Wheatstone, Sir Charles; Wheatstone's Bridge.
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Encyclopaedia Britannica, 11th Edition (1911)
Volume 28, p583 - 585.

WHEATSTONE, SIR CHARLES (1802–1875), English physicist and the practical founder of modern telegraphy, was born at Gloucester in February 1802, his father being a music-seller in that city. In 1806 the family removed to London. Wheatstone's education was carried on in several private schools, at which he appears to have displayed no remarkable attainments, being mainly characterized by a morbid shyness and sensitiveness that prevented him from making friends. About 1816 he was sent to his uncle, a musical instrument maker in the Strand, to learn the trade; but with his father's countenance he spent more time in reading books of all kinds than at work. For some years he continued making experiments in acoustics, following out his own ideas and devising many beautiful and ingenious arrangements. Of these the "acoucryptophone" was one of the most elegant—a light box, shaped like an ancient lyre and suspended by a metallic wire from a piano in the room above. When the instrument was played, the vibrations were transmitted silently, and became audible in the lyre, which thus appeared to play of itself. On the death of his uncle in 1823 Wheatstone and his brother succeeded to the business; but he never seems to have taken a very active part in it, and he virtually retired after six years, devoting himself to experimental research, at first chiefly with regard to sound. Although he occasionally read a paper to scientific societies when a young man, he never could become a lecturer on account of his shyness. Hence many of his investigations were first described by Faraday in his Friday evening discourses at the Royal Institution. By 1834 his originality and resource in experiment were fully recognized, and he was appointed professor of experimental philosophy at King's College, London, in that year. This appointment was inaugurated by two events,—a course of eight lectures on sound, which proved no success and was not repeated, and the determination by means of a revolving mirror of the speed of electric discharge in conductors, a piece of work leading to enormously important results. The great velocity of electrical transmission suggested the possibility of utilizing it for sending messages; and, after many experiments and the practical advice and business-like co-operation of William Fothergill Cooke (1806–1879), a patent for an electric telegraph was taken out in their joint names in 1837. Wheatstone's early training in making musical instruments now bore rich fruit in the continuous designing of new instruments and pieces of mechanism. His life was uneventful except in so far as the variety of his work lent it colour. He became a fellow of the Royal Society in 1837; in 1847 he married; and in 1868, after the completion of his masterpiece, the automatic telegraph, he was knighted. While in Paris perfecting a receiving instrument for submarine cables, Sir Charles Wheatstone caught cold, and died on the 19th of October 1875.

Wheatstone's physical investigations are described in more than thirty-six papers in various scientific journals, the more important being in the *Philosophical Transactions*, the *Proceedings of the Royal Society*, the *Comptes rendus* and the British Association *Reports*. They naturally divide themselves into researches on sound, light and electricity, but extend into other branches of physics as well. But his best work by far was in the invention of complicated and delicate mechanism for various purposes, in the construction of which he employed a staff of workmen trained to the highest degree of excellence. For his insight into mechanism and his power over it he was unequalled, except perhaps by Charles Babbage. A cryptographic machine, which changed the cipher automatically and printed a message, entirely unintelligible until translated by a duplicate instrument, was one of the most perfect examples of this. Cryptography had a great fascination for Wheatstone; he studied it deeply at one time, and deciphered many of the MSS. in the British Museum which had defied all other interpreters. In acoustics his principal work was a research on the transmission of sound through solids, the explanation of Chladni's figures of vibrating solids, various investigations of the principles of acoustics and the mechanism of hearing, and the invention of new musical instruments, *e.g.* the concertina (*q.v.*).

