligible if it is not clear. Quality it is desirable to retain, but a change in quality, so far as it is separable from clearness, is objectionable only in that it may disguise the voice of the speaker or become disagreeable to the ear. Clearness it is absolutely necessary to preserve to the utmost extent possible.

Volume is affected by any conditions which alter the amplitude of the wave.

Clearness is affected by any conditions which alter the positions of the waves (of all periods) with relation to each other.

Quality is affected by any conditions which alter the form of the wave.

Therefore,

1. Volume is reduced by resistance, by leakage, by static induction, and by self-induction; for the effect of all these properties is to reduce the amplitude of the waves.

2. Clearness is reduced by static induction and by self-induction; for the effect of both these properties is to alter the inter-relations of the waves. Static induction causes a rounding off of the crest of the wave, thereby involving a loss of sharpness; and both static induction and self-induction produce an unequal retardation of phase for vibrations of different periods, thus causing interference and a resultant deformed wave.

3. Quality is changed by all the properties which reduce the clearness, and by self-induction in another sense as well. For one effect of self-induction is to reduce the amplitude of the overtone waves to a greater extent than that of waves of longer period.

To successfully accomplish good telephonic transmission of speech, therefore, we must make the self-induction and electro-static capacity of our line and apparatus as low as possible. Resistance and leakage are comparatively unimportant, although it is of course desirable to keep the resistance low, and the leakage within reasonable limits. A slight and well distributed leakage, however, is often an advantage. It allows the static charges to escape, and thus neutralizes to some extent the disfiguring effect of capacity.

When iron or steel wires are used for the transmission of telephone currents, there is, in addition to the effects which have already been described, a further deformation of the waves and decrease in amplitude, beyond what would be caused by the greater resistance. This is due to the fact that the wire is to some extent circularly magnetized, and that this magnetism has to be reversed twice in every vibration. In view of the distribution of alternating currents on or near the surface, it has been contended by many, with some reason, that no magnetization could exist; but the great alteration in form of the waves cannot be accounted for by the greater resistance of iron. There must be also some considerable increase in self-induction, due to the magnetic properties of the metal.

ELECTRO-MOTIVE FORCE AND VOLUME OF THE TELEPHONE CURRENT.

The electro-motive force of the telephone current, as generally used, has never, to my knowledge, been measured; and we can only arrive at a rough approximation to its value by calculation. The electro-motive force will depend, evidently, upon the transmitter used, the condition of the battery if the transmitter is a microphone, and upon the induction coil. With the best forms of transmitter now in commercial use, and a battery of three cells in good condition, there is a change in potential at the terminals of the primary coil of one-half a volt, more or less. The electro-motive force which this will induce in the secondary depends, of course, on the winding of the coil, and can be determined approximately from a knowledge of the relative number of turns in the primary and in the secondary.

Owing to the nature of the telephone current, the measurement of its volume involves many difficulties which cannot readily be overcome, except in the best appointed laboratories where the most delicate apparatus is at hand and can be used, and where sufficient time can be devoted to thorough and careful investigation. The Massachusetts Institute of Technology took up the subject of telephone currents for investigation some years ago, and careful experiments on this subject have been carried on during each year since. Owing chiefly to these efforts, we have now some definite knowledge of the volume of the telephone current, and the effects due to different forms of transmitter.

With the single contact microphone transmitter, of which the Blake is the typical form, the volume of current produced in the secondary is usually somewhere between .0001 ampère and .0007 ampère; the exact value depending, as has been pointed out above, upon the conditions of battery, induction coil, and initial loudness of sound.

With the granular instruments, or multiple contact microphones, of the type of the long-distance transmitter, the current in the secondary will have a volume of .0002 to .001 ampère, the exact value, as before, depending upon the conditions of battery, induction coil, and initial loudness of sound. The latest and most improved forms of granular transmitter have never yet been tested in this way; but as they are far superior to the older forms, which have been tested, it seems probable that it will be found that they produce in the secondary a current of as great a volume as .01 ampère. The figures given are for the *mean* value of the current. This, in a simple sine curve, is 0.6369 of the maximum value.

In considering the question of loudness, it must be borne in mind that the different vowel sounds produce currents differing widely in volume. The volume of current produced by the sound of the vowel *e*, for instance, is much less than that produced by the sound of the vowels *a* or *o*.

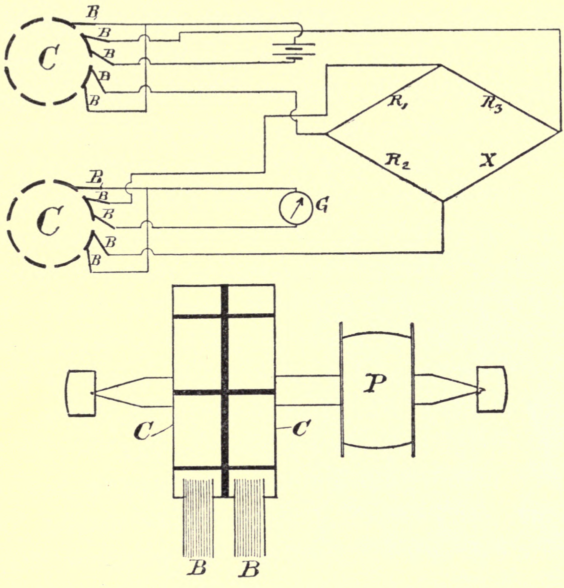
CHAPTER X.

MEASUREMENT.

In order that we may work intelligently it is most necessary that we should be able to obtain values for the quantities with which we have to deal. We must be able to measure *impedance*, *capacity*, *resistance*, and it is highly desirable that we should be able to measure *volume* or current strength also. The methods of obtaining the values of capacity and resistance are too well known to need any description; but easy methods of measuring impedance and volume are not so well known.

We may find the impedance of any circuit by obtaining its co-efficient of self-induction, according to methods given in many text-books, and by calculation. As, however, the methods referred to are rather difficult and tedious, and as the co-efficient of self-induction itself is practically of less importance than the impedance, we may measure the impedance directly in the way shown in the cut on the following page.

C is a commutator mounted on a shaft which can be revolved by any desired means. It may advantageously be done through a pair of cone pulleys belted on to the pulley P, and driven from any source of constant speed. Then, by shifting the belt



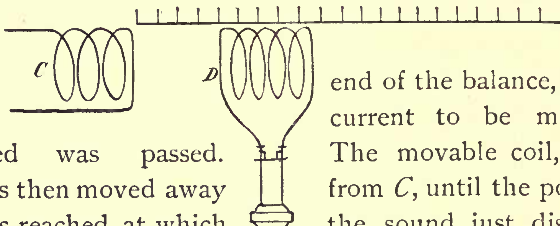
along the cone pulleys, any desired speed may be obtained at the commutator. The speed of the commutator shaft may be measured by the use of a mercury-box and column, as used by Professors Ayrton and Perry, or by a ball governor whose height can be read off a graduated scale previously calibrated. Knowing this speed and the number of segments in the commutator, the period of alternation, n, may be obtained. B, B, B, are brushes bearing on the commutator; and if the commutator and brushes are made and mounted according to the best practice in dynamo work, this arrangement will give little or no trouble. By an inspection of the diagram it will be seen that the battery and the galvanometer are reversed at the same instant. An ordinary Wheatstone bridge forms the remainder of the apparatus. It is most desirable that the known resistances in the bridge should have no self-induction and no capacity; but even with the usual double-wound resistance coils, results may be obtained that will be sufficiently approximate for most practical work. The resistance at the contacts between the brushes and the commutator will evidently not enter into the measurements at all. If desired, an alternating current ammeter may be inserted in the arm of the bridge containing the unknown impedance, but correction must be made for this in the results. If a telephone is used instead of the galvanometer, a variable self-induction must also be used to obtain silence, making the apparatus a Hughes induction balance.

In using this apparatus, the resistance should first be measured with the commutator at rest. The commutator should then be run at such a speed as to give n the desired value, and a balance again obtained in the bridge. We have then found R and impedance, in ohms, and know n, in vibrations a second, and can calculate ϑ, the angle of retardation, from the formulæ $tan\ \vartheta = \frac{2\pi\, n\, L}{R}$ and impedance $=$ $\sqrt{R^2 + (2\pi\, n\, L)^2}$.

We may be able to find L from these same measurements, but not necessarily. For, if the period is small and L is large, the currents do not at any time attain their steady value, and the value obtained for L by calculation from our observations would be smaller than its real value. If we wish to find L we must make n so large that two values of L, obtained from two sets of observations, with different values of n, are found to agree. In practical work, however, as we have seen, it is the impedance we want to find, and we do not care what the value of L may be. The values of the angle ϑ, found with different values of n, will give an idea of the deformation of the resultant wave experienced in traversing the circuit under consideration; and different circuits or pieces of apparatus may be compared in this way with highly instructive results. It has been advanced as an objection to this method that the commutation of a battery current does not give a true sine curve. The approximation, however, is probably sufficiently close to serve the purposes of comparison, although the method could not be used, without modification, to obtain absolute values. It has the advantages of ease and quickness in operation.

Volume, or current, may be measured most accurately by means of a dynamometer. But this method also requires great care and conditions often difficult to attain. A method of easily obtaining the comparative volumes of different sounds is by the use of the apparatus described below :

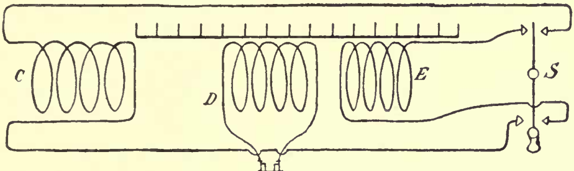
This apparatus, as originally designed,* depended for its operation on the finding of the point of disappearance of the sound in a secondary coil as it was moved away from the coil carrying the current to be measured. Through a fixed coil, *C*, at one



end of the balance, the current to be measured was passed. The movable coil, *D*, was then moved away from *C*, until the point was reached at which the sound just disappeared; and this position was read off on the graduated scale at the side. There are, obviously, many difficulties in the way of the practical use of such an instrument. The point of apparent disappearance of the sound will depend on the acuteness of hearing of the observer, on the degree of quiet that could be obtained in the room, and there is a considerable range in which it is difficult to tell whether any sound is heard or not. In practice, these difficulties were found to be so great that the instrument could not be used for accurate measure-

* By Dr. H. V. Hayes, of the Am. Bell Tel. Co.

ments. The apparatus was therefore modified by the writer, as follows :



Rigidly attached to the coil *D*, at a fixed distance, was placed a third coil *E*. *D* and *E* then moved together, and their position could be read off on the scale as before. The current to be measured was then passed through *E*, and the current from a standard source of the same pitch was passed through *C*. The switch *S* enabled the observer to change rapidly from one circuit to the other, so that he heard in the telephone, alternately, the sound produced by the current in *C* and that produced by the current in *E*. It was then possible to so adjust the position of the movable coils that the sound from either source had the same volume. This could be done with considerable accuracy, and an arbitrary value obtained for the sound in *E* from a previous calibration of the instrument ; and by means of these arbitrary values different sounds could be compared with each other, although the actual value of the currents producing them might be unknown. Such an instrument can best be used to compare the transmitting qualities of different lines or apparatus, by using a pair of vibrating tuning-forks working through induction coils. The forks must, of course, be of the same pitch, and the coils alike, and equal battery power must be used with each. Then if one fork is set at work at the distant end of the line, and the other fork worked through the coil *C*, an approximately accurate value can be found for the transmitting power of the line, in terms of *volume* of sound. The chief difficulty in the use of the instrument consists in the change in quality of the sound from the distant source, as heard in the telephone. The quality was always found to be much altered by the properties of a line, of any considerable length, being made round and full and unctuous in character, as compared with the sharp and somewhat harsh note from the near fork.

CHAPTER XI.

PROPERTIES OF CITY LINES.

WITH our knowledge of the telephone current and its properties, we are now in a position to determine the proper disposition of wires for telephone lines and the conditions to be observed for efficient communication over them. In dealing with city lines we will at first confine ourselves to the consideration of grounded circuits. For, although with the constant and rapid growth of the long-distance service metallic circuits in cities are becoming of continually increasing importance, by far the greater part of city exchange lines are still made up of grounded circuits; and the treatment of metallic circuits, as developed later, may properly be applied to overhead metallic circuits in cities, as well as to trunk lines. Underground cables, although used exclusively in cities, and forming now to some extent a part of almost every exchange system, are considered by themselves.

The properties of any telephone line are:

1. Resistance.
2. Capacity.*

* It has been customary to use the term "retardation," meaning anything or everything that produced an interference or confusion or

3. Insulation.
4. Self-induction.

In city lines, considered by themselves, the length of line is comparatively slight (the average length is, perhaps, two miles), so that, as they are usually constructed, none of the properties named will have so great an effect as to make conversation very difficult. The effect of resistance is not important, even when iron or steel wire is used; but on account of the magnetic character of iron and steel, these metals are not suitable for telephone lines, and should not be employed. Copper wire, hard drawn, of a diameter not less than .080 inch, should be used when possible, on account of both its mechanical and its electrical properties. The resistance of the average line, if constructed of this wire, will then be about 17 ohms, and its impedance but little greater. The impedance of iron wire, of considerably greater diameter, is much higher. The impedance offered by the instruments which it is necessary to have in circuit, is, however, so great, as compared with that offered by the line, that for local exchange work, even iron wire, properly placed, will prove fairly efficient.

muffling of sound; and very few have seemed to know just what it did mean. "Retardation" is a convenient term if its meaning is clearly understood. It includes, properly, some of the effects of self-induction, and of static capacity of the conductor under consideration. It includes all conditions which produce an unequal retardation, or "lag," of phase for vibrations of different periods. Retardation may, therefore, be considered a property of a line, but not as separate from the other properties enumerated above.

Electro-static capacity is the property probably the most injurious in its effects, as it acts in a double sense: First, as cause of retardation, muffling and confusing speech, while at the same time it reduces the volume; and second, as a cause of cross-talk. Its effect is independent of the material of the wire, and depends solely on its size and its position with relation to the earth and to other wires. Evidently, therefore, so far as capacity alone is concerned, it is advantageous to have as small a wire as possible; and it is in every respect advantageous to place the wire as far as possible from all other bodies. Here we see an advantage in the use of copper wire. For the same impedance, a wire of copper is much smaller than a wire of iron; and by reason of its less surface, its capacity is correspondingly less than that of the iron wire. As regards distance from other bodies, it is, of course, practically impossible to exceed certain limits, but within these limits there are many degrees of choice. Pole-lines have, in general, less capacity than house-top lines, as the lines in the former case are at a greater distance from the earth than they are in the latter case from the roofs; and electrically, the roofs are practically the same as earth, especially when covered with tin, as many roofs in cities are. Assuming, then, that we have a pole-line of copper wire, it should be our next object to separate the individual wires as widely as may be. Here again, however, we have limits set by considerations of convenience and available space. The wires cannot be placed very far apart, vertically, without using poles of great and absurd height; and they cannot be very widely separated, horizontally, without using unduly long cross-arms.

Considering carefully all the points that have been named, the desirability of a great separation of all the wires from each other and from the earth, and the limitations in space imposed upon us in practice, we are led to adopt, as on the whole the best, the dimensions usually employed in long-distance construction. The wires are placed one foot apart, horizontally, and about two feet apart, vertically; and the poles should be not less than thirty-five feet high, preferably forty feet. The wires should be of copper, not less than .080 inch in diameter. A line so constructed will unite efficiency in transmission with ease of inspection and maintenance.

INSULATION.

From the facts which have already been considered, we see that it is not necessary that the insulation on short lines should be kept very high. And, in fact, it would be difficult to keep it high. The smoke, dust, dampness, and acids, which are abundant in the atmosphere of the busy portions of cities, are fatal to high insulation. It is the usual rule, in exchanges, that the insulation of the lines shall not be allowed to fall below one megohm per mile, and although the insulation should preferably be considerably higher than that, and generally is higher, the loss of volume due to a leakage of one-half a megohm (for a line two miles long) is not sufficient to seriously interfere with transmission. Moreover, as has been pointed out, a well-distributed leakage is an assistance to clearness, as the static charges are allowed to escape, and the disfiguring effect of capacity upon the telephone current is thereby avoided.

It is much easier to keep up the insulation of a pole-line than of a line run over house-tops; for the smoke and gases from the chimneys readily cause a deposit upon insulators placed near them. Pole-lines, being usually below the level of the chimneys, do not so easily accumulate this deposit on the insulators. It is especially difficult to maintain high insulation in cities situated on the sea coast. When the wind blows from the salt water, and indeed, at all times to some extent, a thin film of salt is formed all over the insulator. This is not entirely washed off by rain, and readily absorbs moisture, so that the insulator may never be quite dry. For good insulation in bad weather, an insulator should have a narrow opening and long petticoat.* This keeps a considerable length dry during rain, and seems to dry out practically as rapidly as one with a wider opening. Moreover, it does not so easily

* See tests given earlier.

become coated with a film of moisture during fog or mist. It is not necessary, in this country, that the insulators should be so large as those in common use in England. The element of conspicuousness is, therefore, not an important one with us, and porcelain may be used without fear that the insulators will be mischievously broken. Porcelain is in many respects superior to glass, notably in toughness.

RETARDATION.

If, as has been recommended above, copper wire were used for exchange lines, the retardation in the line itself would be inappreciable. As most of the existing city exchange lines, however (and many trunk lines also), are of iron wire, the retardation even in a short line may be considerable. The effect of retardation is to confuse and muffle speech, and is much more injurious, so far as successful intercommunication is concerned, than the effect of any other property that the line possesses. In this case retardation can be reduced only by reducing the electro-static capacity, and by using non-magnetic metal for line wire.

DISTURBANCES.

On grounded telephone circuits, much more trouble is caused by interfering currents, from various sources, than by a lack of efficiency due to the properties of the line itself. These disturbances come in from the earth, from the air, and from other wires; from telegraph wires, electric light and power currents, and electric railways; and unless great precautions are taken, as much disturbance is caused by the weak telephone current itself, as by the powerful current used to propel the cars or light the streets.

CROSS-TALK.

This interference with a telephone current by another telephone current is called cross-talk, and has already been explained. It is due to electro-static induction, as has been conclusively shown by Mr. Carty's experiments, and to guard against its occurrence, therefore, we have to so construct our lines as to make the electro-static capacity of one wire to another as small as possible. This we can do in three ways: By using a dielectric medium of minimum specific inductive capacity; by using a wire of minimum surface; and by placing the wires at a maximum distance apart. The limits in regard to surface and distance have already been settled so far as outside lines are concerned, by practical considerations of convenience and available space; and as we are striving, in the cases of both impedance and capacity, for the same end, we must accept these limits as the best we can attain. As a dielectric medium, dry air has as low a specific inductive capacity as any that could be used, and no improvement can be looked for in that direction over what nature provides us with. The method of preventing induction by neutralizing the effect in opposite sides of the circuit, as practised in metallic circuits, it is, of course, impossible to use with grounded circuits.

