2.1 Comment: Putting the Parts Together

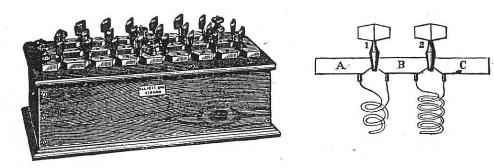
The actual physical embodiment of most of the bridge circuits described so far was usually a bench top combination of fixed, decade and variable passive elements, connected to a voltage source and suitable detector each with its own adjustment circuit elements. These assemblies not only took up a lot of space, they also were not easy to set up or use and were subject to errors. As the use of electricity, and later electronics, rapidly increased, measurements spread out from the scientist's laboratory into industry where the awkward bench-top layouts were intolerable. There was an urgent need for more compact, simplified apparatus that could be used by those who were not expert in the theory and who just wanted to get good results.

2.2 Early Dc Bridges

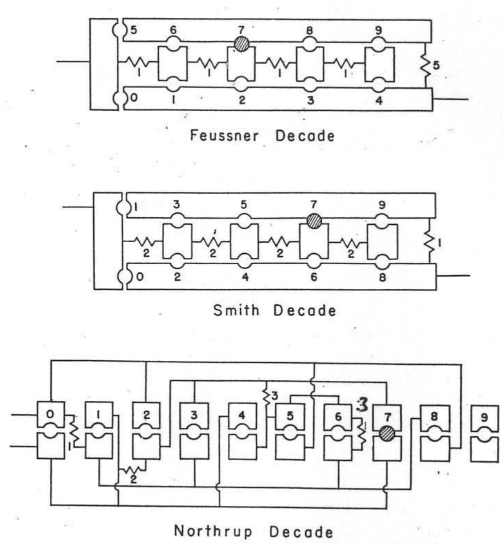
Dc bridge elements; resistance standards, decade boxes (used as adjustable arms), slide-wires and ratio boxes (used for ratio arm pairs) were made by many early companies such as Elliot Bros., Cambridge Instruments, Paul Instruments (which later joined Cambridge) and Tinsley in England, Siemens and Otto-Wolff in Germany, and Leeds and Northrup (L&N) and General Radio (GR) the USA.

L&N, the most famous manufacturer of precision dc electrical measurement equipment, was founded as the Morris E. Leeds Co in 1899 by Leeds (b. 1869) who had previously worked for Queen & Co. in Philadelphia. Edwin Northrup (b. 1866), a physics professor at the University of Texas, joined him in 1903 and the name was changed to Leeds and Northrup. Northrup designed many of their early instruments but left the company in 1910 to join the faculty at Princeton University[1].

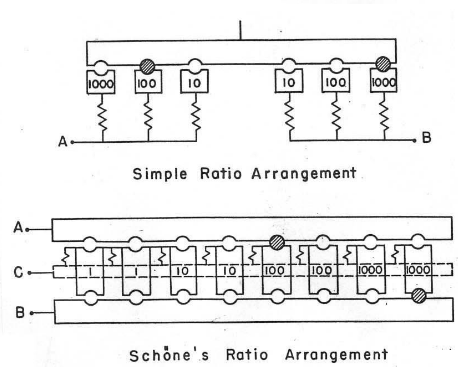
In the earliest decade boxes, such as that made by Elliot Brothers (figure 2-1), the resistance value was switched by taper pins that plugged between blocks of brass making a very low resistance connection. The blocks were arranged in a "pattern" that usually carried the name of its designer. Three types that required only one taper pin per decade to get values from 0- to 9 were those by Feussner (using relative resistor values of 1-1-1-1-5), Smith[2] (using 1-2-2-2-2)and Northrup[3] (using 1-2-3-3), see figure 2-2. Taper pin decades with nine equal resistors per decade were also used and nine resistors are used in most rotary switches decades although sometimes ten were used to get a "10" position. Another rotary decade used only 2-valued resistors and paralleled two of them to get the odd values in such a manner that there were no switching discontinuities[4]. At first these rotary decades used multiple-leaf rotors on brass blocks mounted on top of the panel. It was not until much later that the switches were put under the panel with only the dials visible.