The kaleidophone, intended to present visibly the movements of a sonorous body, consisted of a vibrating wire or rod carrying a silvered bead reflecting a point of light, the motions of which, by persistence of the successive images on the retina, were thus represented in curves of light. In light there are a series of papers on the eye, on the physiology of vision, on binocular vision, including the invention of one of the popular scientific instruments, the stereoscope (*q.v.*), and on colour. The polar clock, devised for use in place of a sun-dial, applies the fact that the plane of polarization of sky light is always 90° from the position of the sun; hence by measuring the azimuthal angle of the plane, even when the sun is below the horizon, correct apparent solar time may be obtained. In 1835, in a paper on "The Prismatic Decomposition of Electrical Light," he proved that sparks from different metals give distinctive spectra, which afforded a ready means of discriminating between them. But it is by his electrical work that Wheatstone is best remembered. He not only guided the growth of scientific telegraphy on land wires, but made the earliest experiments with submarine cables, foreseeing the practicability of this means of communication as early as 1840. He devised the "A, B, C" telegraph instrument, the automatic transmitter, by which messages may be sent at the rate of 500 words a minute, printing telegraph receivers of various forms, electrical chronoscopes, and many forms of electrical recording apparatus,—amongst others two sets of registering meteorological instruments, of which the earlier, described in 1842, was afterwards developed by Father A. Secchi and F. van Rysselberghe, but the later, put forward in 1867, included metallic thermometers and was less successful.

Wheatstone's *Scientific Papers* were collected and published by the Physical Society of London in 1879. Biographical notices of him will be found in his *Proc. Inst. C.E.*, xlvii. 283, and *Proc. Roy. Soc.*, xxiv. xvi. For his connexion with the growth of telegraphy, see *Nature*, xi. 510, and xii. 30 sq.

WHEATSTONE'S BRIDGE, an electrical instrument which consists of six conductors, joining four points, of such a character that when an electromotive force is applied in one branch the absence of a current in another branch (called the conjugate branch) establishes a relation between the resistance of the four others by which we can determine the value of the resistance in one of these, that of the others being assumed to be known. This arrangement was not invented by Sir Charles Wheatstone— although it bears his name and is commonly attributed to him, and was employed by him in some of his electrical researches— but by S. H. Christie, in 1833.[1]

The arrangement of the six conductors is diagrammatically represented in fig. 1. In one of these branches is placed a battery B and in another a galvanometer G; the four other resistances are denoted by the letters P, Q, R, S. The circuits in which the battery and galvanometer are placed are called conjugate circuits, and the circuits P, Q, R, and S are called the *arms* of the bridge, the branches P and Q being called the *ratio arms* and S the *measuring arm*. The circuit in which the galvanometer is placed is the *bridge circuit*. Keys are inserted in the battery and galvanometer circuits to open or close them at pleasure. The resistance forming the four arms of the bridge can be so adjusted that if these resistances have values denoted by P, Q, R, and S, then when P : Q :: R : S, the current in the galvanometer circuit will be zero when an electromotive force is applied in the battery circuit.

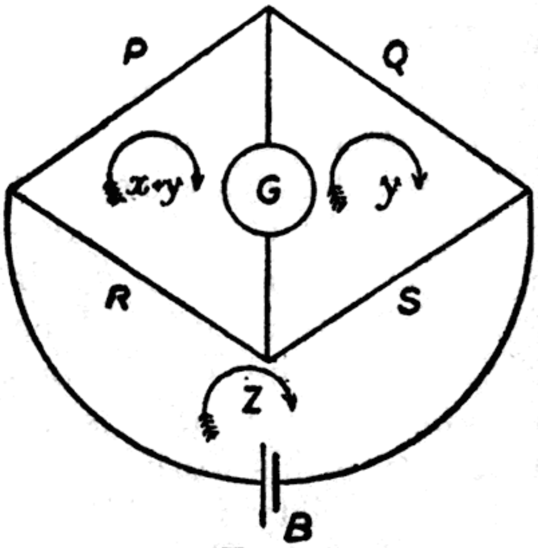

FIG. 1.

