Bridges I Have Crossed

Looking back at...

By Thomas B. Greenslade, Jr.

The Wheatstone bridge was still in use when I received my Ph.D. in physics in the early 1960s. I researched the thermal conductivity of superconducting thin films at Rutgers University in New Jersey using standard 1/10 W Allen-Bradley carbon resistors as thermometers, and measured their resistance with a Wheatstone bridge built from top-of-the line components. Since then, I have moved from experimental physics to the study of apparatus used in physics in the late 19th and early 20th centuries. During this time, the construction of high-precision electrical measurement equipment was raised to an art in the United States by companies such as Leeds & Northrup (L&N) of Philadelphia and General Radio Co. of Cambridge, Massachusetts. In this paper I will discuss some favorite pieces of apparatus in my own collection based on bridge circuits.

Christie's Bridge

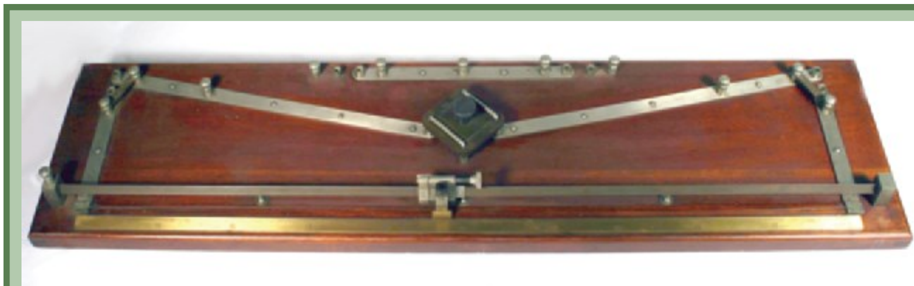

Figure 1. 1903 L&N Wheatstone Reversible Meter Bridge

Most of us attribute the basic diamond-shaped arrangement of four passive elements with a detector across one diagonal and a source of EMF across the other to Charles Wheatstone (1802-75) (Figure 1). However, Wheatstone gave a footnote in the published version of his Bakerian Lecture in 1843 in which he describes methods for measuring resistance. He noted that "Mr. (Samuel Hunter) Christie, in his 'Experimental determination of the laws of magneto-electric induction' printed in the Philosophical Transactions for 1833, has determined a differential arrangement of which the principle is the same as that on which the instruments described in this section have been devised. To Mr. Christie must, therefore, be attributed the first idea of this useful and accurate method of measuring resistances" [1].

Samuel Hunter Christie (1784-1865) was the father of William Christie, the Astronomer Royal from 1881 to 1922. When I read Samuel Christie's paper from his Bakerian Lecture in 1833, it was rather hard going as it had to be translated into modern usage. Christie investigated what we today would call induced EMFs and showed that they had the same effect as thermal EMFs and voltaic EMFs. He showed that the “conducting power [i.e. the inverse of the resistance] of wires varies as the squares of the diameters directly and as their lengths inversely” [2].

In the section of his paper in which he endeavored to “ascertain the law of the intensity [current] as depending on the length of the connecting wire,” Christie set up a diamond shaped circuit driven at two opposite corners by an induced EMF. This was produced by a coil of wire falling past the poles of the huge permanent magnet at the Royal Institution. The detector, connected across the other diagonal of the diamond, was a galvanometer. This bridge was never balanced, but the current in the galvanometer was measured as a function of the lengths of wire on the sides of the diamond.

The Wheatstone Bridge and Other Devices

Figure 2 shows the original design for the Wheatstone Bridge circuit. The wires forming the diamond occupied a space on a board only 14in by 4in (35.6cm x 10.2cm) and were 0.05 in (1.27mm) in diameter. The source of EMF was attached between points C and Z and the galvanometer between points b and a. The gaps were closed with jumper wires and the sliding contact point b was moved until the galvanometer read zero. Then, the jumper wires were replaced by the unknown and the rheostat, point b, stayed fixed and it was adjusted until there was no galvanometer deflection. Then, the jumper wires were replaced by the unknown and the rheostat, and point b stayed fixed. The rheostat was adjusted until there was no galvanometer deflection. The unknown then had the same resistance as the rheostat.

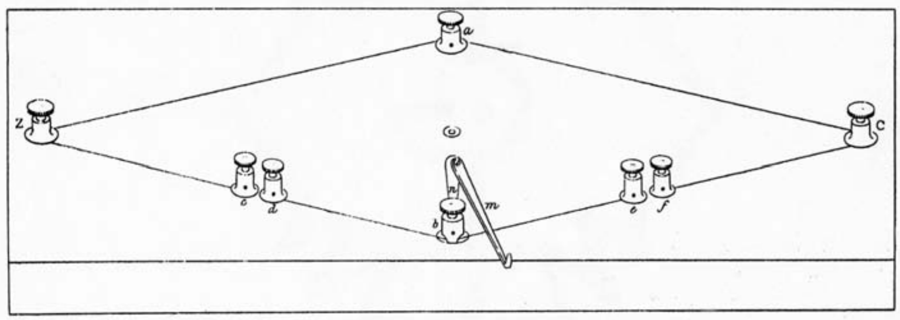

Figure 2. Wheatstone’s original design of the bridge circuit.