2-1 Taper-Pin Resistance Decade and Pin & Coil Detail
Elliot Bros. Before 1907



2-2 Taper-Pin Decade Patterns



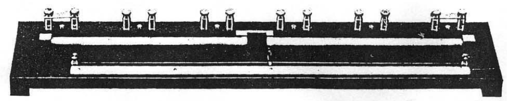
2-3 Ratio-Box Patterns

Separate ratio-arm boxes were also made in several taper-pin "patterns". The simplest used the scheme shown in figure 2-3a, but the most popular was the Schöne pattern[5] (1898) (figure 2-3b] in which any resistor could be put in either arm thereby allowing self-checking of 1:1 ratios.

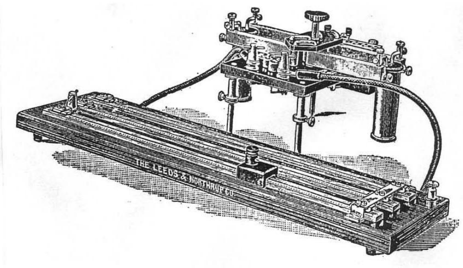
Several companies made separate slide-wires to be used with other elements to form bridge circuits, such as the type 130 by GR [figure 2-4] and many bridges had built-in slide wires as adjustments. The slide wire could be used in several ways. It could be used as single, adjustable, low-valued, two-terminal resistor, but this was not preferable because of the relatively unstable resistance of the sliding contact. It was usually used as a differential resistor (voltage divider) with the slider connected to a high resistance bridge arm or in series with the galvanometer where it would cause little error. The slide wire could form two arms of a bridge for comparing two low-valued resistors or used as a fine balance between the ratio arms. More often the slide wire was put between the unknown and a fixed standard as in the Carey Foster circuit of figure 1-5. L&N made a Carey Foster apparatus, or "coil changer", figure 2-5, that consisted of a test stand with mercury cups to hold the precision fixed resistors being compared, connections for the ratio arms, a mercury cup switch to interchange the resistors and three slide wires of different resistances which could be selected to optimize the circuit[6]. In the Tinsley Wheatstone Bridge of figure 2-6 a double slide-wire is between the unknown and the adjustable arm[7]. H. Tinsley Ltd. was founded in 1904 by Henry Tinsley and is probably the oldest maker of electrical instruments still in business today.

In Kelvin bridges the slide-wire was used alone as a four-terminal standard, as in a bridge made by Nalder Brothers[8], figure 2-7, or with a decade to form the standard as in the L&N Type 4300 bridge[9], figure 2-9. Dual, ganged slide-wires were used in the Hoopes conductivity bridge by L&N[10], figure 2-8. This is a version of the Kelvin Bridge for comparing the relative conductivities of wire samples. The dual slide-wire adjusted both the main ratio arms and the auxiliary Kelvin arms simultaneously.

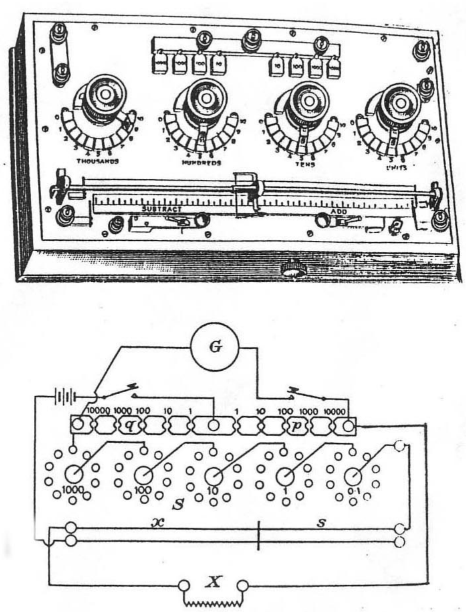
The low-resistance of a slide wire was a drawback except when measuring very low-valued resistances. L&N increased this resistance to 100 ohms by winding fine wire on a mandrel thus increasing the