To prove this statement, let the conductors P, Q, R, S., be arranged in a lozenge shape, as in fig. 1. Let E be the electromotive force in the battery circuit, and let $(x+y)$ be the current through the resistance P, y the current through the resistance Q and z that through B. Then by G. R. Kirchhoff's laws (see ELECTROKINETICS) we have the current equations,

$$(P+G+R)\ (x+y)-Gy-Rz=O$$
$$(Q+G+S)\,y-G\,(x+y)-Sz=O$$
$$(R+S+B)\,z-R\,(x+y)-Sy=E$$

Rearranging the terms and solving for x (the current through the galvanometer), we obtain

$$x=(PS-RQ)E/\Delta,$$

[1] See Wheatstone's *Scientific Papers*, p. 129.

where Δ is a complex expression, involving the resistances P, Q, R, S, G, and B, which does not concern us. Hence when $x=0$, $P : Q = R : S$ and the value of R can be determined in terms of P, Q and S.

In the practical instrument the three arms of the bridge P, Q, and S are generally composed of coils of wire contained in a box, whilst R is the resistance the value of which is to be determined. This last resistance is connected to the other three with the addition of a galvanometer and a battery connected up as shown in the diagram. The operation of determining the value of the resistance R therefore consists in altering the ratio of the three resistances P, Q, and S, until the galvanometer indicates no current through it when the battery circuit is completed or closed by the key. In one form of Wheatstone's Bridge, known as the series pattern plug-resistance bridge, or Post Office pattern, the two ratio arms, P and Q, each consist of a series of coils of wire, viz. two 1-ohm coils, two 10-ohm coils, two 100-ohm coils and two 1000-ohm coils, which are joined up in series in the order, 1000, 100, 10, 1; 1, 10, 100, 1000, the junctions between each pair being connected to brass blocks, a series of which are mounted upon an ebonite slab that forms the lid of the box. The blocks are bored out with a hole partly in one block and partly in the other (see fig. 2) so that they can be connected by accurately fitting conical plugs. When the blocks are interconnected by the plugs all the coils are short-circuited; but if the plug or plugs are taken out, then a current flowing from one end of the series to the other is compelled to pass through the corresponding coils. In series