In the older forms of switch-boards the wires were led in to the back of the board indiscriminately bunched together. This practice, of course, brought the wires of different circuits very near together for some distance, and resulted in an excessive amount of cross-talk, which was always a great source of annoyance, and often caused serious difficulty in carrying on conversation. The only way of avoiding this difficulty was to change the method of wiring the switch-board: to lead the wires in regular cables properly laid up, each circuit being complete, and the two wires of the circuit twisted about each other. If, then, the second wire of the circuit were grounded outside the board, much of the induction in the switch-board would be neutralized, and but very little would be heard on the lines. This plan has been followed in all the modern forms of switch-board, and but little annoyance is now felt from what was once the chief source of cross-talk.

In city exchange lines the length of line is not great; the outside wires do not run parallel for any great distance, and within that distance are favorably situated with regard to each other; and the transmitters employed are too weak to give the wires any considerable charge. The volume of cross-talk due to induction on the outside wires is therefore usually very slight. As the length of two parallel wires is increased, however, the amount of induction is increased. Assuming the source of electro-motive force in the transmitter to be constant, as is practically the case, the volume of the inducing current would decrease with the length of wire, owing to the increased resistance; while, on the other hand, with the increased distance of parallelism the amount of the induced current would increase. To determine just how much an increase in length of two parallel wires would affect the volume of cross-talk, the following experiment was performed: A twisted pair of wires was so arranged that the length used could be varied at pleasure from twelve feet up to about fifteen hundred feet. The twisted wires were fastened to a wooden wall back and forth in straight lines, to avoid electro-magnetic induction, and were carefully tested to avoid leakage from one to the other. A weak alternating current was then sent through one wire, and the current induced on the other wire was measured by comparison with a standard sound, using the balance already described. The length of wire carrying the inducing current was in each case the same as the length of wire carrying the induced current. It was found that the volume of the induced current, or cross-talk, was approximately proportional to the square root of the length of line, or

$$C = K\sqrt{l}.$$

in which K is a constant quantity depending on the capacity of one wire to the other.

In some exchanges where an underground cable system is being established, it is the practice to use the two wires of a twisted pair for separate circuits instead of allowing one wire of the pair to serve as a return for the other, and grounding it at the end of the cable. The result of such a method is, of course, to cause a great deal of cross-talk in the cable, especially between the two twisted wires,* and it is very much better to use a pair of wires in a cable for one circuit only.

* This method is a bad one for another reason. When it becomes necessary to change the circuits from grounded to metallic, an entire rearrangement of connections will be necessary.

CHAPTER XII.

INTERFERENCES FROM OUTSIDE SOURCES.

WITH the earliest use of grounded circuits for telephones, serious disturbances were felt from several outside sources. Electrical disturbances in the earth, so small as to have been entirely disregarded before, were picked up by the telephone wire, and caused sometimes almost deafening noises; disturbances in the air, up to that time unheeded, were sufficiently powerful to seriously interfere with speech. The messages on the telegraph wires, when the telephone wires ran near them, could be easily read in the telephones. With the growth of both telephony and electric lighting, the arc-lighting currents became one of the most powerful sources of disturbances; alternating currents, in their turn, were far worse, and indeed still hold the palm as a source of disturbance; and last, electric railways have proved a source of more or less serious annoyance to telephone users.

AIR AND EARTH CURRENTS.

Air and earth currents do not cause any considerable interference on short lines. They are powerful only during electric storms, and at such times the telephone is not used. On long lines they have proved to be a source of such very serious interference as to render the use of metallic circuits a necessity for successful long-distance work.

In this connection, Mr. J. J. Carty says, in a paper* which has already been extensively quoted :

"One of the most peculiar developments connected with the introduction of the telephone was the presence of remarkable sounds which were heard when the telephone line was of any considerable length. Sometimes it sounded as though myriads of birds flew twittering by; again, sounds like the rustling of leaves and the croaking of frogs could plainly be heard; at other times the noise resembled the hissing of steam and the boiling of water. Even a display of aurora borealis caused powerful currents in the telephone.

"At one time, I think it was in 1882, during the prevalence of sun spots and after the appearance of a comet, the auroral current became so strong on a line from Boston to Brockton as to operate a miniature arc-light which I improvised out of a pair of lead-pencil carbons and connected into the line.

"Some of these disturbances have been more or less satisfactorily accounted for by assuming differences of potential at the two ends of the line; by the sudden heating or cooling of the line; and by the passage of electrified bodies of air or clouds."

Air and earth currents are still often a cause of much trouble in the use of measuring instruments of any

* A New View of Telephone Induction.

great degree of delicacy, in connection with long lines, even although the lines are metallic circuits.

TELEGRAPH INDUCTION.

Induction from telegraph wires is now avoided, as telephone lines are seldom run near to telegraph lines. The telegraph lines run along the railroads, while the telephone lines take the highways. There is an occasional instance of induction from telegraph lines upon telephone lines; but such instances are rare, and are of slight importance.

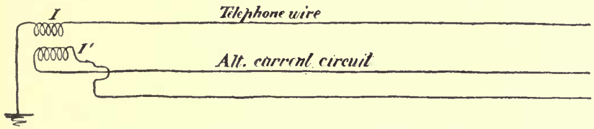
INDUCTION FROM ELECTRIC-LIGHTING CIRCUITS.

The serious nature of the disturbances due to electric lighting currents has been forced upon the attention of telephone companies more and more strongly for some years. Electric railways have still more recently been added to the list of disturbing causes, and it has become imperative that something should be done to prevent or to cure the interference.

Electric currents produced by dynamo-electric machines are, of course, not absolutely steady. The current which is sent out is made up of a number of overlapping single waves, each single wave being produced by a single coil of wire on the armature of the machine. The resultant wave will therefore have an undulating crest, the depth of the undulations—or the variations in electro-motive force—depending on the number of coils with which the armature is wound. Obviously, therefore, all dynamo machines are not alike in the effect that is produced in the telephone. In general, the machines for arc-lighting have fewer coils in the armature than the machines for incandescent lighting, and arc-currents, therefore, produce greater disturbance than any other so-called steady currents. Machines which produce an alternating current will, of course, cause a far greater noise in the telephone, as in this case the full potential of the machine is operative in inducing current on the telephone line. Moreover, the vibrations are very rapid, and the sound produced is of about the same pitch as some of the notes in the human voice. Even if the noise is not overpowering, therefore, it is much more difficult for the ear to distinguish the speech from the disturbance, and to understand conversation, than in the case of slower vibrations, where the pitch of the disturbing noise is low.

All circuits carrying currents for lighting are now insulated from the ground, or nominally so; but it is a difficult matter to keep this insulation high, and of course impossible to make it perfect. There is therefore more or less leakage, at all times, from the lighting circuits to the poles and to the earth. In many places, also, telephone wires and electric light wires run upon the same poles. Therefore, although induction is probably in most cases the chief cause of disturbance from electric light wires, leakage is often an important factor, and must always be considered.

The disturbances arising from these sources have proved a very serious inconvenience in operating telephone exchanges; and although it has always been recognized that the use of metallic circuits by the telephone companies, or the removal or entire readjustment of the disturbing circuits would prevent interference, it has been in most cases impossible to successfully accomplish the necessary changes in the disturbing circuits, and the expense of an immediate and wholesale installation of metallic circuits is enor-



mous. Every plan and device that could be thought of as a remedy for these disturbances was therefore carefully and thoroughly tested. Most of these plans involved the insertion of apparatus in connection with the telephone instruments; but it has been found that all devices of this nature cause a diminution of the telephone current in about the same proportion that the disturbing noise is reduced, so that nothing would be gained by any such arrangement.

One remedy, however, to be used in the case of alternating currents, was more successful. The arrangement is shown in the diagram.

When two coils, I I', connected as shown, were properly adjusted as to direction of current and relative position, the current induced in the coils neutralized the current induced in the wire in the opposite direction. The objection to this arrangement is the necessity of frequent readjustment of the relations between the coils, and the retarding effect of the coils on both the lighting current and the telephone current.

It seems, therefore, that the idea of correcting these evils and obliterating disturbances after permitting them to be created, must be abandoned. The only way to avoid disturbances is to *prevent* their existence by a proper arrangement of circuits.

Several plans which have been advocated as a cure for the disturbances from electric railways, are also, to some extent, a protection from interference from electric lighting currents; but these plans are more especially applicable in the case of disturbance from electric railways, and are described under that head.

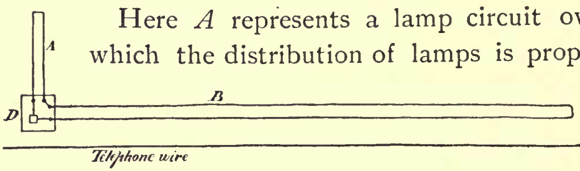
In the arrangement of electric lighting and power circuits with regard to telephone circuits, the first and most important requisite for the prevention of disturbance is distance. If the electric light wires and the telephone wires are only sufficiently far apart, it does not matter what is the arrangement of the lighting circuits. The maximum distance at which induction will be noticed depends upon the system of lighting; that is, upon the rate of variation of the current, and hence upon the winding of the dynamo. This maximum distance, however, is usually not excessively great if the two wires of the electric light circuit are parallel and near together, as is now generally the case. Electric light and telephone wires should not be run on the same side of the street if it can be avoided, and under no circumstances should they be strung on the same poles. Even "steady" currents supplying incandescent lamps may cause disturbance in this case, although, in general, little or no trouble is experienced from this class of currents.

In cases where the two systems are already run parallel and near each other, and where it is impossible to sufficiently increase the distance between them, the disturbances can be reduced to a minimum by a proper arrangement of the lighting circuits. To accomplish this, it is necessary, first, that a return wire be used for the lighting circuit, and that it be placed near and parallel to the outgoing wire. This will not in itself be sufficient to prevent disturbance, if the telephone and electric light circuits are very near together; for both the wires of the electric light circuit cannot be at the same distance from all the telephone wires, and transpositions of the two wires of the former, as practised in the long-distance telephone lines, are manifestly impracticable. A slight lack of balance on the lighting circuit is enough, in such cases, to produce considerable disturbance on telephone wires. This lack of balance is due to an unequal distribution of lamps over the circuit, and if the inequality is great, will result in considerable trouble, however carefully the wires may be arranged in other respects. Both the following conditions, therefore, must, if possible, be strictly observed :

The wires of the lighting circuit must be carried side by side and near together ; and the distribution of lamps must be symmetrical.

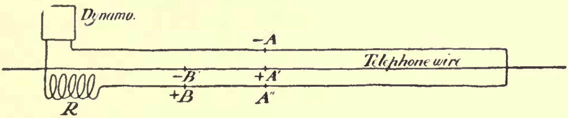
The beneficial results to be expected from a proper arrangement of outside circuits and lamps are often lost, and good intentions frustrated, by the method of connecting in circuits at central stations. It is not infrequently the case that circuits, over which the lamps are properly distributed, are so connected at the station as to make a resultant circuit which is decidedly unbalanced with regard to the telephone wires. An example of this is shown in the diagram, which represents an actual case.

Here *A* represents a lamp circuit over which the distribution of lamps is proper.



B represents a second lamp circuit over which there is likewise a proper distribution of lamps ; and the line of telephone wires runs on the same poles as circuit *B*. When, therefore, circuit *B* is operated alone, there is little or no trouble on the telephone lines ; but when, as sometimes happens, circuit *A* is connected in series with circuit *B*, a decidedly unbalanced circuit results, and a considerable disturbance is caused on the telephone wires.

The action of unbalanced circuits in causing induction may be made clear by the following explanation:

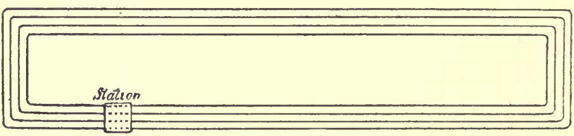


Suppose the telephone wire, in this case, to be equidistant from the two wires of the dynamo circuit, and let *R* represent a resistance or other unbalancing cause in one side of the dynamo circuit. (In practice *R* would be the excess of lamps or transformers on one side over those on the other side.)

Let us consider now a single impulse only. A positive and a negative charge are sent out from the dynamo in opposite directions simultaneously. At a given instant the negative charge has reached the point *A*, and induces at *A′* a corresponding positive charge. If, now, the positive charge (equal to the negative charge at *A*) could reach *A″* at that same instant, the corresponding negative charge would be induced at *A′*; the two induced charges at *A′* would be equal and opposite, and the result on the telephone wire would be *nil*. Owing, however, to the excess of resistance *R*, the positive charge cannot reach *A″* at the instant that the negative charge reaches *A*. The positive charge is, say, at B when the negative charge is at A, and therefore the induced charges do not neutralize each other, and a current results on the telephone wire.*

BELT CIRCUITS.

In the early days of electric lighting, far less care was exercised in running the wires than is now used. No especial pains were taken to run the two sides of a circuit either parallel or near together; and there was one arrangement in particular, known as a "belt circuit" which seems to have been a favorite. Happily for the telephone, this arrangement is rapidly disappearing, but there are still some such lines in use. The method of running belt lines is shown in the diagram, each circuit running perhaps almost

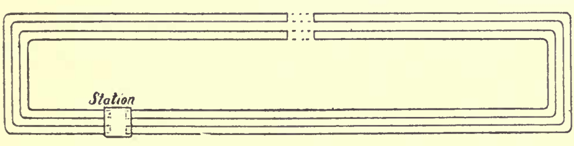


completely around a town, and the lamps being cut in wherever they were located. Any telephone wires running parallel with these belt lines are subjected to the full disturbing influence of the lighting current,

* The explanation by principles of electro-magnetic induction would be exactly similar to that given above for electro-static induction; considering elements of current instead of elements of static charge. That is, the phase of the dynamo current would be delayed more in the B side of the circuit than in the A side, and an induced current would result on the telephone wire.

with no compensating effect from the return wire. It has been claimed by some electric lighting companies that, where a number of belt lines take approximately the same course, the effect from each tends to neutralize the effects from the others. This is, however, rarely the case, the effect from the aggregation of circuits being usually much greater and more annoying than that from one; for it is practically impossible to run the dynamo machines with such regularity that the phases of the current from one shall be exactly, or even approximately, the opposite of the phases from another. The disturbance will rise and fall in volume, in beats, according to the relative speeds of rotation of the armatures.

When there is an even number of these belt circuits running on the same poles, it would be a simple and inexpensive matter to rearrange them into proper metallic circuits, by connecting them up in



pairs in the middle, as shown. The same object could be accomplished also by connecting in pairs at one end, but this would double the number of lamps on one circuit, and would therefore make it necessary to double the electro-motive force at the station, which would be a disadvantage.

There are, therefore, but two ways of avoiding disturbance from electric light circuits.

1st. To use metallic circuits for the telephone lines.

2d. To arrange the electric light circuits according to the following rules:

a. Circuits carrying currents for electric lighting must not be run near telephone wires.

b. Electric light circuits already near enough to cause disturbance, which cannot be removed, must be made up of two wires, the outgoing wire and the return wire.

c. The outgoing and return wires must be placed side by side, and as near together as possible.

d. The distribution of lamps on such circuits must be symmetrical, or approximately so.

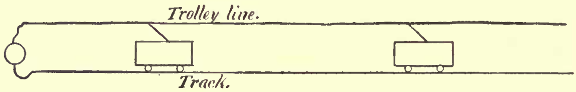
e. No branch circuit should be taken off one side of a main circuit without properly compensating for it on the other side.

Obviously, it will seldom be possible for telephone companies to insist on the observance of the rules just given, and the only entirely feasible way of avoiding all these difficulties seems to be to have all telephone lines made up of metallic circuits.

INTERFERENCE FROM ELECTRIC RAILWAYS.

The electric railway is a comparatively recent development. Many systems of operation have been tried, but the only system that is now extensively in use, or is likely to be for some time, is that using the rails as the return circuit, and known as the "single trolley system." In order that the effect upon the telephone of the operation of such a system may be clearly understood, it is necessary to describe it more fully.

In the single trolley system, a wire of large diameter (from 0''.20 to 0''.32) is suspended over the centre of the track, wherever the cars are to run, and the rails are carefully connected together, electrically, by copper wires riveted into the ends of each rail, bridging across the joints. It has been usual, also, to lay a bare copper wire in the ground near the track, and to connect every rail to it. The object of these rail connections is, of course, to reduce the resistance of the rail circuit, and thus avoid too great a loss of potential; but it is incidentally advantageous to the telephone that the rail circuit shall have a minimum resistance. The positive pole of the generator is usually connected to the overhead line, and the negative pole to the track. It was the practice, in the earlier roads, to carefully ground both the rails and that side of the generator which was connected to them, but this is not always done now. The cars are in multiple, contact being made with the overhead wire by means of a long arm, known as the trolley arm, on the top of the car, and a metal wheel (trolley wheel) running along the under side of the wire. Contact with the rails is made through the car wheels. A constant potential is employed, and it is now the universal custom, on single trolley roads, to maintain the potential at or near 500 volts. The diagram shows the connections.



Even if no pains are taken to make a good connection between the rails and earth, there is at all times a more or less perfect contact. A portion of the railway current, therefore, as it enters the rail from the car wheel, passes into the earth, and through the earth by various paths to the generator. This portion of the current which passes off into the earth is probably comparatively slight; but if it encounters the ground wire of a telephone instrument, it is sufficient to produce in that instrument, and in others connected with it, a considerable disturbance of a rather disagreeable character. The noise produced by the diverted railway current is a harsh hissing sound, entirely different from the sounds produced by induction, and very difficult to talk over.

If telephone wires run parallel with the wires of the railway for any considerable distance, and are sufficiently near, a current will be produced by induction upon the telephone wire. This results in a sound in the telephone similar in character to that produced by arc or alternating currents, but of a different pitch. The pitch of this sound does not seem to correspond to the speed of the generator, nor, in fact, to any sound usually caused by the generator current. Induction from railway current is due to the counter electro-motive force of the motors, and the pitch of the sound produced corresponds to the speed of the motors; the generator current apparently being equalized by the conditions of the circuit. The sound caused by induction is a clear, shrill, ringing sound, not particularly disagreeable to the ear, nor troublesome to conversation, unless very loud.

These disturbances to the telephone from electric railways have led to many controversies between telephone and railway companies, and many devices have been proposed as means of preventing or removing the difficulty. All devices designed to remove the disturbance after it has occurred, are open to the same objection as in the case of disturbance from electric lighting circuits. The most important of the plans for preventing the interference are:

1st. Change of the railway system to double trolley, or complete metallic circuit without ground connection.

2d. Change of the telephone system to complete metallic circuit.

3rd. Common return wire for the telephone system, or "McCluer system."

4th. Change of the telephone system, in part, to metallic circuits, with repeating coils.

5th. Connecting all telephone "ground" terminals together, and removing the earth connections—Wiley-Smith system.