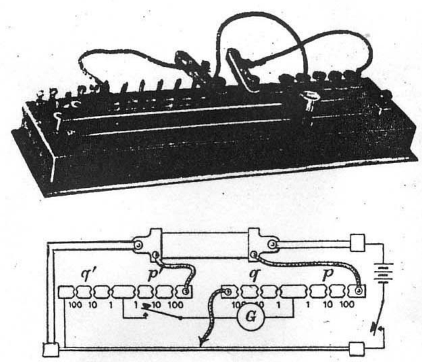
2-4 Slide-Wire Bridge
GR Type 130 1918



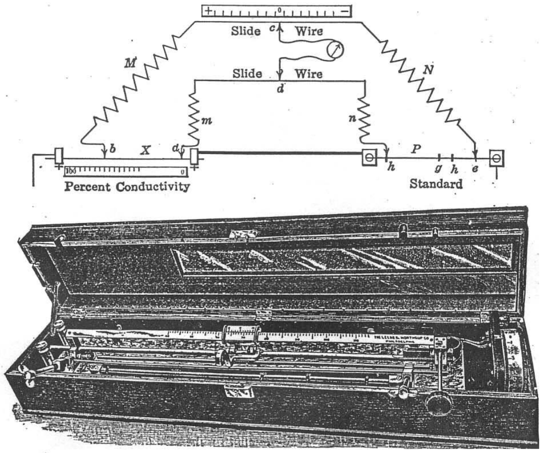
2-5 Carey Foster 'Coil Changer'
Slide Wires and Switch
L&N Before 1917



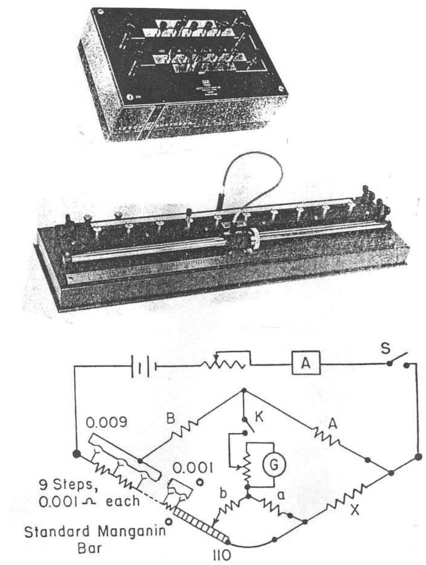
2-6 Wheatstone Bridge with Slide Wire
Tinsley Before 1924



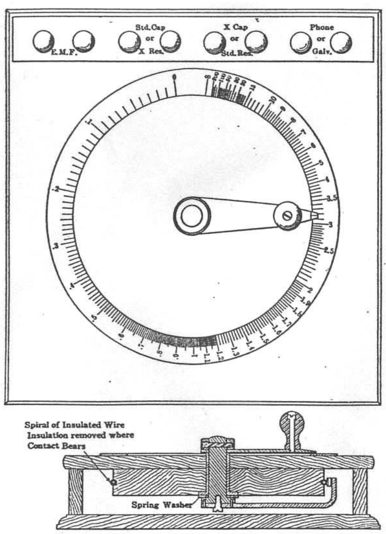
2-7 Kelvin Bridge with Slide Wire
Nalder Bros. & Co. before 1924