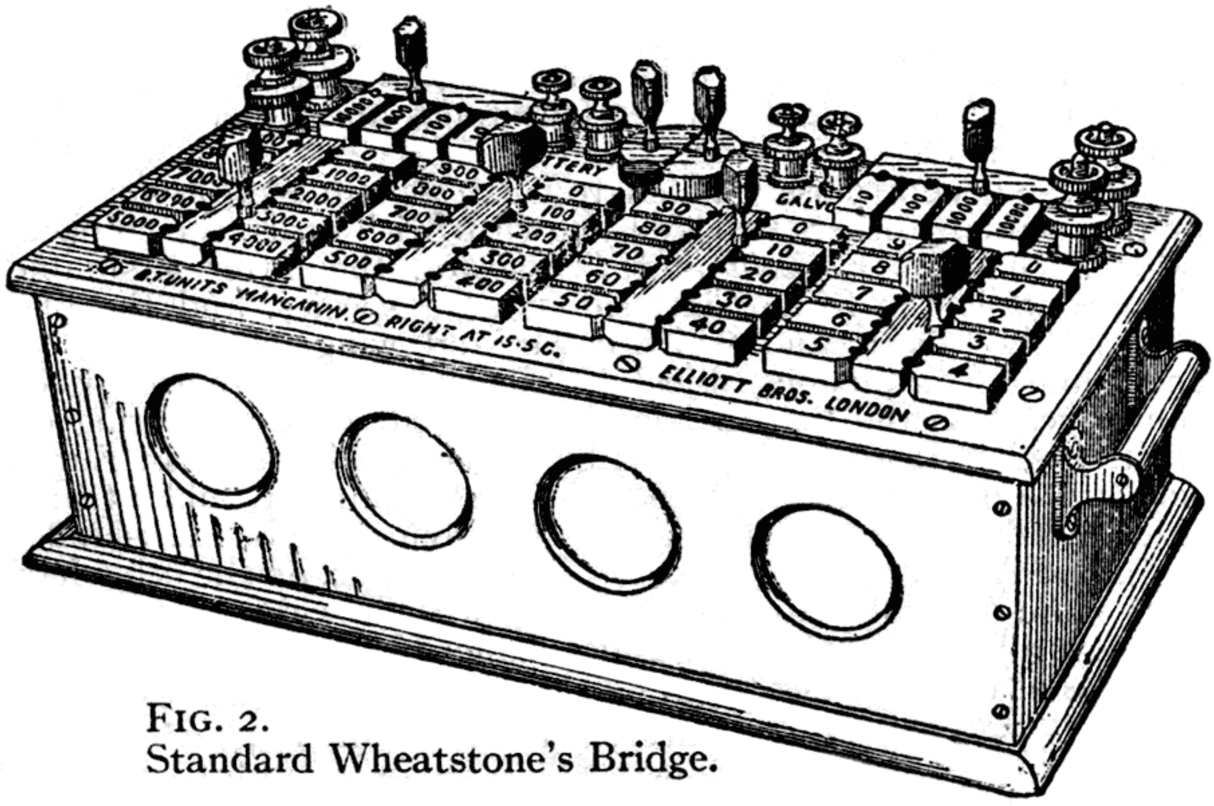

FIG. 2.
Standard Wheatstone's Bridge.

with this set of coils is another set, S, which forms a measuring arm, the resistances of which are generally 1, 2, 3, 4, 10, 20, 30, 40, 100, 200, 300, 400, 1000, 2000, 3000, 4000 ohms. The junction between each pair of coils is connected as above described to a block, the blocks being interconnected by plugs all of which are made interchangeable.

Another form of Wheatstone's Bridge, shown in fig. 2, is known as the *dial* pattern. Ten brass blocks are arranged parallel to or around another brass block, and by means of a plug which fits into holes bored partly out of the common block and partly out of the surrounding blocks, any one of the latter can be connected with the common one. A series of nine equal resistances, say 1-ohm coils, or nine 100-ohm coils, are joined in between these circumferential blocks (fig. 3). It will be seen that if a plug is placed so as to connect