6th. Insertion of a condenser between each telephone instrument and the earth.

THE DOUBLE TROLLEY SYSTEM.

1. In the double trolley system the arrangement is the same as in the single trolley, except that there are two wires overhead, two trolleys, each making contact with one of these wires, and the track is not used as a portion of the circuit. Undoubtedly, the use of the double trolley system would prevent any material disturbance to the telephone, as there is no connection of the railway circuit with earth, except by accident, and the two wires run side by side and near together, thus avoiding any appreciable amount of induction. There is, however, but one city in which the double trolley system just described is running successfully. The leading railway constructing companies refuse to adopt the system, saying that it is not practicable except in very simple cases, and that in the case referred to, in Cincinnati, the road presents such simple conditions of engineering that for that reason only is it possible to operate the system successfully there. It has been found impossible to compel the railway companies to adopt the system; and although this method would be a solution of the problem very satisfactory to telephone

interests, the plan cannot be considered one which it is in the power of telephone companies to apply.

2. The use of metallic circuits for all telephone lines would prove as perfect a means of preventing disturbances from railway currents as the use of the double trolley system by the railways. The arguments already advanced in the case of electric light disturbances apply with equal force to this case, and the only practical objection to the adoption of this system is the cost of installation. It is earnestly to be hoped that metallic circuits will ultimately be used for all telephone lines; for this would not only free the telephone lines from disturbances of all kinds from foreign sources, but in addition to that the lines would be, in some respects, more efficient than grounded circuits.

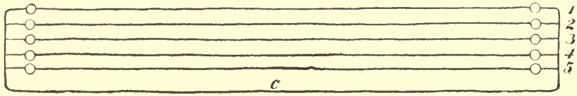
The two methods already described are practically perfect in preventing disturbances to telephones from railway currents. The methods yet to be described furnish but partial protection.

3. The "common return system," or "McCluer system," so called, consists essentially of a wire, of proper size and resistance, strung on the same poles with the telephone wires for which it forms the return. The "ground" wire of each instrument is removed from its earth connection, and connected to this return wire, which is common to all the instruments in the system, and in this respect exactly fulfils the function of the earth.

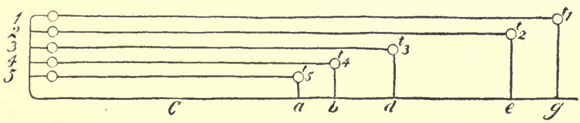
Obviously, if all connection is broken between the earth and the telephone system, no disturbance can take place from conduction of the railway current in its passage from the rails to the power-station, whatever the size or disposition of the common return wire; but somewhat more than this can be accomplished by a proper determination of the size and location of this wire. Assume the resistance of the wire and its location to be such, at each point, that the current induced upon it is always equal to the sum of the currents induced upon all the wires connected with it, then the resultant current in each telephone will be zero, and all disturbance from induction, as well as that from conduction of railway current, will have been eliminated. This happy state of affairs cannot be attained in practice, for reasons which will soon appear, but it can be approached by careful consideration of the conditions met with in each case, and the system can be so constructed as to eliminate a part, at least, of the disturbance arising from induction.

When several telephone wires run together upon a line of poles, it is impossible to place a single wire serving as a return for all, so that it shall be at the same distance as each of the telephone wires from a disturbing wire. If, however, the return wire be run on the same poles as the telephone wires, and at, as nearly as possible, the centre of the group, the variation from actual equidistance will be very slight.

The real difficulty lies in another direction. Suppose 1, 2, 3, 4, 5, to represent a line of telephone

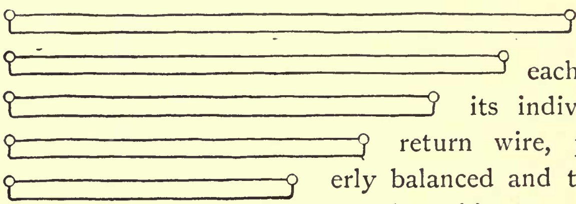


wires, and *c* the common return for them all ; the whole line being subject to induction from a disturbing current of any kind. If *c* be so designed, in size, material, and location, that the current induced upon it is equal to the sum of the currents induced upon 1, 2, 3, 4, 5 ; and if the currents induced upon 1, 2, 3, 4, 5, be exactly equal to each other ; then no disturbance will result in the telephones. Usually, however, the currents induced upon 1, 2, 3, 4, 5, are unequal. Wire No. 1, say, is the longest, has the greatest exposure, and therefore the most disturbance. For similar reasons wire No. 2 has greater disturbance than No. 3, and so on.

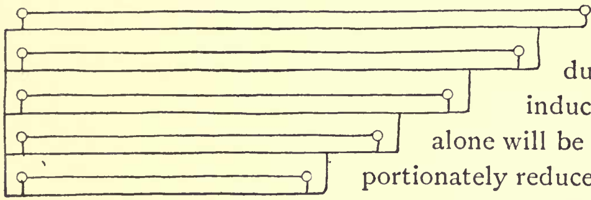


Obviously, then, if *c* be of the same size throughout, the induction from *e* to *g* will more than balance the induction on 1, and a disturbance will result, in t_1. For similar reasons, there will be a disturbance to a less and less extent, in t_2, t_3, and t_4, but none in t_5, if *c* is properly designed for the five wires. For practical reasons it is not convenient, nor is it necessary, to diminish the size of *c* by exactly the proper amount whenever a wire leaves the pole-line. A reasonable approximation to exactness will insure a freedom from disturbance, in all the instruments, sufficient to permit easy conversation. But the proper dimensions of the return wire must be determined with much greater care than has ever yet been used in such a case. It is an engineering problem, and it will not do to put up a return wire by guess-work if good results are to be obtained.

Let us look at it from another point of view. Suppose the same wires, 1, 2, 3, 4, 5, to be provided



each with its individual return wire, properly balanced and transposed, making a system of complete metallic circuits. It will not be necessary to demonstrate that in this case there will be no disturbance from an outside source, for this fact is well known to all telephone engineers. Having such a system, suppose we connect all the individual return wires together. There should be, in this case, no disturbance whatever. And how does such a system differ from a properly designed common return system? Simply in the location of the return with respect to the outgoing wires. We are led, therefore, to the proposition that, a *properly designed* common return wire is practically equivalent, in every respect, to an individual return wire similarly placed. Its use, therefore, will not only prevent disturbance due to earth currents, but the disturbances



due to induction alone will be proportionately reduced as the outgoing and common return wires are more nearly equidistant from the disturbing source.

The proper size to be given to the return wire will be different for different telephone systems. In the closed circuit system, which is the one in most common use, the return wire must be larger than in the Law system, in which the circuits are normally open. In the Law system, the common return wire must be designed for the number of telephone wires likely to be in use simultaneously, which is but a comparatively small portion of the whole number of telephone lines. It is therefore, to some extent, a matter of guesswork to determine the proper size of the return wire, and the common return system cannot, in this case, be made so perfect a protection against disturbance as in the telephone systems using closed circuits, where the number of wires to be provided for is definitely known and is constant.

4. Change of telephone system, in part, to metallic circuits, with repeating coils.

This arrangement is, of course, only a makeshift, and is not to be recommended in cases where it is feasible to have a complete metallic system, or where a large portion of the lines in an exchange are subject to disturbance. Where comparatively few lines are disturbed, however, it can be used to advantage, and satisfactory service obtained by using a combination switch-board. In such cases the disturbed lines are usually all in the same district; and if the daily business in that district is not excessively great, it will not be necessary to provide a great number of repeating coils—perhaps eight or ten. It is perfectly feasible to operate a combination board for such a purpose, the only objection being the slight delay in making connections. After connection is made the service will be as satisfactory as if the railway were not in operation.

The cost of this arrangement depends, of course, on local conditions. When the disturbed lines constitute as much as half the exchange, it will be found cheaper in the end, and more satisfactory in every way, to install the metallic circuit system throughout.

It is unnecessary to describe this arrangement more in detail, as it is exactly similar to that used in cases where metallic circuit trunk lines come into exchanges operating grounded circuits.

5th. Connecting telephone "ground" wires together and disconnecting them from the earth—"Wiley-Smith system."

This system is the cheapest of any that have been named, and has been used with fair success in several exchanges in the West. Its use will obviate all the trouble from conduction of railway currents through the earth, but so far as induction disturbances are concerned, little, if any, relief can be expected from it. It consists in connecting together all the subscribers' "ground" wires, and removing the earth connection; so that the telephone current passing out over a subscriber's line is returned through *all* the other wires together. It has not been found that the use of this method causes any interference of telephone currents with each other.

6th. Insertion of a condenser in the telephone line, between the subscriber's instrument and the earth.

This is a method which can hardly be recommended generally, although it might be of advantage in isolated cases. The result would be comparative freedom from disturbance due to conduction of railway current, and possibly a slight modification of the telephone current, producing a sharper and harsher sound. I know of no instance of the use of this method as proposed.

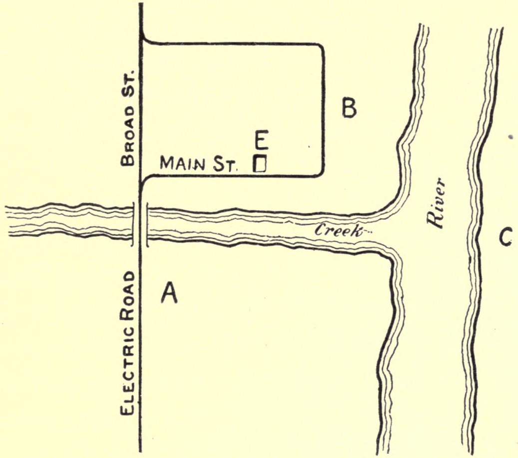
Whenever, then, serious disturbance is caused upon telephone lines by the operation of any circuits carrying heavy currents, it is necessary to adopt some means of preventing the disturbance. If it is possible to so re-arrange the power circuits that they will cause no disturbance, that should be done. If, however, this is not possible, as it generally is not, one of the methods just described must be used; and a careful consideration of the conditions existing in each case will determine just which method it is best and most economical to apply.

In some cases iron rods driven at frequent intervals along the railway track, and connected to the rails, give good results in preventing leakage of railway current. The efficacy of this system, however, must in general depend on the character of the soil. In rocky soil it can be of but little service.

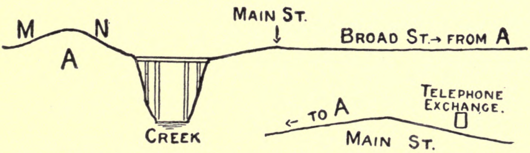
It may be instructive to close our consideration of this subject with an account of an actual case that came under the observation of the author. The situation is roughly indicated in the diagram opposite.

The electric road ran from a distant town, not shown, through the village A, over the creek into the town B, continuing by the straight track to the outer edge of the town. In returning, the cars ran around the loop in B, past the telephone exchange E, and back through A by the straight track.

The greatest trouble was experienced in the B exchange. Here, although the noise on the lines was not troublesome except in rare cases, many of the drops were frequently thrown and held down for some time. Moreover, the conditions were somewhat peculiar and the results unexpected, as it was



not the drops of the B lines which were thrown where the cars were running, but the C drops, connecting with lines grounded at a very considerable distance away from the moving car.



Profile of Road into B and on Main Street.

It was noted that almost invariably, when cars going toward B were mounting the short grade M, in

A, and cars from B were on the grade N, many of the C drops were thrown; and it had been ascertained by experiment that the direction of the current on the affected telephone lines was from C to the Exchange.

When the car was going up Broad Street, a few of the drops in the distant town were thrown, as would be expected, and when the car was on Main Street, passing the Exchange, another set of drops fell.

The reason for the throwing of the C drops by the passage of a car over the grade in A, was probably this: A and C have the same water system. The creek is at the bottom of a deep cut with steep and rocky sides, crossed by a bridge laid with centre-bearing rails. When a car was passing over either of the grades in A, there was no car in B; and owing partly to this fact, partly to the rocky character of the soil, and partly, perhaps, to the fact that the track circuit over the bridge was imperfect, the potential of the track and ground at the hill in A was raised by the passage of a car somewhat above that of the track in B. A current passed, therefore, over the water-pipes to C, upon the telephone grounds, over the lines to the Exchange, and threw the drops, passing out through the central office ground and the grounds of neighboring subscribers. The same effects were observed when the central office ground was removed. This must necessarily have been the case so long as subscribers' grounds existed in the neighborhood, unless the lines were separated at the switch-board beyond the drops.

Several experiments were made on the effect of moving the Exchange ground to different points. When the Exchange ground was moved to a distance of two or three miles into the country, away from the electric road and from C, the trouble with the C drops was entirely relieved, but a number of the B drops fell instead. The Exchange ground was then moved to C, and it was found that only one or two of the drops fell often enough to cause any trouble.

It was proposed by the telephone company that the road should put in the Sabold system of ground rods to avoid the difficulty. In many cases this system would undoubtedly greatly help matters, but the circumstances of each individual case must be considered. In this case the whole country is very hilly, the slopes usually steep; it is underlaid by beds of slate and limestone, and "sink-holes," so-called, are very common. These sink-holes serve to drain off all the surface water which succeeds in reaching the rock, and in fact they do this so thoroughly that the sewage is disposed of by means of sink-holes. It is improbable, therefore, that any particular benefit would have been obtained by the use of the system of ground rods, even if it had been possible to drive them. In many cases this would not have been possible, and in any case probability of reaching a level of permanent moisture in such ground, at any reasonable depth, would have been very small.

MAPPING OUT GROUND POTENTIAL.

In any telephone exchange system, the distribution of potential over the area of ground covered by the system may be very readily found by the use of a direct-reading volt-meter. This practice was inaugurated by the electric railway companies for the purpose of finding the loss in the track circuit; but it was found to give such useful information that it has been adopted by some of the telephone exchanges. To find the potential over a system by this method, connect an ordinary switch-board cord to each terminal of the volt-meter, plug one—usually the negative terminal—into the central office ground, and plug the other successively into the subscribers' lines. The needle of the volt-meter will indicate usually a varying potential; but the average can be estimated with fair accuracy, and the maximum and minimum noted if desired. Having obtained readings from all the lines in the exchange, equipotential lines may then be plotted on a map of the city. As the resistance of the volt-meter is usually high, it is generally unnecessary to correct for the resistance of subscribers' instruments, and a very good approximation is obtained in each case to the difference of potential between the central office ground and the subscribers' ground.

The results obtained in different cases vary very greatly, and depend to a large extent on the nature of the soil. In cities having an electric road with an imperfect track circuit, the difference of potential may rise at times, and on certain lines, to 50 or 60 volts. Where the electric road has a good track circuit and a network of tracks, this difference is usually only a fraction of a volt.

CHAPTER XIII.

PROPERTIES OF METALLIC CIRCUITS.

THE most obvious advantage of metallic circuits over grounded circuits, and the point first looked to in their adoption, lies in the fact that metallic circuits are, and must always be, free from those currents arising from various accidental causes existing outside the circuit. Such currents are continually creeping in on grounded circuits, even when the lines are short; and on long lines a grounded wire is never free from them. It was a necessity, therefore, that metallic circuits should be used if it was expected to successfully transmit conversation over long lines. The other advantages to be gained by the use of metallic circuits were then unknown, or at least not fully appreciated, and were only fully developed after metallic circuits of copper had come into use for the long-distance lines.

In discussing the properties of long distance lines, so called, I shall confine myself to a consideration of trunk lines consisting of metallic circuits of copper wire, as described in a previous chapter, although the discussion will apply, to a great extent, to any metallic circuits of copper, whether trunk lines or not. The mechanical properties of the long distance lines should be well understood from the description already given of the construction of these lines. The electrical properties of any telephone line are:

1. Resistance.
2. Capacity (static).
3. Insulation.
4. Self-induction (retardation).

Retardation may also be considered a property of a telephone line, as it includes some of the effects of both capacity and self-induction; and as it is impossible to separate these effects, we will consider them together as retardation. Let us now investigate these properties in the case of long distance lines, and their effect upon the telephone current.

DESIGN.

It was in connection with the proposed construction of long distance lines that the question of designing the proportions of a line first arose as an electrical problem. If it was desired to transmit speech over a given distance sufficiently well for business purposes, of what size and material must the wire be? What must be the distance of the wires from each other, and how far must they be from the earth? In a word, what values must we give to the properties of the line? As an answer to these questions the empirical rule was deduced from experiment, and supported by some eminent electricians, that the product of the resistance and the capacity must be constant; that is,

$$C R = K$$

where K was given different values according to the transmitter used. R was to be taken without regard to the magnetic properties of the metal used, and C was the capacity measured to "earth." If the line was a metallic circuit, the equation was to be solved for a grounded circuit, and a wire similar to that thus determined was to be run as a return.

RESISTANCE AND IMPEDANCE.

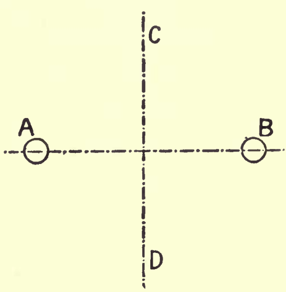
From the consideration we have already given to the telephone current, we see that the impedance offered by a wire to the passage of a telephone current does not necessarily bear any definite relation to its resistance; and we shall see later that the capacity of a metallic circuit does not necessarily bear any definite relation to the capacity of either wire to the earth. Although the formula cited may, as telephone lines are usually constructed, give a very rough approximation to truth, it cannot be considered by any means a basis for accurate calculation.

As the impedance offered by a given wire to the passage of an alternating current depends upon the frequency of alternations, the resistance of the wire becomes of continually lessening importance as the frequency of alternation increases. Hence the resistance of the wire does not come in directly as a factor in determining the volume. Any formula, therefore, in which the first power of R appears alone is mathematically incorrect.

The wire used for long distance lines is hard drawn copper 0.104″ in diameter. This wire has a resistance of about 5.2 to 5.3 ohms per mile; and an impedance for currents of 1,500 alternations per second, only about 1.4 per cent. greater. The average impedance offered by this wire to the passage of telephone currents in which the vibrations range from 200 to 1,500 per second, is practically the same as the resistance, and the difference in impedance for the different rates of vibration is so slight as to be negligible. If the size of the wire is increased, this difference in impedance increases, and in view of the slight effect of pure resistance upon transmission there might be but little gained electrically by lessening the resistance by an increase in the size of wire.

CAPACITY.