2-8 Hoppes Conductivity Bridge
L&N Before 1917



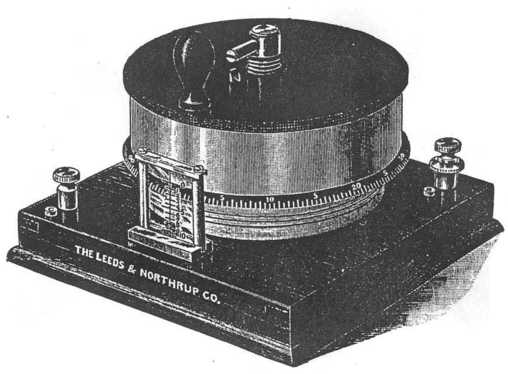
2-9 Slide-Wire Kelvin Bridge
L&N Type 4300



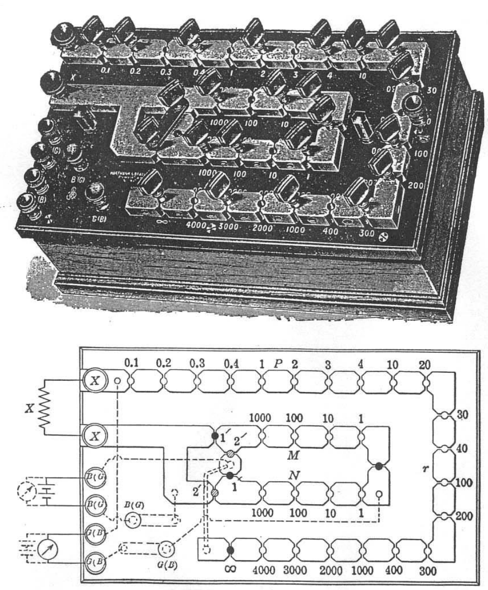
2-10 Rheostat for Wheatstone Bridge
L&N Before 1912

wire's length, an early rheostat[11] (c1910). With it they made a circular "slide wire" that formed the arms of a simple comparison bridge that had a reading from zero to infinity, see figure 2-10. Another way L&N increased the resistance, and the resolution as well, was to increase the wire length by winding the wire in a spiral on a marble drum as shown in figure 2-11. Such a unit was used in a bridge as well as in their famous K2 potentiometer[12].

Some early bridges, such as those by Hartmann & Braun[13], figure 2-12 and by

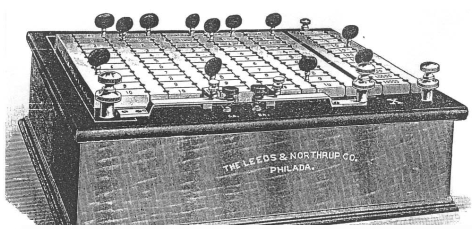


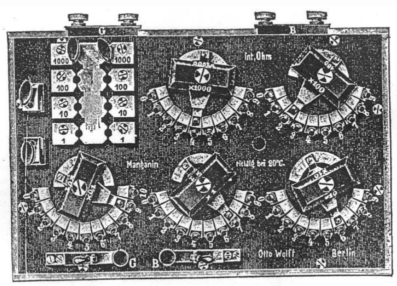
2-11 Multi-Turn Slide Wire
L&N Before 1912



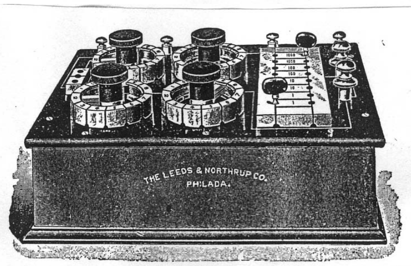
2-12 Taper-Pin Wheatstone Bridge
Hartmann & Braun Before 1924

L&N[14], figure 2-13 used taper pins both for the adjustable arms as well as for the ratio arms. The patterns of the taper pins used in a bridge were sometimes called “bridge tops.” Note the number of taper pins used. It was much easier to adjust rotary switches as used in the Otto Wolff bridge[15] of figure 2-14 and the L&N bridge[16] of figure 2-15. Note that both these bridges used taper pins to adjust the ratio arms because good contact was critical when they were of low value.