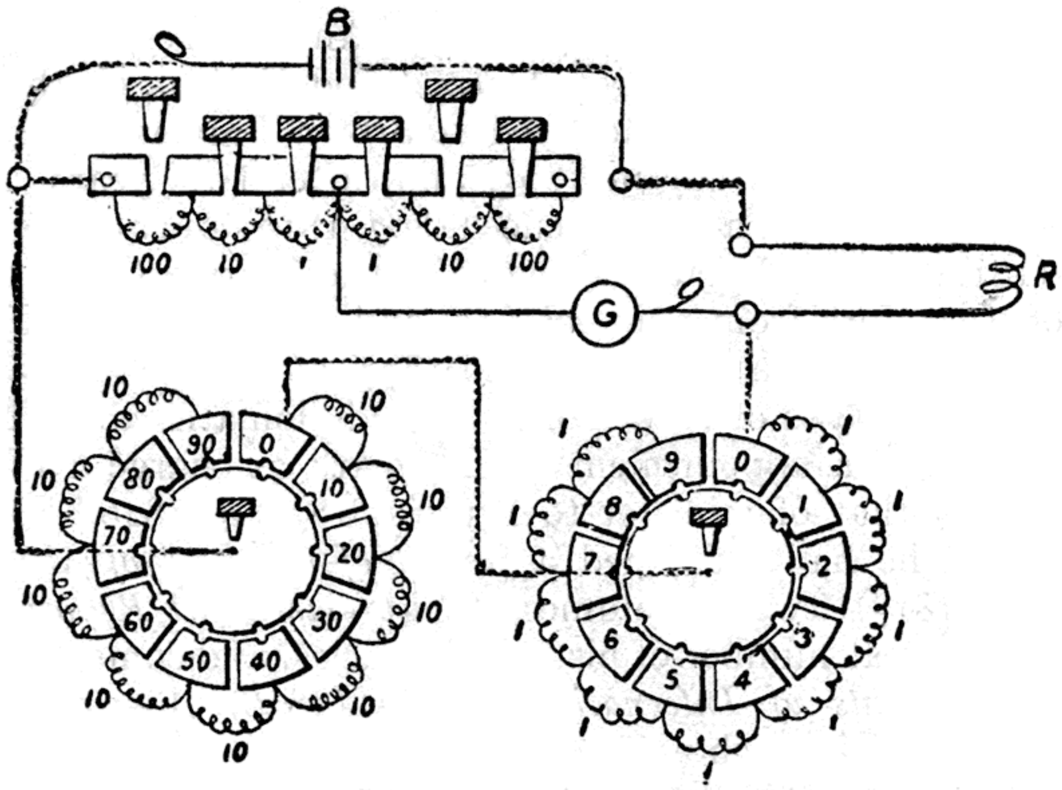

FIG. 3.—Diagram showing Connexions of a Dial and Plug pattern, Wheatstone's Bridge.

any outside block with the central block, the current can only pass from the zero outer block to the central block by passing through a certain number of the resistance coils. Hence according to the magnitude of each coil the total resistance may be made anything from 1 to 9, 10 to 90, or 100 to 900 ohms, &c. Three or four of the " dials " thus composed are arranged side by side, the brass blocks being mounted on a slab of ebonite and the coils contained in the box underneath, and they are so joined up that the central block of one dial is connected to the outside block of the next marked O. This arrangement forms the measuring arm of the bridge, the ratio arms being constructed on the series plug pattern just described. A bridge of this pattern has the advantage that the insertion or removal of a plug in the measuring arm does not tend to tighten or loosen all the rest of the plugs; moreover, there are fewer plugs to manipulate, and each plug is occupied. The resistance coils themselves are generally wound on brass or copper bobbins, with silk-covered manganin wire, which should first be aged by heating for about ten hours to a temperature of 140° C., to remove the slight tendency to change in resistivity which would otherwise present itself.

For the accurate comparison of resistance coils it is usual to make use of the Matthiessen and Hockin bridge, and to employ the method of differential comparison due to G. Carey Foster.[1] On a board is stretched a uniform metallic wire *a b*, generally of platinum silver. The ends of this wire are connected to copper blocks, which themselves are connected to a series of four resistance coils, A, B, and P, Q (fig. 4). A and B are the coils to be compared, P and Q are two other

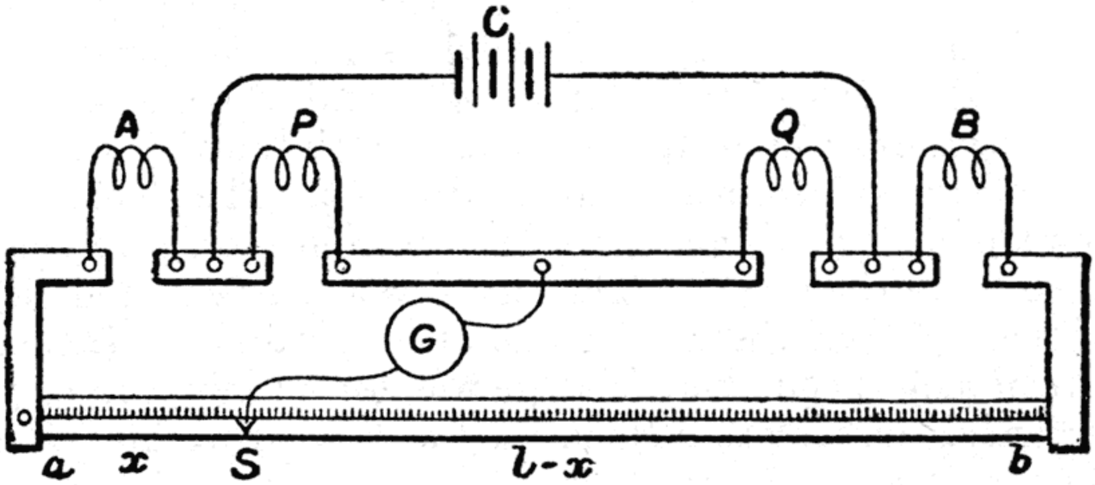

FIG. 4.