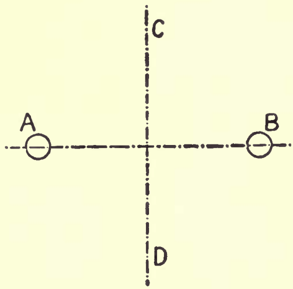
The electro-static capacity is the most important property of a circuit, so far as transmission is concerned. In considering the question of capacity of a metallic circuit, we must always bear in mind that what is meant is the capacity of one wire of the circuit to the other wire. The capacity to earth may be any quantity whatever, so long as it is the same for each wire, without affecting the condition of the two wires as a circuit. For a metallic circuit constitutes a condenser of which each wire of the circuit is one of the plates. Now, the capacity of a condenser depends upon the surface of the plates and their distance apart; and it is unchanged by the proximity of a third plate, provided the third plate is at the same distance from each plate of the condenser. If the third plate be inserted between the plates of the condenser, at the same distance from each plate, the capacity of the condenser is unchanged if the thickness of the third plate be infinitely small. In this case it is necessary to take account of the thickness of the plate only because the distance between the plates of the condenser is virtually diminished by an amount equal to the thickness of the third plate.



Thus in the diagram, if A and B are two wires constituting a metallic circuit, any other wire may be introduced on the line C D without affecting transmission over A B, except when the position of the third wire results in virtually diminishing the distance between A and B. Even then, the maximum effect is that due to the diameter of the wire, which is small in comparison with the distance A B.

Evidently, where the circuit A B is strung on poles, the earth is practically at the same distance from each, and its proximity cannot affect the capacity of the circuit.

The proposition may be generally stated as follows: Given, a pair of wires constituting a metallic circuit. The proximity of any other conductor or conductors symmetrically disposed relatively to it and equidistant from its wires, will not affect its capacity in any way, unless it is so placed, and of such dimensions, as to virtually diminish the distance between the given pair of wires.*



In the case of metallic circuits the presence of any wire lying in the plane C D, will have no effect on the current in A and B. For the potential at C D is always zero, when A and B are charged with equal and opposite quantities. Hence there is no change of potential at C D, due to change of potentials at A and B, so long as the charges on A and B remain equal and opposite. No work is done on C D by the change of current in A

* "Since this spherical surface [in this case of radius $= \infty$, hence a plane midway between the wires and normal to the line joining their centres] is at potential zero, if we suppose it constructed of thin metal and connected with the earth, there will be no alteration of the potential at any point either outside or inside, but the electrical action will remain that due to the points A and B."—Maxwell, § 156.

and B. Therefore the presence of conductors in the plane C D can cause no retardation in the current in A and B.

If the charges on A and B are not equal and opposite — that is, if the metallic circuit is unbalanced, the effect will be to move the plane C D to one side or the other. This will necessitate work by the current in A and B, and will cause retardation in that current.

In the case of metallic circuits upon poles, the distance between the two wires of a circuit is usually great in comparison with the diameter of the wire.* The error involved is therefore very small, if we apply the formula which expresses the capacity of a condenser with flat plates.

$$C = \frac{S}{4 \pi t}$$

where S is the surface of the wires, and t the distance between them.†

As we have seen, in any circuit traversed by telephone currents, the electro-static charges must be rapidly reversed; and this produces an unequal retardation of phase which impairs and destroys the clearness of signals. Another effect of capacity is to reduce the volume, producing interferences of waves which reduce their amplitude. The electro-static capacity of a circuit is the most powerful factor in

* About one hundred and twenty times.

† When the distance between wires is not great in comparison with diameter, this formula does not apply.

reducing the efficiency of transmission; and if the capacity can be diminished the efficiency of the line will be increased.

We can diminish this retarding influence in two ways: The size of the wire can be reduced, thus lessening the surface; or the distance between wires can be increased. This increase of distance can be accomplished either by increasing the length (or number) of cross-arms—which is not advisable for mechanical reasons—or by using as a circuit the two wires farthest apart in the set. This method is of material advantage, and is often employed on the longest lines, when talking is very difficult. In experimenting on the line between New York and Boston, using a circuit about two hundred and fifty miles long, it has been found that the circuit including the pair of wires farthest apart on the poles has an electro-static capacity from twelve per cent. to twenty per cent. less than that of the circuit including a pair of adjacent wires. Both these circuits included also a considerable length of cable whose capacity forms a large percentage of the total capacity of the line; and this portion was, of course, unchanged. As the length of pole-line in use is greater, its capacity is a greater percentage of the total capacity of the line, and the advantage to be gained by this method of increasing the distance between wires becomes proportionately greater.

Retardation, due to electro-static capacity, is less in the case of metallic circuits than on grounded circuits, for two reasons: The capacity of the metallic circuit is usually less than that of the grounded circuit of the same dimensions; and the telephone current is assisted in its work of reversing static charges by the effects of static induction from one wire to the other.

INSULATION.

The insulation of the long distance lines is usually very high. Although the insulator in most common use is a small one, with a comparatively slight length of leakage surface, the insulation frequently measures, in dry weather, as high as 3,000 megohms per mile. In rainy weather it drops to a few hundred thousand ohms per mile — it is generally too unsteady to measure at such times—but, except on very long lines, it is never so low that the leakage seriously interferes with conversation. Although much experimenting has been done in the direction of improving the insulation, the results of experience seem to show that exceedingly high insulation is undesirable on telephone lines. The effect of leakage is to allow a portion of the current to escape, and therefore to diminish the volume. But a slight and well-distributed leakage also allows the static charges to escape, thus clearing the line and diminishing the retardation. The slight loss of volume due to low insulation is more than counterbalanced by the gain in clearness, provided only that the leakage is fairly well distributed over the whole length of line, as is usually the case. A line having an insulation of 4,000 or 5,000 megohms per mile, for instance, will probably not "talk" so well as when its insulation is only four or five megohms per mile, or perhaps even lower.

SELF-INDUCTION.

The self-induction of a circuit made up of copper wire not larger than 0.104″ diameter is very slight. In comparison with the effects of static capacity, the effects of self-induction in the line wires themselves are practically negligible. The self-induction of apparatus which always forms a portion of any circuit traversed by telephone currents is often considerable, and plays a very important part in changing the characteristics of the current; but it cannot be considered here. We are now considering the line itself, without apparatus.*

* The self-induction of aërial wires has not as yet been accurately measured; but the table below gives the results of calculations of the inductance of single wires of copper (calculated by Mr. Kennelly from formula given by Maxwell).

Diameter.		Elevation above ground, 400 cm., 13.1 ft.		Elevation above ground, 700 cm., 23 ft.		Elevation above ground, 1,000 cm., 32.8 ft.		Elevation above ground, 1,300 cm., 42.7 ft.	
Cm.	Inch.	Per kilom.	Per mile.	Per kilom.	Per mile.	Per kilom.	Per mile.	Per kilom.	Per mile.
0.10	0 039	1.986	3.196	2.109	3 393	2.170	3.493	2.222	3.576
0.20	0.079	1.848	2.974	1.960	3.154	2 031	3.268	2.083	3.352
0.30	0.118	1.766	2.842	1.878	3 022	1.950	3.138	2.002	3 222

These results are given in myriametres.

MUTUAL INDUCTION.

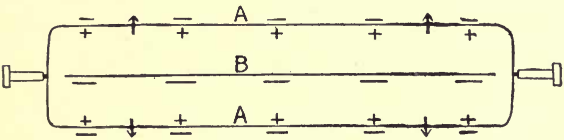
Electro-magnetic induction—what has been called "dynamic" or "kinetic" induction—more properly *mutual* induction—has no retarding influence in a metallic circuit. Although it is very small, its effect is distinctly beneficial. In respect of retardation there is, therefore, a slight gain in the use of metallic circuits, in addition to the freedom from external noise.

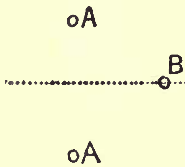
In metallic circuits of copper, then, the effect of self-induction in producing retardation is very slight, and is to some extent counterbalanced by the effect of mutual induction in lessening retardation. The chief cause of retardation, so far as the line wires alone are concerned, is electro-static capacity.

In the use of metallic circuits of iron there is a very considerable retarding effect due to the magnetic properties of the metal. Iron wire is in no case a suitable material for telephone lines.

CROSS-TALK.

Long-distance lines would be, on account of their length, particularly liable to disturbance from cross-talk, were not some means found of preventing it. On circuits one hundred miles or more in length, the effect of static induction, even by so slight a potential as that of the telephone current, would be very considerable; and when from ten to fifty circuits on the same line of poles were working at the same time, the sound produced by induction upon any one circuit would be so confused and so loud that it would be impossible to carry on any conversation at all. There are two cases in which cross-talk will not be produced on a circuit by the passage of alternating or varying currents on a neighboring wire. The first case is when the neighboring wire is at an equal distance from each of the wires of the circuit in question, and may be represented thus



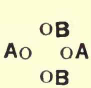


A A is the metallic circuit, and B the third wire. B may be anywhere on the centre line between the two wires. Suppose B to be first charged negatively. Then the induced charges on A A will be distributed somewhat as shown, the positive charge being on the side of the wires A A nearest to B, and the negative charge on the opposite side. When the charge on B is reversed, the induced charges on A A will be reversed also, and a temporary current will flow *across* the wire A. An alternating or varying current in B, therefore, will produce a corresponding alternating current *across* the wire

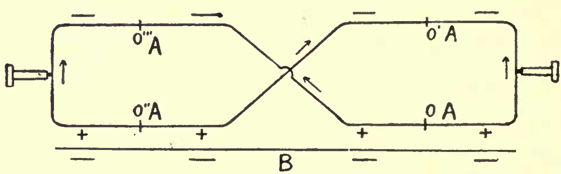
A, but will produce no effect in the wire A longitudinally, and no sound will be heard in the telephones at the ends of the line.

TRANSPOSITIONS.

If it were possible to so string the wires in a line that the condition of equidistance would be fulfilled, there never would be trouble from cross-talk. A short consideration, however, will show that this relation



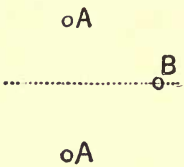
can be maintained for four wires, or two circuits only, as A A and B B. It is therefore necessary to resort to the second method to prevent cross-talk. This case is represented in the diagram.



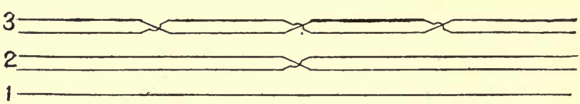
Here B, the disturbing wire, is nearer to one of the wires of the circuit A A than it is to the other, and normally there would be an induced current through the telephones, depending upon the length of the circuit. If, however, the wires A A be crossed or transposed, as shown, the currents will be diminished. In this case the currents may be made as small as desired by increasing the number, and so decreasing the length of the transpositions; and in practice the transpositions are made so short that the current resulting in the telephones is inappreciable.

Suppose B to be charged negatively. The induced charges upon the wires A A are distributed as shown. When the charge on B is reversed, the induced charges flow away in both directions, producing currents as indicated by the arrows. Moreover, as the charges flow away in both directions, there must be, in each transposition, corresponding neutral points, o o' o'' o''', etc., at which points there is no current. In the case of simple wires with no apparatus, these neutral points would be at the longitudinal centre of each transposition; but the introduction of apparatus at the ends of the line causes the neutral points of the end transpositions to move nearer the apparatus. For the retardation of the apparatus tends to prevent the flow of current through it, so that the greater part flows in the other direction through the wires whose retardation is small. The existence of retardation in the apparatus at the end of the line, therefore, makes it possible to use longer transpositions than could be used with simple wires, or with apparatus having no retardation; and the greater the retardation of the apparatus, the longer the transpositions may be without producing any appreciable cross-talk.

There is a third method of preventing cross-talk, more strictly applicable to cables. This consists in twisting the two wires of the circuit about each other. It will be evident, on consideration, that this method combines the features of the two methods just described. In portions of the twisted circuit the relations will be as in the first method; and in other portions the effect will be the same as in the case of transposition.*

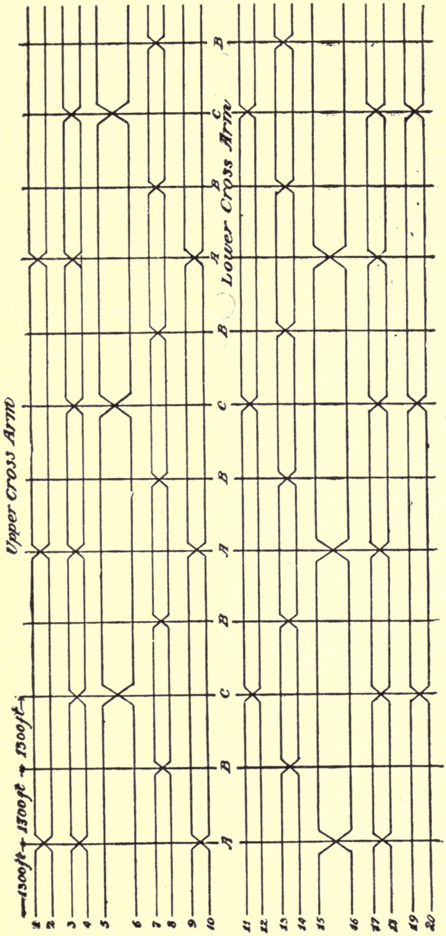


The method of transpositions is the one universally used for pole-lines; and it would seem, from the development of it so far, to be a very simple problem. As the number of circuits on a line of poles increases, however, the difficulty in planning our transpositions increases also. For instance, if we have two circuits it is very easy to so transpose one of them that there shall be no cross-talk. If, however, we have a third circuit and transpose it as we did the second, there will be cross-talk from the second to the third, because their relations to each other are the same as if there had been no transpositions at all. To get over this difficulty we must transpose the third circuit twice as often as we did the second.



A fourth circuit may be transposed at the middle points of the last transpositions, and so on.

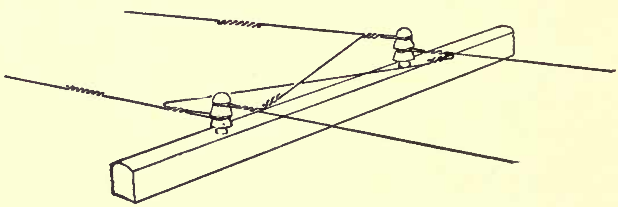
* See Appendix B, for Mr. Carty's experiments on this subject.



Scheme of Circuit Transpositions, New York-Chicago Telephone Line.

In practice it is not necessary that the transpositions for each circuit shall be such that the induction currents are exactly balanced. It has been found possible to use the same transpositions for every other cross-arm; and the wires on the 1st, 3d, 5th, 7th, and 9th cross-arms are therefore transposed in the same way.

It is usual to plan out the transpositions for each set of cross-arms, transposing every twenty or forty poles, that is, about every half-mile or mile. It was formerly the practice to use double cross-arms for making the transpositions, but it is now accomplished on a single arm by using double, or "transposition," insulators.



The "transposition" insulator consists of two single insulators on the same pin, as shown. The lower one has no top, and the pin projects through it, the upper insulator being secured on the top of the pin in the usual manner. In making the transposition the wires are crossed, as shown, or they may be terminated at their insulators and the cross-connections made by insulated copper wire. This form of insulator is mechanically not the best, as the greatest strain is brought on the end of the pin, tending to break it off between the insulators. It seems, however, that the arrangement must have been found to be sufficiently strong, as it is much used.

LOSS IN VOLUME OF CURRENT IN TRANSMISSION.

Some experiments made at the Massachusetts Institute of Technology, on the volume of the telephone current, show that on the line from Boston to New York (about 250 miles), the current at the receiving station is only about one per cent. of that at the transmitting station. These results probably do not accurately represent the conditions obtaining in actual practice, as the resistance (and impedance) of the dynamometer and hand-telephone used was not only much higher than that of the receiving instruments at the end of the line, but was added to the impedance already in the line, thus materially diminishing the strength of the current. Moreover, the sources of sound at the ends of the line were neither identical nor equal, nor is it likely that the transmitting apparatus were of equal power. One telephone transmitter and induction coil will often differ considerably in power from another set after being in use a short time, even if the transmitters were at first adjusted to the same value. Undoubtedly, however, the loss in volume of current in a line of this length is very great. This loss is due, as we have seen, to the combined effects of resistance, leakage, and retardation.

VERY LONG LINES.

The application of the arrangement already referred to, and described later, devised by Dr. Pupin, in which inductances of definite value are placed at carefully determined intervals, should, if successful, prevent great losses. More important, it will avoid the unequal attenuation for different periods and should make it possible to extend commercial service to almost indefinite distance.

Lines considerably more than 1,000 miles long have been in commercial operation for some years past.

The line between New York and Chicago consists of copper wire weighing about four hundred and thirty-five pounds per mile. Such a wire has the advantage of great mechanical strength, and adds much to the stability of the line. It might be even better practice to use a large number of small wires and couple them up in multiple for the long-line service. These wires would have a lower self-induction, for a given amount of copper, than the larger wires, but a greater capacity; and a slightly greater mechanical strength, *provided* they were given the same tension. The cost of construction would be greater with the smaller wires, for a given weight of copper, and they might be liable to more heavy loads from sleet and snow than a single wire of their aggregate weight.

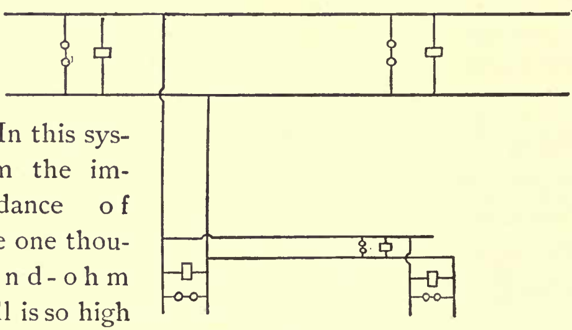
PARTY LINES ON METALLIC CIRCUITS.

In using grounded circuits, when it was desired to place several subscribers on the same wire, it was the custom, and still is to a considerable extent, to "loop in" the several telephones, that is, to place them in series so that any conversation must be transmitted through the coils of all the call-bells which happened to be in the circuit between the subscribers talking. Obviously, in this method, the number of instruments through which easy conversation could be carried on was very limited, and, moreover, the system entailed great annoyance to all subscribers so connected. When metallic circuits came into use, the same method was at first tried, but had to be abandoned almost immediately, as the circuit thus became unbalanced. The method next tried was that of carrying both wires to each subscriber and bridging the instruments across the circuit, as indicated in the diagram.

In this method the bells were wound to a resistance of five hundred ohms each, and placed in series with the transmitting and receiving apparatus. It was found that the talking was cut down materially by a partial short circuiting through the other instruments, and not more than three or four subscribers could be successfully placed on one circuit. Moreover, although it was not necessary to do so, it was the practice to carry both wires of the circuit out and back to a subscriber off the main line, making four wires for each subscriber.

CARTY'S "BRIDGING-BELL" SYSTEM.

A third method has, however, been devised by Mr. J. J. Carty, of the Metropolitan Telephone Company of New York, which overcomes the objections to the first two methods described. It is really a development of the second method, and gives very satisfactory results. In this third method the call-bells are wound to a resistance of one thousand ohms each, and are placed in multiple with the transmitting apparatus, which is, of course, automatically cut out of circuit when not in use. The wiring is all in multiple, as in wiring for incandescent lighting.