2-14 Bridge with Rotary-Switch Decades
Otto Wolff Before 1912

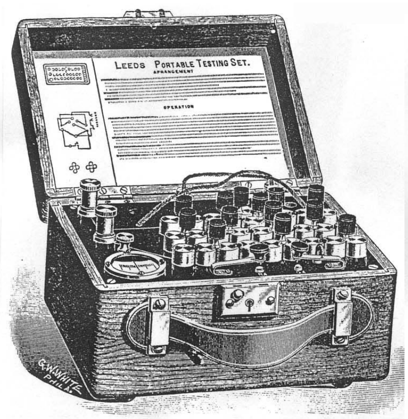


2.15 Rotary-Switch Wheatstone Bridge
L&N Before 1917

An important step in convenience was the introduction of L&N’s famous portable bridge, the Type S “Dial Decade Testing Set” introduced in 1915[17], see figure 2-16. This was preceded by a taper-pin version[18], the “The Leeds Portable Testing Set” of figure 2-17 and a rheostat version[19], “The L&N Fault Finder” shown in figure 2-18 (designed by Northrup himself), both introduced before 1912. The Type S had rotary dials with hidden contacts for both for setting the ratio as well as the main adjustment that ha four decades. It also included a battery and galvanometer and switches for reversing polarity and adjusting sensitivity and it all fitted in a small wooden box. Besides being a general-purpose Wheatstone bridge, these instruments included Murray and Varley "loops", bridge circuits for locating wiring faults, and were standard equipment for maintenance of power and telephone lines. The Type S was manufactured for many years without substantial changes except to its name and type number. It was probably the most popular dc bridge ever built, perhaps the most popular bridge of any kind, ever. It was copied by several other companies.

A class of bridges still used in precision work is the direct-reading ratio set, or DRRS, made by L&N, Biddle and others[20]. This compares two closely equal resistors, and usually two of precise 10:1 ratio also, with a Wheatstone or Kelvin bridge with very narrow range, less than a few percent. These used Waidner-Wolff (or "shunted") decade adjustments[21], see figure 2-19, developed at NBS in 1902 that were highly immune to switch contact resistance because small changes in resistance were obtained by switching resistors of much higher value in

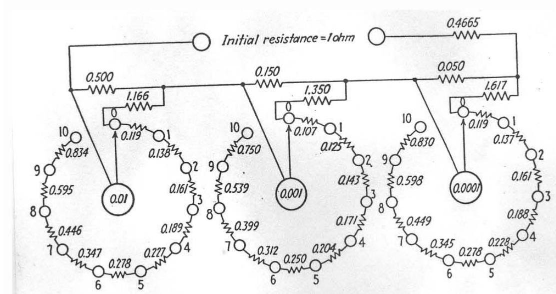
2-16 Dial Decade Testing Set
Wheatstone Bridge & Test Loops
L&N Type S 1915



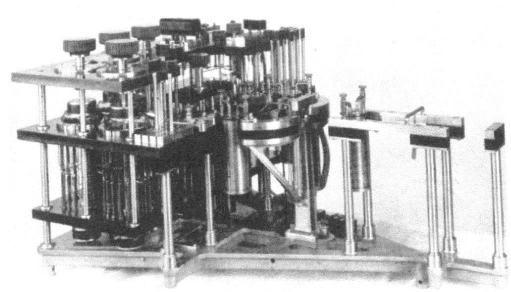
2-17 Leeds Portable Testing Set
L&N Before 1912

2-18 'Fault-Finder' Bridge
L&N Before 1912

parallel with a fixed resistor. By contrast a universal ratio set, URS, could compare resistors of any ratio. It acted like a switched high-resistance slide-wire in that it had resistance decades in two arms that were ganged such that the total resistance was constant. However, the precision Waidner-Wolff adjustments could not be used so that the switch resistance was critical.