coils of convenient value. Over the stretched wire moves a contact maker S, which makes contact with it at any desired point, the position of which can be ascertained by means of an underlying scale. A battery C of two or three cells is connected to the extremities of the slide wire, and the sensitive galvanometer G is connected in between the contact-maker and the junction between the coils P and Q. The observer begins by moving the slider until the galvanometer shows no current. The position of the coils A and B is then interchanged, and a fresh balance in position on the bridge is obtained. It is then easily shown that the difference between the resistance of the coils A and B is equal to the resistance of the length of the slide wire intercepted between the two places at which the balance was found in the two observations.

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[1] "On a Modified Form of Wheatstone's Bridge, and Methods of Measuring Small Resistances," by Professor G. Carey Foster. *Proc. Soc. Tel. Eng.* (1872), 1.

Let the balance be supposed to be attained, and let x be the position of the slider on the wire, so that x and $l-x$ are the two sections of the slide wire, then the relation between the resistance is

$$(A+x) / (B+l-x) = P/Q.$$

Next, let the position of A and B be interchanged, and the slide-wire reading be x'; then

$$(B+x') / (A+l-x') = P/Q.$$

Hence it follows that $A-B=x'-x$, or the difference of the resistances of the coils A and B is equal to the resistance of that length of the slide wire between the two points where balance is obtained.

Various plans have been suggested for effecting the rapid interchange of the two coils A and B; one of the most conveni nt was designed by J. A. Fleming in 1880, and has been since used by the British Association Committee on Electrical Units for making comparison between standard coils with great accuracy (see *Phil. Mag.*, 1880, and *Proc. Phys. Soc.*, 1879). In all very exact resistance