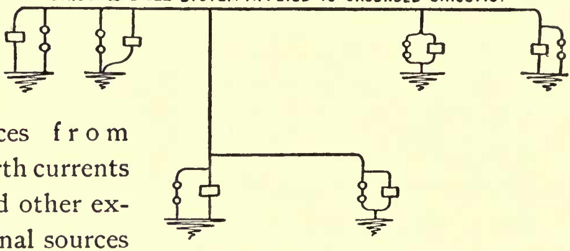


In this system the impedance of the one thousand-ohm bell is so high that it acts as an effectual bar to the passage of the telephone current, and conversation between any two subscribers is practically unaffected by the presence of the bells bridged across the circuit. There appears to be no limit within the range of practice to the number of subscribers who can be connected into one circuit in this way. In several cases in New York City, more than twenty have been placed upon one circuit without detriment to the service. The construction work is simple, less wire is used than in any of the other methods, and additional "extension" bells—that is, bells at a distance from the telephone—may be put in with perfect freedom. In cable work it is possible, by this method, to use one circuit for any number of subscribers, which could not be done by the old methods.

Another development in this system consists in furnishing the subscribers on such circuits with magneto-generators wound for low potential, and making the central office "drop" of low resistance. Subscribers will therefore be unable to ring each other, as their bells are of such high resistance, and all connections and calls will have to be made by the operator. This will obviate many of the annoyances and delays due to the attempts of subscribers, under the old systems, to ring each other without calling the central office operator.

There is one distinctly beneficial effect from this method of bridging. The numerous cross-connections through the bells tend to free the line from static charges and thus diminish its retardation. As the system can be applied to grounded circuits with perfect success, this effect is of considerable importance, as the cross-connections also allow the disturb-

BRIDGING BELL SYSTEM APPLIED TO GROUNDED CIRCUITS.



ances from earth currents and other external sources to escape. A grounded circuit with several bridging-bell connections—a "party line"—may, therefore, furnish better service than it would without these connections.

As an instance I may cite the case of a subscriber who used two lines about fifty miles long, connecting his mill and his office. One of these wires was a party line, having some eight or nine instruments looped in, in series. The other wire ran direct between the two terminal points without additional instruments. Both wires were grounded. It soon became impossible to use the party line at all, except under exceptionally favorable conditions, while the direct wire worked fairly well. When the connections on the party line had been changed according to the "bridging-bell" method, with one thousand-ohm bells, this line gave better service than the direct wire.

CHAPTER XIV.

CABLES.

UNDER this head we shall consider only cables containing metallic circuits of copper. For iron, owing to its manifest unfitness, has never been used in cables, and the cable made up of single wire circuits has now become a thing of the past.

Cables may be divided into two general classes: Those in which the insulating material is of the nature of rubber or some of its compounds, and those in which it is some fibrous material. Although rubber compounds have some advantages over fibre, and although cables with an insulation of rubber are used extensively for electric light work, the high specific inductive capacity alone of this material would be a sufficient objection to its use for telephone cables. Fibre not only has a specific inductive capacity much lower than rubber, but it is also cheaper. As fibre of any kind absorbs water very easily by capillary action, it is necessary to make the fibre cables water-proof by providing a sheath; and for this purpose an alloy of lead and tin has been found most suitable. It was for a long time the universal practice, in making fibre cables, to saturate the fibre with some insulating material which is impervious to moisture. Cotton has been most generally used for the insulation, and the process of making the cable is, roughly, as follows:

MANUFACTURE.

The wire, of copper, 0.035″ in diameter, is first wound with a double insulation of cotton, to a diameter of one-eighth of an inch. Two of these wires are then twisted together, the length of twist being about three inches, and are bound together by a strand of cotton. The desired number of these twisted pairs are then cabled together, and the bunch tightly bound by a winding of cotton. The core, which has been at various stages of manufacture saturated with the insulating substance, is then placed in the sheath, and more of the insulating substance forced in. In cabling, the circuits are placed in consecutive layers about a central core, and the layers are given a slight spiral twist in alternately opposite directions. The insulating material used to saturate the cotton, and the method of applying it, differ with the different manufacturers. It was at one time the practice of some makers to form the sheath separately and draw the core in. That is not done now, but the sheath is formed directly upon the core.

In the cables known as the "Faraday," the cotton insulation is subjected to a process which extracts the sap, and its place is filled with paraffine. In the "Standard" cables, one of the petroleum products is used to saturate the fibre, and in other cables resin-oil, and like substances are used. In the Western Electric Company's cables the core was formerly drawn into the lead sheath, and paraffine and carbonic acid gas (CO_2) forced in under considerable pressure. In a cable since made by that company, known as a "dry" cable, the cotton is unsaturated for most of its length. In making a length of "dry" cable, after the cable core has been drawn into the sheath, carbonic acid gas (CO_2) is first forced in under a pressure of about 75 lbs. to the square inch, displacing the air. Paraffine is then forced in for a distance of about 25 feet at each end, under a pressure of nearly 100 lbs. to the square inch. This prevents the entrance of moisture at the ends in drawing in, splicing, and making connections.

More recently there have come into use cables in which the insulating material is paper. The paper is put on the wire in the form of strips, which may be either wound about spirally or laid lengthwise. In the paper cables made by John A. Roebling & Sons Company, two paper strips are laid on lengthwise, as loosely as possible, being held in place by thread wound about them. This gives a large air-space. The wires are twisted and cabled in the usual manner, and dried with great care. The lead covering is then immediately formed about the cable core by a hydraulic press exerting a pressure of 600 tons. It is found that any small quantity of moisture in such a cable is absorbed and distributed by the dry parts, and provided the sheath does not continually admit moisture, the insulation rises again. Paper cables are made by other manufacturers in a very similar way. It is claimed by some that pressing the lead on cold gives better results.

All cables used in this country for telephone work are made in substantially the same manner as those just described. Their characteristics are the same, and their properties are similar, differing only in degree.

DIMENSIONS OF UNDERGROUND LINES.

Evidently, a metallic circuit of copper in a cable will have the same properties as a metallic circuit in air; but as the proportions of an underground metallic circuit are different from those of an aërial circuit, the inter-relations of the properties will be changed.

Underground circuits must of necessity be used chiefly, if not entirely, in cities. Pole lines can be used in 'cross-country stretches and in the suburbs of large cities; but in the cities themselves overhead wires of all kinds have become so numerous as to be a nuisance, and telephone and telegraph, as well as electric-light wires are being placed underground as rapidly as possible. Here a new problem confronts us. The available space beneath city streets is very much restricted, and the streets are already in many cases pretty nearly filled up with gas-, water-, and steam-pipes, and below them with sewers. It is imperative, therefore, that underground cables should be designed to occupy the least room, and yet possess the greatest efficiency, possible. The fulfilment of these conditions has been a matter of considerable difficulty, and one requiring an extended experience. The specifications of the American Bell Telephone Company embody the best results of the experience of the telephone companies in this country, and practically all the underground cables for telephone use are now made in accordance with them. They formerly called for a conductor of the best Lake Superior copper, 0.040″ diameter and having a conductivity of ninety-eight per cent. of that of pure copper. This wire must be insulated to a diameter of $\frac{1}{8}$ inch, two such wires twisted together, and the length of twist must be between $2\frac{1}{2}$ and $3\frac{1}{4}$ inches. In cabling, the adjacent layers must be given a slight spiral twist in opposite directions, and the cable laid up without compression. The electro-static capacity of a wire must be not more than 0.18 microfarad per mile, each wire being measured against all the others put to earth. The resistance of this wire is about 36 legal ohms per mile.

Many cables, made in accordance with these specifications, have been put down; but the advances in cable manufacture have been so great that the specifications now call for an electro-static capacity of .085 microfarad per mile, with a wire of about 0.035″ diameter. This decrease in the electro-static capacity is due chiefly to the use of paper, and some cables have been made with a capacity as low as .075 microfarad per mile.

PROPERTIES OF CABLES—IMPEDANCE.

The impedance of copper wire 0.040″ in diameter for telephone currents is of course somewhat greater than its resistance, but the difference is so small that its effect is inappreciable. Moreover, in cables, the injurious effect of the resistance upon the current is very slight in comparison with the effects of the other properties of the circuit; and although there is in this case the same action that is always caused by resistance, it needs no particular treatment.

ELECTROSTATIC CAPACITY.

When we consider the capacity of a circuit having the dimensions which have been given, it is evident that we can no longer assume the formula for a condenser with flat plates to apply. The radius of the wire is no longer negligibly small in comparison with the distance between the wires. The capacity of a condenser consisting of two parallel cylindrical conductors, each of radius r, and with a distance d

between their centres, is the same as if the whole charge of electricity on each were concentrated on a line in the plane joining their centres, these lines being at a distance apart $= \sqrt{d^2 - 4r^2}$.

The electro-static capacity of such a pair of wires will then be, if air is the dielectric,

$$\frac{r\,l}{\sqrt{d^2 - 4r^2}},$$

in which l is the length of the circuit. For we may treat the wires as a pair of plates at a distance apart $= \sqrt{d^2 - 4r^2}$. Now the capacity of a pair of plates is expressed by the formula

$$C = \frac{S}{4\pi a},$$

where S is the surface and a the distance between the plates. Substituting for S and a the values in the particular case we are considering, for unit length,

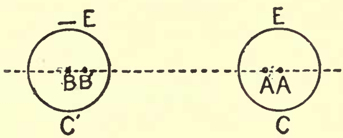
$$C = \frac{4\pi r}{4\pi\sqrt{d^2 - 4r^2}}.$$

For length l, this becomes $\frac{r\,l}{\sqrt{d^2 - 4r^2}}$, which, for convenience of calculation, may be written

$$C = \frac{r\,l}{\sqrt{(d - 2r)\,(d + 2r)}}.$$

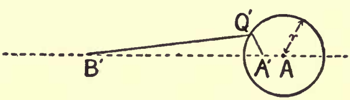
In using this expression for the capacity of a pair of wires, we are assuming that the total surface of the wires acts as the opposing surfaces of the condenser plates. This is not strictly true, but the error involved in the assumption is inconsiderable, for our purposes, and we may in this way compare the capacities of different circuits with entire accuracy.

The derivation of the expression for the virtual distance between the wires is given below.



If C and C′ are two wires, a charge of E on C, and – E on C′, the condenser thus formed has a capacity the same as if the same quantities of electricity, E and – E, were concentrated on lines having projections at A′ and B′, respectively. The virtual distance between the plates is A′ B′ = $\sqrt{d^2 - 4r^2}$, where d = A B.

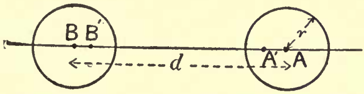
The points A′ and B′ are determined by the method of inversion of electrical images,* as follows:



Let E be a charge concentrated at A. Invert the system with respect to a point B′, making A B′ = mr. Then A A′ = $\frac{r}{m}$.

This is equivalent to a combination of charge E at A′ and a charge – E at B′, which is the image of A′ with respect to the circle. The circle is an equipotential surface with respect to A′.

* See Maxwell's Electricity and Magnetism, § 189, Vol. I.



$$AB' = d - AA' = mr. \qquad m = \frac{d - AA'}{r}.$$

$$AA' = \frac{r}{m} = \frac{r^2}{d - AA'}.$$

$$d\,AA' - (AA')^2 = r^2. \qquad (AA')^2 - d\,AA' = -\,r^2.$$

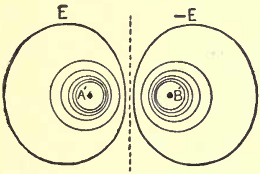
$$AA' = \pm\sqrt{\frac{d^2}{4} - r^2} + \frac{d}{2}.$$

$$A'B' = d - 2AA'.$$

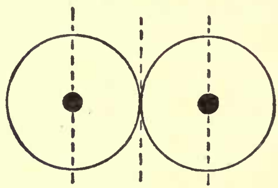
$$\therefore\; A'B' = \cancel{d} \pm 2\sqrt{\frac{d^2}{4} - r^2} - \cancel{d}.$$

$$A'B' = \sqrt{d^2 - 4r^2}.$$

The meaning of this may perhaps be more clearly seen if the problem is attacked in another way. Suppose we have two lines, A′ and B′, having upon them equal and opposite quantities of electricity, E and — E. Draw the system of equipotential surfaces. Then we may distribute the charge E upon any one of the surfaces



around A′ without in any way changing the action at B′; and we may distribute the charge — E upon any one of the surfaces around B′ without in any way changing the action at A′. If, therefore, we start with two equal and opposite charges on equipotential surfaces around A′ and B′, respectively, the effect is the same as though those charges were concentrated on the lines A′ and B,′ for which the surfaces are equipotential. Now, the surfaces of the two wires of a metallic circuit are two such equipotential surfaces; and the effect of equal and opposite charges of electricity upon these wires is the same as though the charges were concentrated along the lines A′ and B′. We could find by this method the capacity of any pair of wires, whether equal or unequal, and bearing any relation to each other; but as, in cable work, the two sides of the metallic circuit are similar, it is unnecessary to investigate any other cases.



In cables made up of twisted pairs, the dimensions are as shown in the sketch, where $d = 0.125''$ and $r = 0.020''$. The points A′ and B′ will, therefore, be situated at a distance apart $= \sqrt{(0.125'')^2 - 4\,(0.02)^2} = 0.119''$, which is the virtual distance between the plates of the condenser. Evidently the thinner the insulation the greater will be the relative diminution in virtual distance, provided r remains the same.

In what has preceded we have considered those cases only in which the dielectric separating the wires is air, but in underground cables this is never the case. The capacity of the condenser formed by a metallic circuit in a cable will be K times the capacity of an exactly similar circuit with air between the wires, as determined by the formula given above, where K is the specific inductive capacity of the insulating material used in the particular case under consideration. Moreover, it has been found by experiment that the specific inductive capacity for alternating currents of the character and period used in telephony is usually different from that determined by means of single static charges, as are those given in most text-books.

Comparatively recent experiments on this subject have given the following results for the dielectrics named, the specific inductive capacity of air being taken as 1. In parallel columns are the values given by Dr. Jenkin for the same substances:

	Values of K. (Jenkin.)	Telephonic. (Jacques.)
Air	1.0	1.0
Resin	1.77	
Pitch	1.80	
Beeswax	1.86	
Glass	1.90	4.6
Sulphur	1.93	
Shellac	1.95	
India rubber	2.8	3.7
Vulcanized rubber	3.1	
W. Smith's gutta-percha	3.59	3.9
Gutta-percha	4.2	4.2
Mica	5.0	
Paraffine	1.98	2.0
Petroleum		1.6
Cotton saturated with paraffine, in vacuo		2.0
" boiled in paraffine		2.6
Water		6.3

Evidently, in using cables we are at a great disadvantage in regard to capacity as compared with pole lines, for two reasons: The wires must, of necessity, be very much nearer together than in the case of overhead lines, and the dielectric separating them must, in addition, have a specific inductive capacity considerably higher than that of air. We have seen that the effect of capacity is in any case very injurious to transmission; and in cables, where the capacity is comparatively very high, it is necessary to take every means of keeping the capacity low. This can be done in several ways:

1st. By separating the wires widely.

2d. By reducing the surface.

3d. By using a dielectric with a low specific inductive capacity.

4th. By making the insulation low, so that the charges can unite and have no effect in retarding succeeding impulses.

All these methods can be used to some extent, but a wide separation of the wires necessitates large cables, and, therefore, large conduits. The surface has already been reduced somewhat by reducing the diameter of the wire from 0.040″ to 0.035″. As the virtual distance between wires is practically unchanged, this means a reduction of capacity in proportion to the surface. The first method named cannot be used for cables of this class.

The third method named furnishes one of the most obvious means of improving the transmission through cables, and much attention has been devoted to it. Various processes have been invented for treating the fibre insulation, or the material with which it is saturated, so as to reduce the capacity. The best results would be attained, however, by the use of air or other gas as a dielectric. Obviously, air alone cannot be used, for the wires must have a nearly continuous support to keep them at a constant distance from each other, but air can be used in part by making the insulation to consist of dry cotton or other fibre, which is more or less loose in texture, although sufficiently firm to keep the wires in place. It is essential, however, that a cable so made shall be very thoroughly sealed, for the slightest moisture would be readily and quickly absorbed by the dry fibre. The so-called "dry" cable and the paper cables, already described, are intended to fulfil these requirements, the gas under pressure in the main portion of the cable keeping out any moisture that might tend to be absorbed through minute crevices, and the paraffine under pressure at the ends serving to keep in the gas and maintain its pressure, as well as to keep out the moisture. "Dry" cables are also made by other methods, but if successful, the result is accomplished in the same way.

The fourth method mentioned, that of keeping the insulation low, has been employed with success in cable making. As has been pointed out, a moderate leak, well distributed over a line, is an advantage, as it allows the small static charges to unite, thus clearing the line and reducing retardation. It is necessary, however, that the lowering of the insulation shall not be due to the presence of moisture; for in that case the insulation resistance would soon begin to fall rapidly, and this would continue until the cable became useless. The presence of moisture in a cable, causing low insulation, can be detected by the rise in capacity; for moisture, if present in small quantities, increases the capacity. This is ascribed by some to an increase in the specific inductive capacity of water, for rapidly varying currents, over its capacity in the case of a single charge; but it seems more probable that the effect is really due to the fact that the presence of many small globules of water virtually reduces the distance between the wires.* Suppose, in the figure, A and B are the plates of a condenser. The distance AB, in Fig. 1, is in Fig. 2

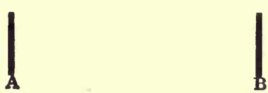


FIG. 1.

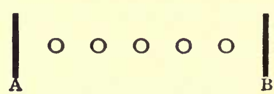


FIG. 2.

reduced by the sum of the diameters of the globules of conducting or partially conducting liquid between

* For a mathematical treatment of this point, see The Newtonian Potential Function, B. O. Peirce, pp. 125 to 127.

the plates. It is possible that both these causes are operative.*

INSULATION.

The question of insulation is of importance chiefly because of its relation to retardation. Very high insulation is distinctly a disadvantage so far as clearness in transmission is concerned; and with a low insulation the loss from leakage is usually more than counterbalanced by the gain in clearness, unless the leak amounts almost to a short circuit. This rarely happens unless the cable has been injured mechanically.

SELF-INDUCTION AND RETARDATION.