2-19 Waidner-Wolff Shunted Decades
1.000 to 1.111 Ω in steps of .0001 Ω

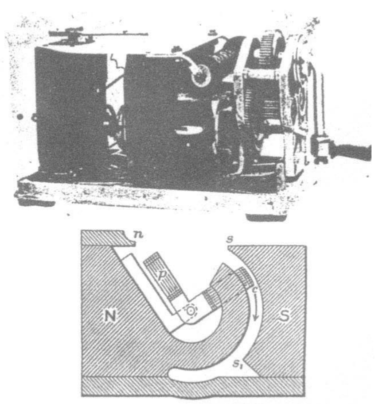


2.20 NBS High-Precision Bridge or 'Wenner Bridge'
Removed from Oil Bath 1940

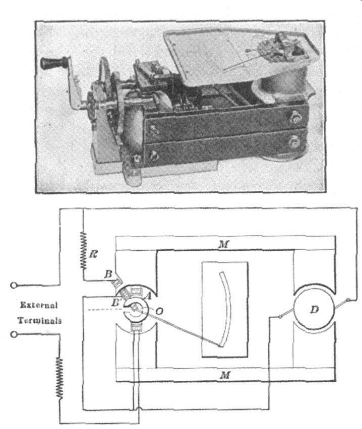
Perhaps the ultimate dc bridge is the NBS Precision Bridge, or Wenner Bridge[22], designed in about 1918. This was a collection of standard resistors, Waidner-Wolff decades, taper-pin switches and mercury contact stands all in a large oil bath, see figure 2-20. It was precise as well being impressive. It could be configured in several ways but its main use was as a DRRS with a 1:1 ratio or 10:1 ratio, the latter used to scale the calibration of decade-valued resistor standards over a wide range. A few of these bridges were made by Eppley Labs in about 1960 for use in military laboratories and those of major defense contractors. The original NBS bridge was retired in 1982 after many years of use.

2.3 Other Early Dc Instruments

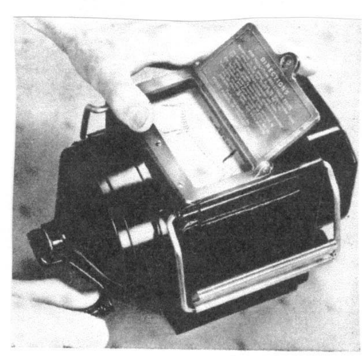
By far the most common way to measure resistance, albeit not very precisely, was to use an ohmmeter calibrated directly in ohms. It is directly descended from Ohm's circuit but with a battery source and with the additions of a calibrated meter scale, switched ranges and a zeroing adjustment which corrected for variations in the battery's voltage and resistance. Millions of ohmmeters have been made. The dependence on the source voltage was reduced by the cross-coil ohmmeter principle, ascribed to Ayrton and Perry[23]. It used a meter with two coils at right angles to each other, one carrying the current through the unknown and the other a current proportional to the applied voltage. The freely rotating, soft-iron needle lined up with the resultant field which depended on the ratio of the two currents and thus proportional to resistance. The scale went from zero to infinity. Early, commercial instruments of this type were made by Clark (figure 2-21), Evershed, Paul, Record, Weston and several other companies[24]. Many of these had hand-cranked