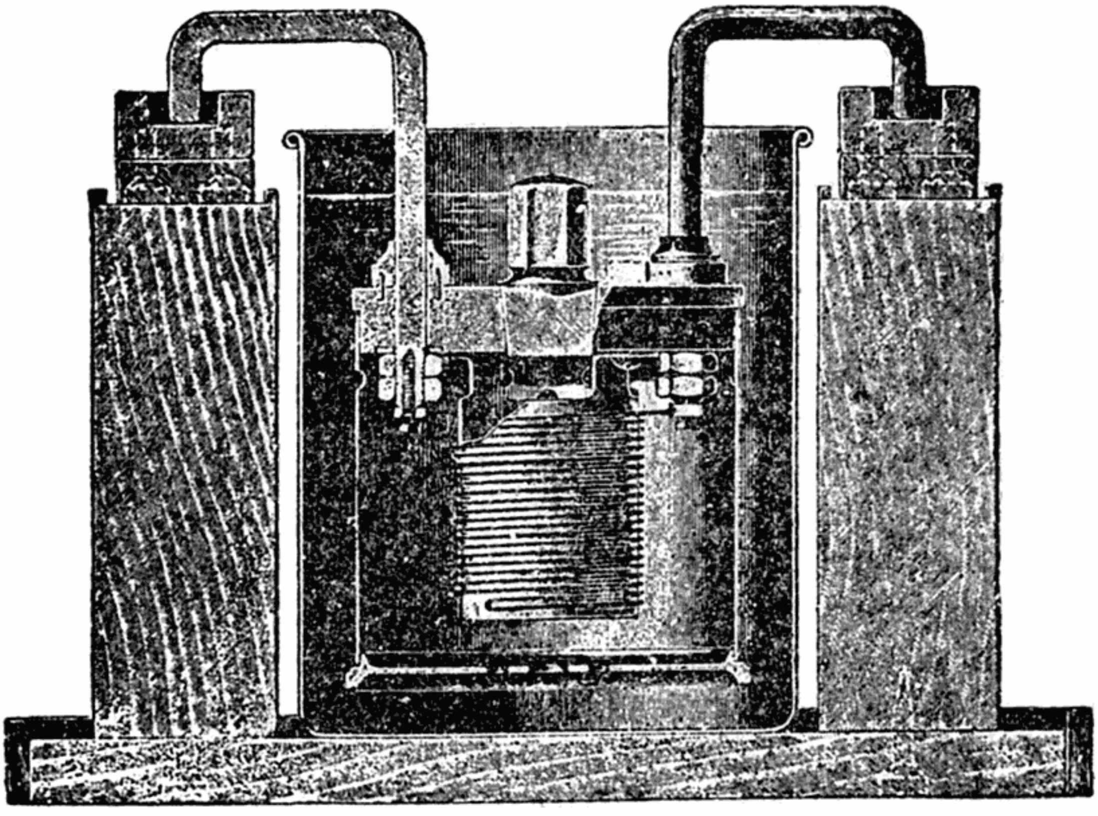

FIG. 5.

measurements the chief difficulty, however, is not to determine the resistance of a coil, but to determine the temperature of the coil at the time when the resistance measurement is made. The difficulty is caused by the fact that the coil is heated by the current used to measure its resistance, which thus alters in value. In accurate comparisons, therefore, it is necessary that the coils to be compared should be immersed in melting ice, and that sufficient time should be allowed to elapse between the measurements for the heat generated in the coil to be removed.

The standard resistance coil employed as a means of comparison by which to regulate and check other coils consists of a wire, generally of manganin or platinum silver, insulated with silk and wound on a brass cylinder (fig. 5). This is soldered to two thick terminal rods of copper, and the coil is enclosed in a water-tight brass cylinder so that it can be placed in water, or preferably in paraffin oil, and brought to any required temperature. In the form of standard coil recommended by the Berlin Reichsanstalt the coil is immersed in an insulating oil which is kept stirred by means of a small electric motor during the time of making the measurement. The temperature of the oil can best be ascertained by means of a platinum resistance thermometer.

For the measurement of low resistances a modification of the Wheatstone's bridge devised by Lord Kelvin is employed. The Kelvin bridge consists of nine conductors joining six points, and in one practical form is known as a Kelvin and Varley slide. Modifications of the ordinary Wheatstone's bridge for very accurate measurements have been devised by H. L. Callendar and by Callendar and E. H. Griffiths (see G. M. Clark, the *Electrician*, 38, p. 747). A useful bridge method for measurement of low resistances has been given by R. T. Housman (the *Electrician*, 40, p. 300, 1897). These and numerous modifications of the Wheatstone's bridge will be found described in J. A. Fleming's *Handbook for the Electrical Laboratory and Testing-Room*, vol. i. (1903).

REFERENCES:—F. E. Smith, "On Methods of High Precision for the Comparison of Resistances," Appendix to the Report of the British Association Committee on Electrical Standards, *British Association Report* (York, 1906), or the *Electrician*, 57, p. 976 (1906); C. V. Drysdale, "Resistance Coils and Comparisons," *British Association Report* (Leicester, 1907), or the *Electrician*, 57, p. 955 (1907), and 60, p. 20 (1907); J. A. Fleming, "A Form of Resistance Balance for Comparing Standard Coils," *Phil. Mag.* (February, 1880); "A Design for a Standard of Electrical Resistance," *Phil. Mag.* (January 1889); G. Aspinall Parr, *Electrical Measuring Instruments* (1903); W. H. Price, *The Practical Measurement of Resistance*; A. Gray, *Absolute Measurements in Electricity and Magnetism* (1900); Rollo Appleyard, "The Conductometer," *Proc. Phys. Soc. London*, 19, p. 29 (1903); also *Proc. Inst. Civ. Eng.* 154 (1903); and *Proc. Phys. Soc., London*, 17, p. 685 (1901). (J. A. F.)