The effect of self-induction alone, in each conductor of the dimensions usually employed in underground telephone cables, is very slight. The retardation, however, including the effects of both self-induction and capacity, is considerable. The effect of electro-static capacity upon the telephone current has been shown, for the general case, and the usual relations in the case of overhead lines have been dis-

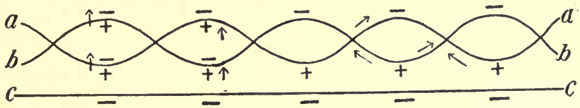
* The increase in specific inductive capacity for rapidly varying currents may be only apparent. In a substance of very low conductivity, the more rapid the alternations of charge, the more nearly would the conditions approach those of a dielectric. With very rapid alternations, the impedance would be enormously high, the charges would be able to neutralize each other but slightly, and the effect would be an *apparent* increase in the specific inductive capacity.

cussed. We see also, from the formula and development, that in the case of cables the electro-static capacity is very much greater than in overhead lines; so much so that in a complete trunk line from one exchange to another, including a few miles of cable at each end, and many miles of pole line between, the retardation in the relatively short length of cable is much greater than in the long stretch of overhead line. As has been pointed out in discussing metallic circuits, any changing about of circuits—easily accomplished in the pole line—while it may materially reduce the retardation due to the pole line alone, has but slight effect on the retardation of the whole circuit, as that due to the cable is so large a portion of the whole.

The relative dimensions of cable circuits and overhead lines should therefore be determined, so as to reduce the cable retardation as much as possible, even if the resistance is thereby increased somewhat. For while the capacity of the cable is a large proportion of that of the whole line, its resistance constitutes but a small portion of the whole.

CROSS-TALK.—TWISTED PAIRS.

Owing to the proximity of the wires in cables, there would be a great deal of cross-talk, were not some means taken to prevent it. The most effectual means yet tried for preventing cross-talk is the twisting of the two wires of the circuit about each other. When this is done, the action, in a twisted pair, due to a disturbing current in any third conductor, is twofold,* being a combination of the actions which take place in the case of transpositions, and of those occurring when the disturbing wire is equidistant from the two wires of the circuit.



If *a* and *b* constitute a circuit, and *c* is a disturbing wire, there will be, at each change in *c*, a slight *transverse* flow of current in *a* and *b*, and a flow of current from one twist to the next, as well. These two actions are shown in the figure separately, in two parts of the circuit.

Although the twisting of the two wires of a circuit about each other is practically a remedy for cross-talk, it is possible for cross-talk to occur between two circuits, even in a cable made up of twisted pairs. This can happen only when the two circuits have exactly the same length of twist, and when they are so laid in the cable that these twists lie just side by side. It would be perfectly possible, if desirable, to arrange that in any one cable no two of the circuits should have the same length of twist; or, the circuits

* See Appendix B.

could be slightly displaced in the direction of their length.

In any form of twisted circuits there is a slight increase of both capacity and resistance over those existing in the case of straight lines, owing to the greater length of conductor used in making the twist. In the ordinary form of twisted pairs the increase from this cause is only about one per cent.; but when the circuits are cabled tightly, so as to lie as close as possible, there is an increase of capacity, due to the compression of the insulation at and near the points where the wires cross each other. By this compression the distance between the two wires of a circuit is diminished, and the capacity, therefore, correspondingly increased. To remedy this fault it was determined to cable the pairs loosely, without attempting to force them to lie close. By this practice, although the increase in capacity is avoided to a large extent, the size of the cable for a given number of circuits is correspondingly increased, and it is not possible to put so great a number of circuits in a duct of given size.

CONCENTRIC CABLES.

"Concentric" cables have been used to some extent in Europe for telephone service. A concentric cable consists of a wire surrounded by a cylindrical mass of insulating material, in the usual manner, the insulation being in turn surrounded by a thin tubular conductor. Around this second conductor is a thin covering of insulation. The central wire forms one side of a metallic circuit, and the tubular conductor the other side. So far as its relations with outside currents are concerned, the concentric cable gives the most perfect protection from disturbance, and is the ideal form. It is objectionable, however, for telephonic work, as it has a very high electro-static capacity, and consequently great retardation.

The capacity of a concentric cable is given by the following formula:

$$C = \frac{l}{2 \log \frac{a'}{a}},$$

where a and a' are the radii of inside and outside conductors, respectively.

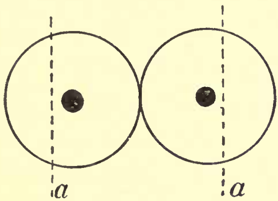
It will be found, therefore, in comparing a concentric circuit with a twisted circuit—the inside conductor of the concentric circuit being of the same diameter as each of the conductors in the twisted circuit, and the thickness of insulation between wires being the same—that the concentric circuit has a far greater capacity, although a somewhat less resistance. The comparatively great capacity of the concentric circuit is so serious an objection as to prohibit its use, notwithstanding its advantages in some other respects.

EFFECT OF CAPACITY IN RECEIVING AND IN TRANSMITTING.

In the use of long lines made up of both aërial lines and cable, it has been noticed that the effect of the cable upon the current is more injurious when the cable is at the receiving end of the line than when it is at the transmitting end. There have not, to my knowledge, been any measurements made upon this phenomenon, and its existence has been doubted. It seems probable, however, that it does exist, as it has been observed independently in many separate instances. No really satisfactory explanation has ever been offered; but the most plausible is, that at the transmitting end of the line the electro-motive force is higher, and consequently the retardation of the cable is overcome with less degradation of the current than when the electro-motive force is low, as at the receiving end of the line.

SPIRALLED PAIRS.

We have seen, in the consideration of metallic circuits, that the capacity of a circuit is not affected by the proximity of external conductors, provided such external conductors are equidistant from the two wires of the metallic circuit, and provided also that the relations are such as not to virtually diminish the distance between the wires of the circuit. In cables made up of twisted pairs, each circuit is made up of two wires independently insulated, and then twisted about each other.



The cross-section is of this form. Obviously, from the considerations advanced above, the insulation outside of the vertical lines *a a*, is useless for the purpose of increasing the distance between the conductors of the circuit and outside conductors. No great distance is here required, as it is only necessary to provide that outside conductors shall be, on the average, at equal distances from the two conductors of the circuit. This is accomplished by the twist. If, therefore, the circuits can be so laid up as to avoid the use of any but a thin insulation on the outside of the wires, while at the same time preserving the original distance between them, it will be possible to put into a cable of given external diameter, a greater number of circuits so made, than of twisted pairs; while the efficiency will be the same in each case. Or, for a given number of circuits in a cable it will be possible to increase the efficiency of each circuit, if laid up according to this new method, over that of twisted pairs.

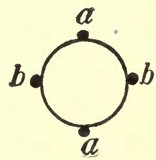
This is accomplished in the following manner: *

A core of insulating material is first chosen, of diameter equal to the distance which it is desired to maintain between the wires of a pair, and about this

* Devised by the author.

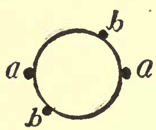
core are spiralled a number of strands of suitable insulating material, the two wires of the circuit being wound in place of two diametrically opposite strands. The whole is then wound with a layer of cotton, jute, or other suitable material, sufficient for proper insulation and for mechanical protection.

By an extension of the same idea we may wind four wires on the core instead of two, the wires *a a* constituting a pair, and being equidistant from the wires *b b*, which make up the other pair. Evidently this will not increase the diameter in the least, and will enable twice as many circuits to be placed within a sheath of given diameter as can be placed there when but two wires are wound on a core. Each circuit will, nevertheless, in the method of "spiralled fours," have the same properties as a spiralled pair of the same dimensions.



Although, in a twisted circuit, the two wires are, *on the average*, at equal distances from all surrounding or external conductors, they are not so equidistant at all points of their length. It may be that the distance between different pairs cannot be absolutely neglected in its effect upon transmission, even when no diminution of the virtual distance between the wires of the pair is thereby produced; and it may be, therefore, that the retardation in any twisted circuit, which is at some points very near to other conductors, is somewhat greater than it would be were the second circuit removed. This effect, however, must depend, in amount, upon the length of twist; and for the length of twist employed in cables it cannot be great.

In making cables of "spiralled fours" it will be necessary to lay up the circuits with considerable care. If the four wires are so wound about the core that one pair is not on the average midway between the other, as in the figure, cross-talk is sure to result.



The only way to prevent this trouble is to use care in laying up the circuits, so that *a a* shall be just half-way between *b* and *b*.

FUTURE IMPROVEMENTS.

Up to a recent time all experiments and improvements on cables have been made with a view to finding some dielectric of very low specific inductive capacity, or some means by which the linear distance between wires could be increased.

The careful and complete experiments carried on by Dr. Hertz on the propagation of electrical impulses, have been a great incentive to further and extended experiment by many workers along the same lines; and have led to the complete development of the mathematical side of the subject—a work with which the name of Heaviside is perhaps most prominently associated. The latest development promises to be of the most far-reaching importance. It is that already referred to as due to Dr. Pupin, and a more extended account follows.

TELEPHONY OVER CABLES AND LONG-DISTANCE AIR LINES.

Abstract of a portion of a paper read by Dr. M. I. Pupin before the American Institute of Electrical Engineers, May 18, 1900.

WAVE-PROPAGATION OVER UNIFORM CONDUCTORS.

Transmission of electrical energy over conducting wires is a *wave*-transmission when the distance between the transmitting and the receiving apparatus is sufficiently long to permit the development of electrical waves. Such a transmission exists in long-distance telegraphy and telephony.

The conditions of wave-transmission and of ordinary electrical transmission are different. In ordinary transmission over comparatively short lines, the reactions set up in the receiving apparatus are the most important reactions which the force impressed by the transmitting generator has to overcome. The reactions in the line itself are comparatively unimportant.

If, however, a long transmission line is involved, the transmission is no longer direct. The energy is first stored up in the medium surrounding the line and thence is transferred, with some delay, to the receiving apparatus. While stored in the medium, it exists there partly as magnetic energy stored in the field of magnetic flux and partly as electrical energy stored in the field of electrical flux. The process of propagation consists in the progressive transformations of the magnetic into the electrical energy and *vice versa.* When the electromotive force impressed by the transmitting generator is periodic, the propagation will be in the form of a continuous series of harmonically varying electrical waves.

The expression "electrical wave" is nothing more nor less than a brief statement of the physical fact that, in the case under consideration, the energy which at any moment is stored up in the medium surrounding the transmission line, is distributed periodically over this line. The current and the potential also vary periodically. At points of maximum magnetic energy the current is maximum, and at points of maximum electrical energy the potential is maximum. Roughly speaking, points of maximum current are points of minimum potential and *vice versa.*

WAVE-LENGTH.

Consider now the distance between any two consecutive points of minimum current or minimum potential. This distance is a half wave-length. Suppose the impressed electromotive force is a simple harmonic of frequency 600 periods a second. Suppose the wave-length is found to be 18 miles. The velocity of propagation will be 10,800 miles per second. This is much less than the velocity of light, but it must be remembered that this is not a case of propagation in free space. The velocity of propagation of electrical waves of telephonic frequencies over conducting wires may be anything from the velocity of light in a vacuum down to a few inches, or even less than an inch, per second, in accordance with the inductance, resistance, and capacity of the line. The less the velocity, the shorter, of course, the wave-length for a given frequency. The *wave-length*, then, may be considered one of the characteristic constants of wave-propagation.

ATTENUATION CONSTANT.

The other constant which, with the wave-length, completely defines electrical wave-propagation, I call the *attenuation constant*. Consider two consecutive half wave-lengths at any moment. The energy stored in the medium about A, the one nearer the transmitter, is greater than that in the medium about the other, B. Therefore wave-energy is gradually dissipated during its propagation from the transmitting to the receiving apparatus, and both current and potential diminish in amplitude as the energy progresses.*

The degree of attenuation, or the amount of decay of the current, may be determined from the *attenuation constant*, which depends upon the resistance, capacity, and inductance of the line, as well as the frequency of the impressed electromotive force.

The fact that a conductor possesses inductance and capacity shows that the medium surrounding it is capable of storing energy; it cannot possibly signify that energy propagated along it will be dissipated. The dissipation is due to imperfect conductivity of the wire and to that alone. Inductance and capacity regulate it, but do not cause it. The dissipation of energy will be diminished by increasing the inductance of the wire, for with high inductance, relatively small currents are sufficient to transmit a given quantity of energy, and small currents incur but small resistance losses.

* The ratio of the current amplitude at a distance s to that at the transmitting end, if the length of the line is infinite, is

$$\frac{U_s}{U} = e^{-\beta s}$$

in which e is the base of Napierian logarithms. β is called the *attenuation constant* and its value is given by the expression

$$\beta = \sqrt{\tfrac{1}{2} n C \left[\sqrt{n^2 L^2 + R^2} - n L\right]}$$

in which n is the frequency-speed,

C is the capacity, } per unit length.
L is the inductance, } per unit length.
and R is the resistance, } per unit length.

DISTORTIONLESS WAVE-CONDUCTORS.

Another important advantage is gained by increasing the inductance. Attenuation depends on frequency and increases with it. Hence, in telephonic transmission, where waves of complex harmonic frequencies are propagated over the line, there will be distortion of the waves because upper harmonics will be attenuated more vigorously than the lower frequencies. This results in a distortion of speech, which is noticed in long-distance telephonic transmission as defective articulation. High inductance obviates this difficulty.* All frequencies are attenuated alike, so that high inductance not only diminishes attenuation, but also renders the circuit distortionless. Such a circuit is the ideal circuit for telephonic and telegraphic wave-transmission.

WAVE-PROPAGATION OVER NON-UNIFORM CONDUCTORS.

Mr. Oliver Heaviside was the earliest advocate of wave-conductors of high inductance, but his proposition to employ such conductors contained a serious difficulty. It is this: How can a wave-conductor be constructed so as to have a high inductance? Ordi-

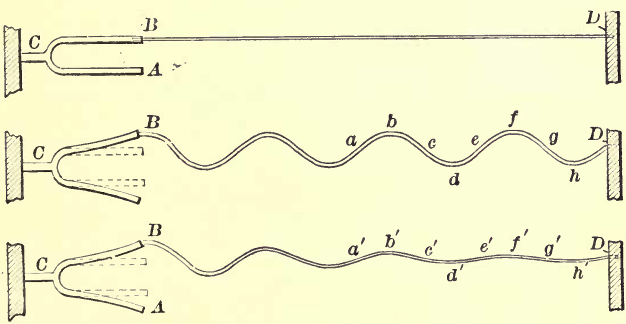
* Suppose the inductance is large in comparison with the resistance

$$\beta = \frac{R}{2}\sqrt{\frac{C}{L}}$$

and the attenuation is independent of the frequency.

nary circuits can be endowed with as much inductance as may be required by simply introducing a coil of proper dimensions, with or without an iron core. This will not do in the case of a wave-conductor; for a coil introduced that way will act by reflection as a barrier to electrical waves. Wave-propagation experiments over long wave-conductors containing a certain number of coils in series at periodically recurring points have actually been tried by telephone engineers, with invariably disappointing results. The cause of such failures and the main features of the mathematical theory of wave-propagation over such conductors may be made clearer by a simple mechanical illustration.

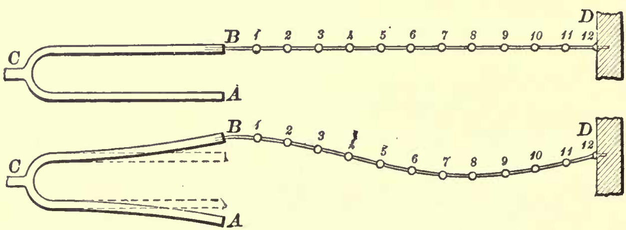
Suppose a tuning-fork, with its stem rigidly fixed, to have a flexible cord attached to one of its prongs,



the other end of the cord being attached to a rigid support. Let the fork vibrate steadily. The motion of the cord will be a wave-motion, which, if the frictional resistances are small and the frequency properly adjusted to the length of the cord, will take the form of standing waves. The direct and the reflected waves in this case will be of nearly the same amplitude. But if the frictional resistances are not small, there will be dissipation of the propagated energy, the amplitudes will not be nearly equal and their interference will therefore not produce stationary waves.

Experiments will show that other things being equal increased density of the string will diminish attenuation, because a larger mass requires a smaller velocity in order to store up a given quantity of kinetic energy, and smaller velocity brings with it a smaller frictional loss. This is a striking mechanical illustration of a wave-conductor of high inductance. It should be observed here that an increase of the density will shorten the wave-length.

Suppose now that we attach a weight, say a ball of beeswax, at the middle point of the string, in



order to increase the vibrating mass. This weight will become a source of reflections and less wave-energy will reach the point *D* than before. The efficiency of transmission will be smaller now than before the weight was attached. Subdivide now the beeswax into three equal parts and place them at three equidistant points along the cord. The efficiency of wave-transmission will be better now that it was when all the wax was concentrated at a single point. By subdividing still further the efficiency will be still more improved; but a point is soon reached when further subdivision produces an inappreciable improvement only. This point is reached when the cord thus loaded vibrates very nearly like a uniform cord of the same mass, tension, and frictional resistance.

If an increase in efficiency of wave-transmission over a cord thus loaded is to be obtained, it is evident that the load must be properly subdivided and the fractional parts of the total load must be placed at proper distances apart along the cord, otherwise the detrimental effects due to reflections resulting from the discontinuities thus introduced will more than neutralize the beneficial effects derived from the increased mass.

The problem of finding the proper distance at which the loads should be placed is a definite mathematical problem of Analytical Mechanics, but unfortunately it was never solved. The figure represents a cord carrying loads at proper distances apart. Experiments with cords of this kind will soon convince one that the distance between the loads should be considerably smaller than one-half of the wave-length of the wave which is to be transmitted. So that though a given cord may be properly loaded for some wave-length it will not be properly loaded for shorter wave-lengths. It is impossible to load a cord in such a way as to make it equivalent to a uniform cord for all wave-lengths; but if the distribution of the loads satisfies the requirements of a given wave-length it will also satisfy them for all longer wave-lengths. It should be observed now that the wave-length which is considered here is not the wave-length of the cord without the loads, but the wave-length which the frequency under consideration will have on the properly loaded cord, or what is the same thing, on a uniform cord of the same mass, tension, and frictional resistance, as the loaded cord. This point is of fundamental importance, for the wave-length corresponding to a given frequency may and generally will be much shorter on the loaded cord than on the cord without the loads.

A cord of this kind is a mechanical analogy to an electrical wave-conductor. The mathematical law in accordance with which such a cord moves is the same as that in accordance with which the electrical current is distributed over the wave-conductor under the action of similar forces. The reason for that is not far to seek. We have the same reactions in both cases, viz.: Kinetic or mass reaction, tensional reaction, and resistance reaction in the case of the cord. Electrokinetic reaction, capacity reaction, and ohmic resistance reaction in the case of the wave-conductor. The mathematical form of these reactions is the same in both cases, hence one is an exact analogy of the other.