Wheatstone developed the rheostat during this time period and added it to his bridge circuit [3] (Figure 3). The rheostat design was based on the observation of Georg Simon Ohm (1789-1854) that, for a wire of uniform cross section, the resistance is proportional to the length. Wheatstone wound a brass resistance wire 0.01in. diameter from one cylinder to another with the crank and the length of the wire remaining was read from a scale between the cylinders and from the dial at the end of the cylinder. The modern version of this device is the ten turn Helipot™.

Figure 3. Wheatstone’s 1843 Rheostat by J. White of Glasgow in the apparatus collection of Miami University in Oxford, Ohio, USA .

Wheatstone is properly remembered for many experimental techniques and devices [4]. In 1834, he measured the speed of the electric signal in a wire by using the rotating mirror technique later used for velocity of light measurements. Three years later he and Josiah Cooke patented a widely used telegraph system, and the next year Wheatstone wrote the seminal paper on stereoscopic effects.

Those who make precision electrical measurements should read Wheatstone’s 1843 Bakerian Lecture, “An account of several new Instruments and processes for determining the Constants of a Voltaic Circuit”, given to the Royal Society of London [1]. He discussed resistivity and methods for systematically measuring resistance using Ohm’s Law.

Leeds & Northrup Wheatstone Bridges

Leeds & Northrup was formed in 1903 when Edwin Northrup joined forces with Morris E. Leeds to produce precision instruments used mostly for direct current measurements. The company's products can immediately be identified by their massive switches, thick Bakelite top plates and beautifully-crafted wooden bases. Opening an instrument reveals thick, smooth solder joints.

The L&N Wheatstone Reversible Meter Bridge in Figure 1 is the bridge design closest to Wheatstone's original circuit that I have. The scale is engine divided and has a slow-motion vernier scale to allow the meter-long slide wire to be read to the nearest 0.0001 m. (To produce a high-quality scale, companies use a machine called a dividing engine that scribes marks on a scale one after another; thus called an engine-divided scale.) The unknown and the two resistances making up the ratio arms can be attached to the gaps in the flat copper conductors with screw connections or mercury cups. There is a reversing switch in the center that is picked up and rotated by 90° to interchange the two resistors which make up the ratio arms, and it also has mercury contacts. At that time, it cost $115 and was out of the catalogue by 1920. Many other bridges with additional features were available.

Figure 4. (L) The classic 1903 L&N Post-Office Pattern Wheatstone Bridge, and (R) the 1907 L&N Decade Resistance Box and Wheatstone Bridge.

Figure 4 shows two small bridges that stayed in the catalogue. These instruments are still viable. On the right-hand side in Figure 4 is the L&N Decade Resistance Box and Wheatstone Bridge from 1907 that cost $60. An unusual feature is the arrangement of the two plugs for the two resistors making up the ratio arms. By inserting them properly, ratios of 1 to 10,000 up to 10,000 to 1 may be obtained, going in steps of ten. Each resistance coil in the ratio arms is good to 0.05%. The instrument can also be used to measure high-quality resistance; its coils were adjusted to 0.1% accuracy.

On the left-hand side of Figure 4 is the classic L&N Post-Office Pattern Wheatstone Bridge, later designated for student use. The design, by the British Post Office Department, was in the very first L&N catalogue from 1903 and the instrument in the catalogue still bears the name of Morris E. Leeds, the parent company. The goal was to produce a quality bridge at a low price ($40) by using standard parts made in great quantities. The ratio arms are non- reversible and are adjusted to 0.1% while the resistors in the rheostat section are good to 0.2%. To aid the student, the circuit was engraved on the top plate and there are tap switches for the galvanometer and the power supply circuits. This design was copied or sold by other American apparatus makers (Ziegler, Knott, Welch, Chicago Apparatus and Cenco) into the second half of the 20th century.

Figure 5. The 1914 L&N Type S portable testing Wheatstone bridge

In the latter years of the 19th century, self-contained, portable Wheatstone bridges were developed, and L&N offered ones with plug-type resistors as early as 1907. The Type S Portable Testing set from 1917 in Figure 5 had the new style, switch-selected resistance decades that L&N patented in 1914, and it cost about $90, and this one is still usable. The galvanometer could be clamped down to prevent damage when the instrument was "transported over rough roads in small automobiles" [5]. Complete operating instructions are printed inside the top of the hinged lid of the oak case suggesting that the instrument may have been largely used to locate faults in cables and lines in the field. As Wheatstone bridges, I found them sensitive enough to use for a number of years in a first year physics experiment on the temperature coefficient of resistance of #40 copper wire. The coils and ratio arms have the same specifications as the Post Office Bridge.