The insertion of inductance coils at periodically recurring points along the wave-conductor produces the same effect upon electrical wave-transmission as the distribution of the small loads along the stretched cord produces upon mechanical wave-transmission along the cord. The mathematical theory of wave-propagation over non-uniform conductors of this kind is at the same time the mathematical theory of wave-propagation over a loaded cord described above. The main object of this theory is to find an answer to the question : *Under what conditions are non-uniform conductors described in this paper equivalent to their corresponding uniform conductors?* The answer which the mathematical theory gives to the question just proposed is definite. To formulate it introduce here a convenient technical term. Consider the distance between the two consecutive inductance points, that is, the points at which the inductance coils are introduced. Denote it by l and let the wave-length which is to be transmitted be λ. Now introduce an angle ϕ such that

$$\frac{\phi}{2\pi}=\frac{l}{\lambda}.$$

The angle ϕ is called the *angular distance* between the points at which inductances are inserted. 2π is an angular distance of a wave-length. The law determining the degree of equivalence between a non-uniform conductor and its corresponding uniform conductor can be stated as follows:

A non-uniform conductor is as nearly equivalent to its corresponding uniform conductor as sin. $\frac{\phi}{2}$ is to $\frac{\phi}{2}$.

Evidently, to attain the same degree of equivalence for different wave-lengths, the distance between inductances must diminish as the wave-length diminishes.

If a wave of complex harmonic frequency, such as occur in telephony, be transmitted over a non-uniform conductor, then the action of the conductor will be different for the different components of this complex harmonic wave. If, however, the non-uniform conductor acts with sufficient approximation as a uniform conductor toward the highest important frequency of this complex wave, then its approximation to a uniform conductor will be even closer for the lower frequencies and hence for all the frequencies of the wave.

Considering, as a numerical example, a cable 250 miles long, of the usual dimensions, having no inductance, resistance of 9 ohms per mile and capacity of .074 microfarad per mile; if it is required to make the attenuation constant .015, a choice of coils of 9 ohms requires an inductance of .056 henry. The attenuation at the end of the cable, 250 miles away, would be, roughly 2 per cent., which is sufficient for telephonic purposes; but better results could have been reached by using higher inductance.

The next step is to find the wave-length for the highest important frequency in telephony—750 periods a second—over a *uniform wave conductor* having the same values for resistance, capacity, and inductance as the non-uniform conductor assumed above. This wave-length is found to be 14.6 miles.

If, now, a reactance coil of inductance $L = .056$ henrys and resistance $R = 9$ ohms be placed at each mile, the difference in attenuation between this non-uniform conductor and the corresponding uniform conductor will be less than one per cent. Such a difference could not be detected in practice.

In submarine cables, the attenuation constant should be much smaller, and the capacity of such a cable is comparatively high. Therefore the inductance per mile must be high and the wave-length will be comparatively short. This means placing the coils near together, perhaps less than 1,000 feet apart.

The rules enunciated, and followed in computing the numerical examples, were fully supported by experiments.

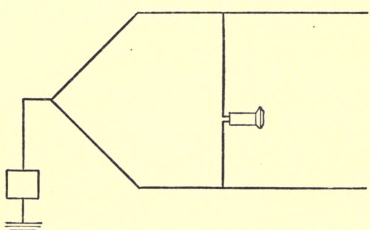
CHAPTER XV.

"COMPOSITE" WORKING AND WIRELESS TELEPHONY.

"COMPOSITE."

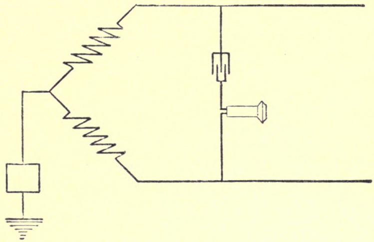
SIMULTANEOUS Telegraphy and Telephony over the same wires, or "composite," as it is called, has always been an attractive subject for experiment. In spite of the thought and labor which have been and are still being expended upon this branch, however, surprisingly few successful devices have been brought out.

The bare skeleton of the method is very simple. Telegraph and telephone currents can be sent over

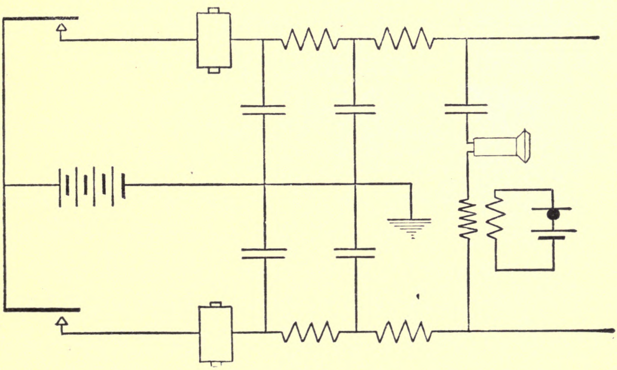


the same wires without confusion. In such an arrangement of circuits, therefore, as shown in the cut, the telegraph impulses, giving no potential difference at the terminals of the telephone, would produce no sound in the telephone circuit.

To insure independence it would be necessary to insert retardation coils in the arms of the telegraph circuit and a condenser in the telephone circuit; and in adapting the method to actual service, it is found necessary to insert other condensers and coils at different points.



Of the various systems of simultaneous telegraphy and telephony which have been devised, the one which has operated with the greatest success is that due to Van Rysselberghe. The connections are shown in the diagram.



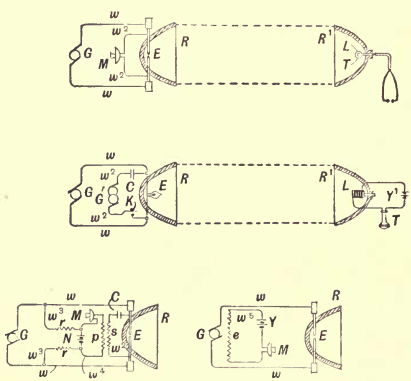
Van Rysselberghe.

The coils should be made of low resistance and high retardation.

WIRELESS TELEPHONY.

The problem of telephoning without wires is an old one. It was attacked in the early days of telephony, without success, but is now likely to be solved in accordance with the present methods of wireless telegraphy. A method slightly different from this was offered a few years ago by Hayes and Cram of the American Bell Telephone Co.

The radiophone, as the instrument is called, employs the light from an electric arc, preferably, for transmission, the energy of the arc being varied in accordance with the sound waves by the use of a transmitter connected in one of the ways shown. These



energy-waves are received by an absorbing substance of great sensitiveness—lampblack enclosed in a tube or perhaps a selenium cell—which reproduces the sounds at the microphone transmitter. A parabolic reflector is used at each station.

It does not seem likely that the radiophone can be used to any considerable extent, although conditions can readily be conceived in which such an instrument would be extremely useful. It does seem likely, however, that wireless telephony, growing out of the developments in wireless telegraphy, will be an accomplished fact within a reasonable time. Indeed, several inventors have already announced their success; but such announcements are usually not accompanied by a description of the method.

PREECE'S METHOD.

Sir William Henry Preece has been experimenting in this direction since 1894, and states that "wireless telephony across the sea is now a practical and commercial system." He has used the regular telephone instruments, the communication being between two long wires separated by a distance not large in comparison with the length of the longer wire. Preece's method, therefore, appears to be based upon the more familiar inductive action between wires. By the stretching of a term, it may be called a "cross-talk" method. It is not the method from which the greatest results are to be anticipated. In the wireless telephony of the future, the transmitting source will be of high power and the exciting wire or body of a size insignificant in comparison with the distances over which messages are sent.

APPENDIX A.

OSCILLATIONS.*

IF a state of strain is established in any body, when the stress producing that strain is removed the body returns to a state of equilibrium. But in returning to equilibrium, if the body has mass, its property of inertia causes the point of equilibrium to be passed, and a strain is thereby set up in the opposite direction. In this way oscillations are caused which would continue indefinitely, were it not for the fact that the medium in which they take place possesses the property of *viscosity*. That is, it offers a resistance to the motion, in virtue of friction or some analogous property. A most familiar example is that of the pendulum, whose oscillations gradually die away, owing to the viscosity of the air. In this case the strain is set up, probably, in the ether, and tends always to a minimum, which exists when the distance separating the pendulum from the earth is a minimum. If the viscosity of the medium through which the motion takes place is sufficiently great, there

* For the material in this Appendix I am indebted to the works of Dr. Lodge and Dr. Fleming.

will be no oscillation, but the point of equilibrium will be slowly reached and not passed.

When a condenser is discharged through a conductor the energy runs down in the form of an electric current. This may or may not be oscillatory in character, according to the conditions of the discharge circuit. The most exact analogy * to this action is that of a loaded spring, bent aside in a resisting medium and let go. Gravity is therefore not concerned in the motion. The elasticity of the spring then corresponds to the capacity of the condenser, its displacement to the electric charge. The load, or inertia, corresponds to the self-induction of the circuit, and the viscosity of the fluid to its resistance. It can readily be seen, then, that, according to the relations between the inertia of the spring and the viscosity of the fluid, the motion will be oscillatory or not.

A knowledge of the character of oscillatory impulsive discharges leads naturally to a consideration of protectors against lightning. Extended experiments by Dr. Oliver Lodge show us very clearly the conditions often existing in lightning discharges.† The principle on which "lightning arresters," so called, are usually designed, is generally pretty well understood, and is, briefly, that an impulsive discharge of

* Pointed out by Dr. Lodge.

† For a full account of these experiments see London "Electrician," Vol. XXI., pp. 234, 273, 302.

high potential will rather jump a small space of dielectric than traverse a circuit having self-induction. To this end the ground wire from the plate arrester must be such as to carry off the energy from the dielectric as rapidly as possible, and dissipate it as heat where it will do no harm. From our knowledge of the method of origin of electric currents, we can see that surface of conductor is more important than cross-section. Therefore a tape or ribbon conductor, one made up of many small wires separated from each other, is better than a solid rod. It appears, also, that iron has advantages over copper for this purpose. It would naturally be supposed that iron would be inferior to copper, on account of its magnetic permeability; but, as such discharges as we are considering are very rapid indeed, they penetrate but a very small distance into the conductor. Moreover, as the rate of change of the discharge current is very great, there are eddy currents produced in the surface layers which are in phase nearly opposite to the discharge current, and hence shield the inner layers from magnetization. The inductance of the iron is therefore not increased by its magnetic permeability beyond what it would be if the metal possessed no such property. The high resistance and high fusing-point of iron are advantages, as they enable an iron conductor to dissipate safely a greater amount of energy than a copper conductor of the same dimensions.

Any conductor possessing sensible inductance tends to produce side flashes to any other conductor which is connected to earth. This is on the same principle as the operation of the common lightning arrester.

There are two notable ways in which lightning discharges take place. The first is when the strain between the cloud and earth is gradually increased until the elastic limit is reached and the cloud sparks directly to earth. In such cases points are of advantage in *preventing* discharge by relieving the strain, a slight but fairly continuous discharge taking place from the cloud to the point, sometimes visible as a brush at the point. In the second case, the strain exists between two clouds, or between a cloud and some distant point. When this strain is broken down, the balance is destroyed at other points, the difference of potential instantly becomes enormous, straining the dielectric beyond its limit, and secondary discharges take place, which may be more severe than the primary discharge. In such a case the point affords no protection, and conductors of any shape are struck indiscriminately. The longer secondary discharge indicates that oscillations are set up. The hydraulic ram is a somewhat imperfect analogy to this case. Here the water is discharging through an orifice, the valve leading to which is suddenly closed. This creates a rebounding wave of pressure which, joining with the incoming wave, will force the liquid to a height greater than that from which it originally fell.

The impedance offered by a conductor to sudden discharge is even higher than its impedance for slowly periodic currents. For enormously rapid oscillations, the impedance to impulsive discharges is proportioned to the frequency, and depends on the form and size of the circuit, but not at all on its specific resistance, magnetic permeability, or diameter. Dr. Lodge found the impedances of a No. 2 wire and a No. 40 wire, two and a half metres long, bent into a circle, to be as follows:

	No. 2. Ohms.	No. 40. Ohms.
12,000,000 oscillations per second.....	180	300
3,000,000 " "	43	78
250,000 " "	4	6
0 (steady current)	0.004	2.6

Hence we may conclude that for frequencies as high as those of lightning discharges, there is but little difference in the impedance of all reasonably conducting circuits. The impedance is entirely unaffected by conductivity and permeability, and scarcely at all affected by considerable changes in diameter.

APPENDIX B.

INDUCTIVE DISTURBANCES IN TELEPHONE CIRCUITS.*

BY J. J. CARTY.

IT was not known until 1838 that the earth might be used instead of a return wire in the circuit of a telegraph line. This fact was discovered by Steinheil, while making experiments to determine whether the track of a railroad could be used to complete the circuit instead of a return wire. Steinheil's discovery has been considered as one of the most important in the art of telegraphy, and since his time it has been the almost universal practice to use the earth as a return in telegraph circuits. When, however, the earth return is used with the telephone, it is found that, owing to the extreme sensitiveness of that instrument, many foreign currents, which would produce but little effect on telegraph instruments, become a source of serious trouble. For this reason, in telephony it is often necessary to use a complete metallic circuit. Thus it has come to pass that a re-

* A paper read at the Fifty-fifth Meeting of the American Institute of Electrical Engineers, New York, March 17, 1891. Reprinted by permission.

turn to the original practice of employing metallic circuits, as in the case of the crudest telegraph instruments, is now regarded as a most important improvement in connection with that most highly developed of telegraph instruments, the telephone.

To obtain complete freedom from inductive disturbances in the telephone, it is necessary not only to use a metallic circuit, but to place the two wires composing the circuit in a special relation to the source of disturbance. One of the methods of so arranging the wires is shown in Fig. 1.

In this case the two sides of the circuit L^2 and L^3 are twisted spirally about each other, so that their average distance from the disturbing wire L^1 shall be the same. With such a plan, the telephones *a* and *b* are not affected by induction from the wire L^1. This fact has usually been explained by assuming that a current, commencing to flow in L^1, tends to induce two currents in the opposite direction to

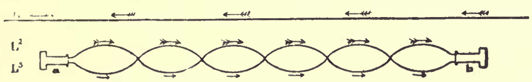


FIG. 1.

itself, one in the wire L^2 and the other in the wire L^3; that both currents are of the same strength, because the average distance of L^2 and L^3 from the disturbing wire L^1 is the same; and that the telephones *a* and *b* are silent, because they are acted upon by two equal and opposite forces. The above theory seems at first sight to be correct, and indicates the line of explanation adopted in many works treating of the subject.*

I have made a number of experiments which seem to prove that, in the case described, the inductive action, instead of tending to produce a simple current in each side of the metallic circuit, actually does produce a number of different currents in each wire and in both directions.

In Fig. 2, L^2 and L^3 are two well-insulated copper

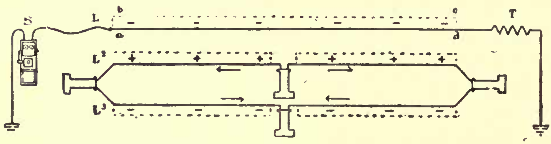


FIG. 2.

wires, five hundred feet long and three feet apart. These wires are joined together at each end through an ordinary telephone. L^1 is a well insulated wire similar to the other two and placed within one-half an inch of L^2. At one end of L^1 is placed a Blake transmitter T, and at the other end is placed a subscriber's bell S; L^1 being grounded at both ends as shown. When the transmitter T is operated, either by speaking into it or by vibrating a powerful tuning-

* "A Handbook of Practical Telegraphy," R. S. Culley, 1885, p. 330. "The Telephone," Preece & Maier, 1889, p. 134. "Die Technik des Fernsprechwesens," Dr. V. Wietlisbach, 1886, p. 135.

fork in front of it, disturbances are produced at the end telephones.

If telephones are inserted at the centre of L^2 and L^3, it is found that at those points no sound is heard, while the noise of the end telephones continues as before. This constitutes a simple case of inductive disturbance, and can only be explained by assuming that the wire L^1 acts electrostatically upon the circuit composed of L^2 and L^3, or, in other words, that we are dealing with a system of condensers in series, of which L^1 constitutes one plate, the earth another, and the wires L^2 and L^3 two intermediate plates, which are joined together through the end telephones.

Let us assume that at a given instant the height of potential along the wire L^1 is represented by the lines *a b* and *c d*, and the charge upon L^1 by the rectangle *a b c d*. The presence of this charge, which we will say is of the minus sign, is accompanied by an equal but plus charge on L^2. This produces a minus charge on the wire L^3, which in turn acts upon the earth. Now we will assume that the potential on L^1 is reduced to zero. This causes a restoration of the equilibrium in the circuit composed of L^2 and L^3, which is accompanied by a set of currents as represented by the arrows. The plus charge on L^2, flowing through the end telephones, neutralizes the minus charge on L^3, thus leaving a neutral point at the centre of each of the wires L^2 and L^3.

In this and the succeeding experiments the induced charges are represented by rectangles. This is not a strictly accurate method, but as an error in this respect only affects the result quantitatively, and cannot alter the conclusions, I have adopted it on account of the simplicity of treatment which it permits.

The potential along the wire L¹ at a given instant is represented as being constant, as it is found that, owing to the high impedance in the instruments, there is practically no fall of potential in the wire itself. Furthermore, it was found in the experiments about to be described that the results were the same whether the disturbing wire was open or connected to earth through the bells. There would be a fall of potential along the wire L¹ if it were of such a length as often found in practice, and the distribution of the charge would be modified accordingly. But as this fact would only affect the location of the neutral points, the question of the fall of potential will not be taken into consideration, and the disturbing wire will be shown open at one end.

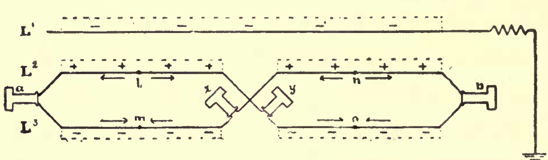


FIG. 3.

Fig. 3 shows the same circuits as used in the previous experiment, except that the wires L² and L³ are caused to change places at their centres, but are continued in the same plane, as in Fig. 2. This is what is called a "transposition." The telephones at the ends and in the middle are retained as before. Under these conditions, when the transmitter is operated, a diminished sound is heard at *a* and *b*; and *x* and *y*, instead of being silent, as in the first case, now emit a sound of the same intensity as *a* and *b*. When telephones are placed at the quarters, *l*, *m*, *n*, *o*, the sounds at *a b* and *x y* continue as before, but nothing is heard at *l*, *m*, *n*, *o*. The effect of this one transposition has been to reduce the disturbance at the end telephones *a* and *b*, and to cause a shifting of the neutral points from the centres to the quarters, and an increase of their number from two to four.