An aside: The logo of the Cambridge Instrument Company displays a wonderful scientific pun: a diamond (representing the bridge) with the representation of a cam inside it.

The Kelvin Bridge

It is now time to look at an offshoot of Wheatstone's original design. One problem with the original form of Wheatstone's bridge was its inability to measure very low resistances. The resistance of the wires connecting the bridge to the sample could be comparable to the sample, leading to errors. Lord Kelvin (1824-1907) devised a modification that allowed measurement of the resistance of a few tens of centimeters of thick copper rod. Common to all Kelvin bridges is a large diameter, low resistance rod that serves as a resistance standard.

A Kelvin bridge found in most American electrical measurements laboratories is the L&N Student Kelvin Bridge introduced about 1920. The instrument in the foreground of Figure 6 is an example. This sold for $70.00 in 1927. The bridge can measure resistances from 0.00001 Ω to 0.1Ω. The sample is held between the massive clamps at the rear and the standard resistance is a brass rod of uniform cross section at the front of the instrument. A sliding contact to this rod allows the bridge to be balanced. The standard resistance bar has a uniformity of 1% and the ratio arms are good to 0.2%. This is a fine instrument and can still occasionally be found, unused, in storage rooms of American physics departments.

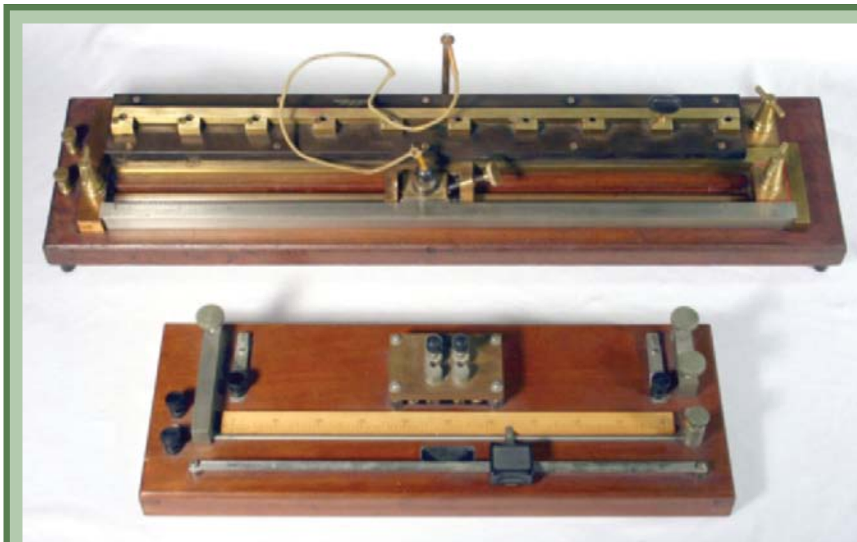

Figure 6. (Front) The 1920 L&N Student Kelvin Bridge, and (back) a 1905 L&N Resistance Standard instrument

For research purposes, L&N offered modular Kelvin bridges. The heart of the bridge was the free-standing, adjustable standard low resistance to which a box was added containing ten ratio coils and a set of stout copper current and potential clamps that were applied to the sample. A galvanometer completed the ensemble. The ratio coil box cost $100 and had coils good to 0.01%. It looks like a typical plug-type resistance box. It was not usually preserved.

The standard resistance apparatus at the back of Figure 6 was listed in the 1906 L&N catalogue for $200. The basic construction can easily be seen in this instrument. The electrical connections are made to massive blocks of copper and the standard resistance rod is made of manganin. This copper-manganese-nickel alloy has a low temperature coefficient of resistance, and the relatively high thermal conductance of the rod keeps both ends at the same temperature, almost completely eliminating thermal EMFs. The contact point can be moved manually to a point on the bar and then is driven by a slow motion screw connected to a vernier scale as the balance point is reached. The bar has a resistance of 0.01 Ω and can be read to one part in a thousand. Coarser adjustments are made with a series of ten precision resistances, each 0.01 Ω, contained in the body of the instrument and selected with the plug.

ac Bridges

The alternating current bridge has long since been removed from the undergraduate physics curriculum but in the second half of the 1950s, it was a key element of the Electricity and Magnetism course. We became expert at complex impedances: $Z = jL\omega$ for an inductance of value L with a sinusoidal signal of angular frequency ω, and $Z = -j/C\omega$ for a capacitor of value C under the same circumstances.