An examination of the induced charge shows how these results have been brought about. It will be seen by reference to Fig. 3, that there is on the first half of L^2 a positive charge, and on the second half a negative charge, and on the first half of L^3 a negative charge, and on the second half a positive charge. When the positive charge on L^2 discharges, half of it goes through the telephone *a*, and half through the telephone *y*. The positive charge on L^3 escapes in a similar manner, half going through telephone *x*, and half through telephone *b*. This produces four currents, two starting from point *l* and two starting from the point *n*. One of the currents from *l* meets a current at *o*, coming from the point *n*, and one of the currents starting at the point *n* meets a current at *m*.

which started from *l*. The currents flowing through the end telephones in this case are not so strong as when no transposition is employed, because they are due to an induced charge which is represented by an area half as great. It is found that as the number of transpositions is increased, the number of neutral points is also increased, and that the area representing the charge which escapes through the end telephones is reduced. To obtain silence, therefore, it is necessary to increase the frequency of transpositions until the discharge through the end telephones is so small as not to produce sounds therein. Fig. 4 shows a circuit containing three transpositions, one at the centre and one half-way between the centre and

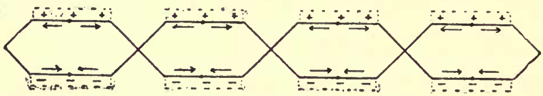


FIG. 4.

each end. In this case, if we could neglect the resistance of the telephones, the current going through the ends would be reduced to one-fourth of its original proportions, and eight neutral points would be produced, one in each wire at the centre of each transposition.

In practice the impedance of the telephones must be taken into consideration, so that, if in Fig. 3 the middle telephones *x* and *y* were omitted, the neutral points would be found to move toward the ends, and the currents flowing through the end telephones would be correspondingly reduced.

According to this theory of transpositions, if the instruments and distances between wires on a given circuit remain constant for a given period of alternations in the disturbing wire, the number of transpositions necessary to obtain silence will depend on the E. M. F. of the disturbing wire, and the specific inductive capacity of the dielectric. An increase in the value of either of these factors will, if silence is to be maintained, require additional transpositions, their number depending upon the value of the change which is made.

Where the disturbing wire is placed at an equal distance from both sides of a metallic circuit, no noise is produced in telephones located in that circuit, and a balance once being obtained, it is independent of both the E. M. F. of the disturbing wire and the specific inductive capacity of the dielectric. Fig. 5 shows such an arrangement of circuits—L^2 and

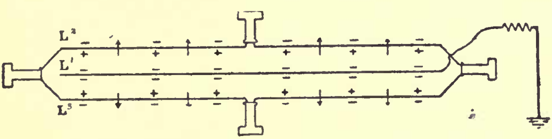


FIG. 5.

L^3 are the two wires composing the metallic circuit placed the same distance apart as before, and the disturbing wire is at an equal distance from both

When the disturbing wire is in operation, no sound is heard at the end telephones, or at telephones located at the centres. This may be accounted for by assuming that at a given instant a negative charge is on the disturbing wire, which produces a positive charge on the inside of L^2 and L^3 and a negative charge on the outside of those wires; and that when the charge is removed from the disturbing wire, a set of currents is set up in the wires L^2 and L^3 in a direction at right angles to their axes, as shown by the arrows. In this case the flow is lateral, and no current passes through the end telephones or through telephones located at the centres. It will thus be seen that this method of arranging wires differs essentially in its action from the plan of using transpositions. Unfortunately, however, its practical application is limited to two circuits.

Where the disturbing wire occupies the position shown in Fig. 5, the flow in the conductors is lateral only when the wires L^2 and L^3 are insulated from the earth. If a ground be attached to the centre of L^3, as shown in Fig. 6, the flow of current becomes longitudinal, and the telephones *a* and *b* are found to be affected by loud disturbances, while the telephone *x*, at the centre of L^2, is found to be silent. This is because the disturbing wire, which we will say is negatively charged, induces a positive charge upon L^2 and L^3 and a negative charge upon the earth. The discharge in this case is effected by two currents starting from x, which thus becomes a neutral point, and passing through the end telephones to the

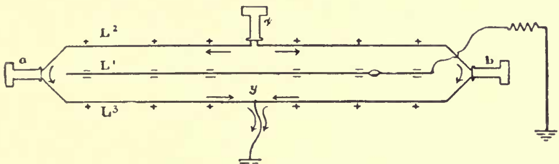


Fig. 6.

ground, as shown by the arrows. If the ground be removed from the point y toward the telephone a, the neutral point will be found to move toward telephone b, and if the ground be put at the centre of resistance of the telephone a, the neutral point will be found to be at the centre of the telephone b. This is well illustrated in Fig. 7, where a and b are telephones of special construction, admitting of the attachment of grounding keys K^1 and K^2 at their respective centres. In this instance, when the disturbing wire is in operation and both keys open, no sound is heard at any of the telephones, the flow of current being lateral. If the key K^1 be closed, sound is immediately heard at telephones x and y located at the centres of L^2 and L^3, but the telephones a and b are still silent. This is because the charge and discharge take place along the conductors L^2 and L^3 to and from the earth at K^1, thus passing through x and y, a being silent because the currents go through it differentially, and b is silent because it is located at a neutral point. To prove that current flows through telephone *a*, another telephone may be inserted in the ground branch at K^1, and it will be found to be loudly affected. If both keys K^1 and K^2 are closed, silence is again obtained in the four tele-

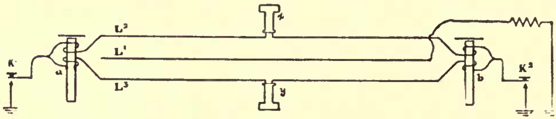


FIG. 7.

phones *a*, *b*, *x*, *y*. In this case the charge and discharge from the wires L^2 and L^3 divide at the centre and flow back and forth at both ends, *x* and *y* being silent because they are at neutral points, and *a* and *b* are not affected by the currents which flow through them because of the differential action referred to.

Two systems have now been described, one in which the induced current is lateral, and the other in which it is longitudinal. I think it follows from the foregoing experiments that where wires are twisted about each other, as shown in Fig. 1, both of these actions are combined. At the left hand of

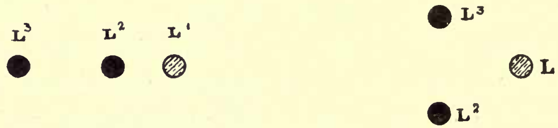


FIG. 8.

Fig. 8 a cross-section of the three wires L^1, L^2, and L^3 [Fig. 1] is shown. In this position the wires occupy a place with reference to each other exactly as in Fig. 2, and the tendency of the disturbing wire is to cause a longitudinal flow in L^2 and L^3. If repeated cross-sections of these wires are made, a point will be reached at which the three wires are disposed as shown at the right hand of Fig. 8, where it is seen that the disturbing wire L^1 is at an equal distance from L^2 and L^3, and the tendency is to produce a lateral flow. The actual currents produced must be the resultant of these two actions.

Fig. 9 shows a plan quite different in principle from anything heretofore employed. It is of interest not so much on account of any practical application which it may have at present, but because it is a very striking proof of the electro-static nature of inductive cross-talk between telephone circuits. L^1,

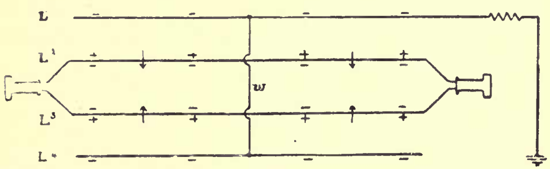


FIG. 9.

L^2, and L^3 are the same wires as used in the previous cases, L^1 being half an inch from L^2, with the addition of an extra wire, L^4, placed half an inch from L^3 and joined by a conductor *w* with the disturbing wire L^1. L^2 and L^3 are three feet apart. When in this condition the transmitter is operated, no disturbance whatever is heard in the end telephones; if the wire *w* be disconnected, the usual noise is heard, but is found to disappear as often as L^1 and L^4 are joined together. This action is explained by the fact that L^4 is at the same potential as L^1, on account of being joined to it by the wire *w*, and acts with the force on L^3 that L^1 does on L^2. The flow in this case is lateral, as indicated by the arrows; and the telephones are silent.

Neutral points may be produced in a circuit by the use of shunts. Fig. 10 shows the usual arrangement of circuits with the telephones *a* and *b* at the ends, and another telephone *x*, of equal impedance, branched between the two wires at the centre. In this case four neutral points are found, two in each wire. The

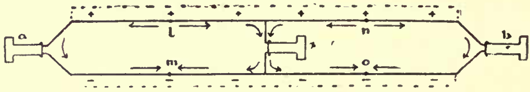


FIG. 10.

currents produced by the discharge are indicated by the arrows. Thus, by the addition of one shunt, the disturbing currents in the end telephones have been reduced one-half. If similar shunts were placed at the quarters, the currents at the end telephones would be still further reduced to one-quarter of their original strength.

This plan is not a practicable one, because of its shunting effect on the telephone current, but is of value as showing one of the actions which occur when instruments are bridged into metallic circuits. It is interesting to note that in Fig. 10 the telephone x is affected by a current twice as great as that which flows through either of the end telephones.

Before closing I shall describe one more experiment. In Fig. 11, L^1 is the disturbing wire and L^2 is a grounded telephone circuit placed half an inch from L^1. At the centre of L^2 there is an ordinary

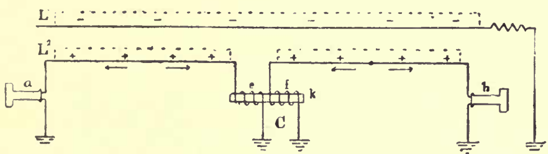


FIG. 11.

telephone repeating coil or transformer, C, containing two windings, *e* and *f*, of copper wire, each having a resistance of 160 ohms. One end of each winding is grounded, and the other end is connected to the line as shown. Assuming that the impedance of each telephone is equal to that of each coil of the transformer, a neutral point will be found at the centre of each half of L^2, and the disturbing currents flowing through the end telephones will be only half as strong as though the transformer were omitted. If, now, the connections of the transformer be reversed so that the discharges from the two sections of line pass through it in opposite directions, no magnetism will be produced in the core *k*, and consequently the transformer coils offer an easier path to the discharge.

This causes the neutral points to move toward the end telephones, and consequently reduces the disturbance still further.

I have not had an opportunity of trying this experiment with a transformer whose coils contained a lower copper resistance and a high inductance, but according to theory we might expect that such a transformer having its coils connected differentially, should free a grounded line of considerable length from cross-talk and other electro-static disturbances. The number of such coils which can be worked in a given line is of course limited, but with properly designed apparatus a large number of them might be used. This arrangement is also interesting when considered with reference to electro-magnetic induction, and brings to mind a question as to whether we may not at some future time abandon the use of metallic circuits and again make use of Steinheil's discovery.

In the discussion on this paper, Mr. Thomas D. Lockwood, although acknowledging that Mr. Carty was correct in attributing a large share of the disturbance to electro-static influences, yet maintained that insufficient importance was given to the effect of electro-magnetic induction. He said, also, that while the twisted metallic circuit "is indeed a specific against electro-magnetic inductive disturbance, it also tends to increase the retarding effect of electro-static induction exercised between the two wires of the circuit." The correctness of this view may be very seriously questioned.

Mr. Lockwood further calls attention to the fact—which had long been recognized, and which was mentioned by Mr. Carty in a previous paper—that an electro-static charge, *while it is changing*, is an electric current. The action must therefore be a compound one, and electro-magnetic induction must be a factor in causing disturbances.

This same point was mentioned by several others who took part in the discussion. It is not denied by Mr. Carty, and in fact he has in several places distinctly stated that electro-magnetically induced currents must exist. His experiments, however, show quite clearly that in comparison with electro-static influences, under the conditions usually met in practice, the electro-magnetic induction is negligibly small. His account of further experiment sustaining him in this view was as follows:

" I will now show what I consider the most favorable condition for creating electro-magnetic induction

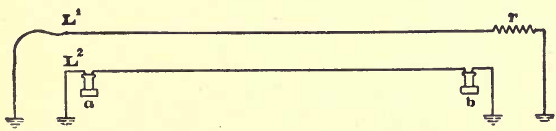


Fig. 12.

between two telephone wires. That [indicating T, Fig. 12] represents the coil of a long-distance transmitter sending the most powerful telephone current that it is now possible to generate. L^1 represents the wire connected to earth. It may be, we will say, 200 feet long. Parallel to it, and an eighth of an inch away, we will place another telephone circuit. These wires may have an insulation of 10,000 megohms, and the resistance might be considered as one ohm. Now, a current resulting from a given note in the transmitter through the wire L^1, produces a series of changes in the magnetic field surrounding it, and that action is roughly explained by assuming that the current starting in L^1 induces a current in L^2 in the opposite direction, and that the induced current will flow through both telephones *a* and *b*. Now, it is a fact that under those conditions absolutely no sound is heard in the telephones *a* or *b*.

"That represents the strongest current that it is possible to produce by that transmitter—the strongest changes—and consequently we should have the greatest fluctuation in the magnetic field surrounding the wire L^1; but under those circumstances there is absolutely no disturbance whatever effected in the telephones *a* or *b* located in L^2. That, I think, is a crucial test.

"Now, I will describe an experiment which I made with those same wires. We will open the wire L^1 (Fig. 13) at the far end. Then, when the transmitter is operated, noise is immediately found at the telephones *a* and *b*, located at the ends of the second ary wire, and if a telephone, *c*, be located at the exact centre of impedance it will be found to be silent. When the wire L[1] is opened at the far end we have the maximum electro-static and the minimum elec-

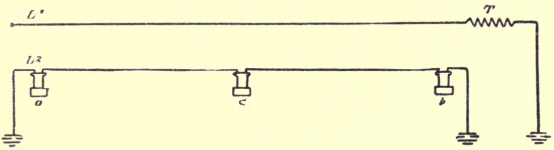


FIG. 13.

tro-magnetic action; when it is closed we have the maximum electro-magnetic action and the minimum electro-static action. The reason that the electro-static action is slight in Fig. 12 can be seen from Fig. 14. Assuming that *m n* represents the height of po-

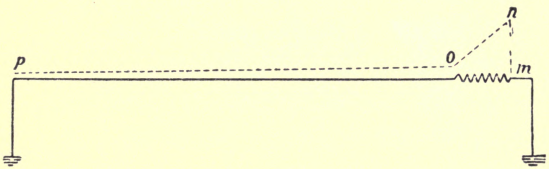


FIG. 14.

tential of the transmitter, the resistance of the circuit is mostly in the transmitter, and the fall of potential therein is very sudden. At any point along the wire L[1] the potential would be practically zero, as shown by the dotted line *o p*.

" I wish to show another experiment in proof of the fact, or what I think is a fact, that electro-magnetic induction is negligible when we consider the action that goes on between two telephone circuits. I expressly limit the statement to the action between telephone circuits, and I am not discussing disturbances in general, but merely inductive cross-talk. Now, I will draw a line—L^2—(Fig. 15), similar to the

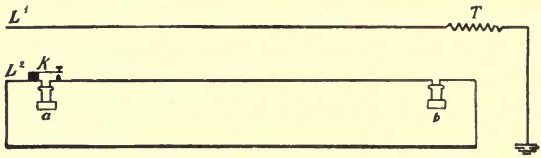


FIG. 15.

one I used before, and we will assume that the circuit is completed by a return wire of no resistance, or of very low resistance, entirely outside of the field of disturbance, so as to eliminate all questions of leakage through the earth. We will say that L^1 is grounded on a gas-pipe. We then have the disturbing wire as before, and when the transmitter is operated, loud tones are heard at the end telephones, *a* and *b*, thus: If this were entirely due to the creation of an electro-magnetic field around the disturbing wire, the effect on the secondary wire would be increased by short-circuiting one of the telephones by the key *k*. Now, it is found that when this is done, instead of increasing the sound in the other telephone, it absolutely removes it. Now, the case just described is another condition where you should get an increase of electro-magnetic action, if the disturbance is due to the magnetic field; but the noise, instead of increasing, disappears entirely. Now, you will see how beautifully the thing may be explained by assuming that the disturbance is due to direct electro-static action. In this case we will say that the wire L^1, at a given instant, has a plus charge upon it which induces a minus charge on L^2. Now, when the inducing charge is removed, the induced charge divides and flows away at both ends. But as there is a great deal of resistance in telephone *b*, and practically no resistance in key *k*, the charge and discharge of L^2 takes place up and down through the key end, and none of it goes through the telephone *b*. Now, I think that is a complete refutation of the statement that any portion of the noise produced in the telephone is due to electro-magnetic action. There is no doubt about it that when the current is going through L^1, in the act of charging it, that there is a magnetic field surrounding that current, but I have shown that it is so feeble that it does not produce any effect in the telephone; that is, the action that is due to the electro-magnetic field is so feeble that the ear is not able to tell whether it is present or not."

In reply to a question by Mr. George B. Prescott, Jr., as to whether any experiment had been tried, using a powerful current as a disturbing source, Mr. Carty says:

"Now, in this case, T, Fig. 12, represents a vibrator connected with a large battery. We had a very powerful current flowing through that wire, L^1. The current was constantly vibrating, and it was a very strong current, indeed. Now, in that case I used the same secondary wire, and a telephone in the centre, and then we found a noise in all three telephones, just exactly what you should expect in dealing with electro-magnetic induction. You would expect to find a current at a given instant, with very slight differences, constant in all parts of the circuit; that is, you would expect to find as much noise at the centre telephone as at the end telephone. You would expect that if this middle telephone was short-circuited the noise would be increased at the end telephones, and then you would further expect that if one end telephone were short-circuited, that the remaining one would be still louder. That was the case. Now, consider the circuit with the middle telephone cut out and one end telephone cut out, and the other end telephone giving a loud noise, with a strong current in L^1; but with the strongest telephone current we could produce in L^1 there was no noise there at all. And further than that, the methods of every-day practice have been changed to meet these views, and our predictions and calculations, based on this way of working, are invariably correct.

All of our cables, which are twisted in pairs, are subjected to a very rigid cross-talk test, and some of the refinements which have to be taken into consideration in making those tests are certainly most surprising."

From data furnished by Mr. Carty, Mr. A. E. Kennelly made some calculations "on the relative degree of disturbance caused by electro-static and electro-magnetic induction between certain simple arrangements of telephone circuits." He found that with the arrangement shown in Fig. 2 of Mr. Carty's

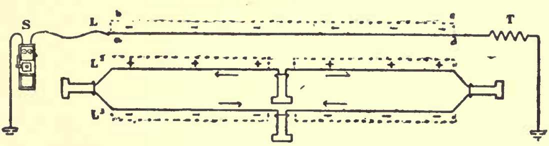


FIG. 2.

paper, the ratio of static to magnetic disturbance is $\frac{\kappa\ \omega_1\ \omega_2}{2\ \mu}$ where $\kappa =$ the mutual electro-static capacity of L_1 and L_2 per centimetre of length; $\mu =$ mutual induction of L_1 and L_2 per centimetre of length; $\omega_1 =$ impedance in the circuit of L_1; $\omega_2 =$ impedance in the circuit of L_2.

"Provided, then, that the impedance of the primary circuit at the receiving end is always large, the ratio of static to magnetic disturbance will be approximately expressed by this equation."

Giving the quantities in this expression the proper values for the case shown in Fig. 2, the impedance ω_1 is found to be nearly twenty times greater than that needed to produce equality between the two kinds of disturbance, " and, roughly, the static disturbance in Fig. 2 may be estimated as twenty times greater than the magnetic."

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