A typical alternating current bridge had combinations of resistances, capacitances and inductances in the four arms and the conditions for balance were obtained by putting the appropriate impedances in the equation for the direct current Wheatstone bridge, now written as Z1 Z4 = Z2 Z3 . There were always two balance conditions: one for the real part of the equation and one for the imaginary part. The source of alternating EMF was a 1000 cycle [sic] “hummer” like the Type 213 General Radio fork-driven oscillator that sold for $34 in 1935. The detector was a pair of earphones and users adjusted two components of the bridge until blessed silence was achieved in the phones clamped to their ears.

General Radio ac Bridges

In the 1930s, the General Radio Company of Cambridge, Massachusetts started to produce a whole range of self-contained bridge instruments for the measurement of resistance, capacitance and inductance. The “Rolls-Royce” of the series was the Type 650A Impedance bridge patented in 1928-29 (on the right in Figure 7). I suspect that very few university and industrial physics labs were without this instrument, which, in my own undergraduate days and early years of teaching, was in constant use in the electricity and magnetism laboratory. It was a heavy, solid instrument that cost $175 in 1935 and the code word when ordering it was BEAST!

Figure 7. (R) A 1930 General Radio Co. Type 650A Impedance Bridge, and (L) a 1935 General Radio Co. Type 635A Skeleton Bridge

The 650A was completely self-contained for resistance measurements with four tall No. 6, 1.5 V dry cells contained in the compartment at the upper end to serve as a dc power supply. The galvanometer on the front panel indicated when the bridge was in balance. Binding posts were available for an external power supply and an external detector for more sensitivity to measure the larger resistances. Even without these you could measure from 1 mΩ to 1 MΩ with an uncertainty of only 1%. A dial with graduations spanned 12in (30.5cm) around the rim helped spread out the readings.

For inductance measurement a self-contained 1000 cycle hummer driven by the internal batteries supplied the alternating signal (an external source could also be used), and the detector was a pair of earphones. The two dials used to balance the ac bridge gave the inductance of the coil and the direct-current resistance. For measurements of capacity, both the capacitance and the power factor (the ratio of the impedance to the resistance) were indicated.

The General Radio Type 635A Bridge (on the left in Figure 7) is a skeleton bridge, as is suggested by the circuit diagram on the lower left side of its top plate. Inside is a pair of 4.5 V batteries, a 1000 cycle hummer and a 10,000 ohm rheostat with a logarithmic scale. The open drawer contains a series of fixed resistors and capacitors to allow the user to construct a custom bridge. Without these, the skeleton bridge cost $65 in 1935 and with them it had the same specifications as the 650A bridge.

The General Radio Bridge in Figure 8 is a Type 216 Capacity Bridge, costing $175 in 1935. The catalogue for that year notes that the bridge was designed to measure small capacitances in the 1μF to 10μF range at frequencies of 200 to 10,000 cycles. This required shielding; the interior of the opened instrument is lined with thick sheets of copper. Ratio arms were provided, but the ac source, the detector and a standard of capacitance were external. The 1935 General

Radio Catalogue "H" noted that "with a power source of 100 volts at a frequency of 1 kilocycle and using a two stage amplifier and telephones as a null indicator, the capacitance balance can be adjusted to one part in a million."

Summary

You perhaps now see why these instruments based on Wheatstone's bridge are among my favorite pieces of electrical measurement apparatus. These instruments range from the most basic to ones with many enhancements. All of the bridges described and illustrated in the figures are from my collection and were donated by various American college and university physics departments. These tools offer a history of the quickly developing field of electrical measurement in the late 19th and early 20th Centuries.

Figure 8. A 1935 General Radio Co. Type 216 Capacity Bridge

References

[1] C. Wheatstone, "An account of several new Instruments and Processes for determining the Constants of a Voltaic Circuit", Philos. Trans. Roy. Soc. London, vol. 133, pp 303-324, 1843.

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[3] T. B. Greenslade, Jr., "Nineteenth Century Textbook Illustrations XXIII: The Rheostat, Phys. Teach., vol. 16, pp 301-302 (1978).

[4] B. Bowers, Sir Charles Wheatstone, Her Majesty's Stationery Office, 1975.

[5] Leeds and Northrup Catalogue, 1927, "Apparatus for Electrical Resistance Measurements, Catalogue 40", Leeds & Northrup, Philadelphia, 1927, p 19.

About the Author

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His museum of early apparatus is a wing on his 1857 house fronting the Kenyon campus and holds over half of the 700 items in his collection. He writes and lectures frequently on early apparatus and the history of photography (including a series of over 375 pictures in American Journal of Physics), and he served for eight years as the chair of the Committee on the History and Philosophy of Physics of the American Association of Physics Teachers.