2.21 Clark's Ohmmeter
and Two Coil Arrangement
Before 1924

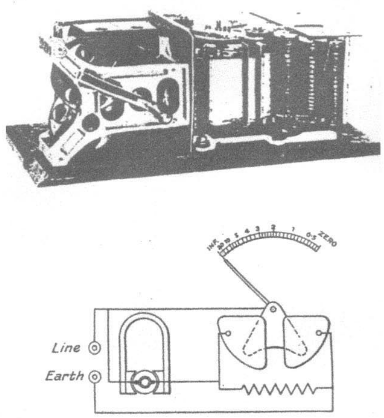


2.22 'Megger' High-Resistance Ohmmeter
Evershed Before 1917



2.23 'Megger'
Biddle 1940

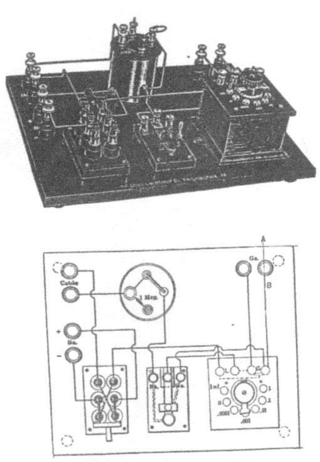
magnetos to generate the test voltage thus avoiding famous instrument to use the two-coil method was the "Megger" that measured very high resistances. It was first made by Evershed in England[25] (figure 2-22) who licensed the James G. Biddle Co. in the US in 1940, see figure 2-23. These had a hand-cranked magneto to develop a high voltage, usually 500v, roughly regulated by a governor. In this instrument the moving coils are between the fixed pole pieces and a coaxially mounted C-shaped iron core that provides a non-uniform field that shapes the meter scale. A somewhat analogous instrument also used for high-resistance measurements was the electrostatic ohmmeter made by Nalder Bros. & Thompson (figure 2-24). It used the electric attraction between capacitor plates to drive the meter pointer. The net attractive force between the two stators and rotor depended on both voltage and current in such a manner that the deflection was largely independent of the magneto-generated voltage applied to the circuit[24].



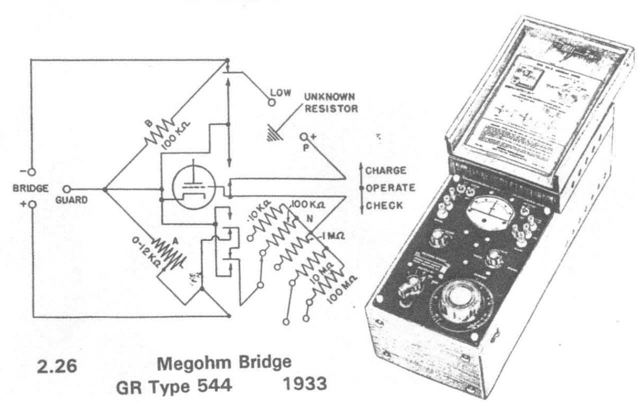
2.24 Electrostatic Ohmmeter
Nalder Bros. Before 1924

Very high resistances were also measured by "Megohmmeters" and "Megohm Bridges". Probably the first megohmmeter was the General Radio 487-A, designed by F. Ireland[27] in 1936. It was an ohmmeter that measured current by measuring voltage across a high-valued standard, in series with the unknown, with a vacuum-tube voltmeter. This class of instrument is made to this day. Their accuracy depends on both the accuracy of the applied voltage and the accuracy of the voltmeter as well as that of the standard resistor.

An early high-resistance bridge was the cable resistance test set by L&N[28], figure 2-25. The first so-called Megohm Bridge, the GR 544-A, see figure 2-26, was designed by R.F. Field in 1933[29]. This was a multi-range Wheatstone bridge using standards as high as 100 MΩ and a vacuum tube (type 32) with low grid current as a detector. Also the variable arm, a rheostat ("pot"), was in the arm adjacent to the unknown so that its resistance was proportional to the conductance of the unknown. However the dial was calibrated in resistance and hence went to infinite resistance when the rheostat was set to zero, a useful way to extend the highest range to extremely high values.



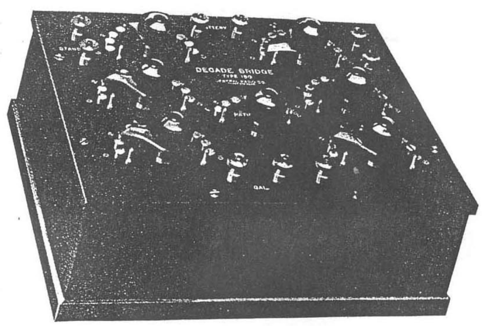
2.25 'Factory Cable Testing Set'
High-Resistance Bridge
L&N Before 1912



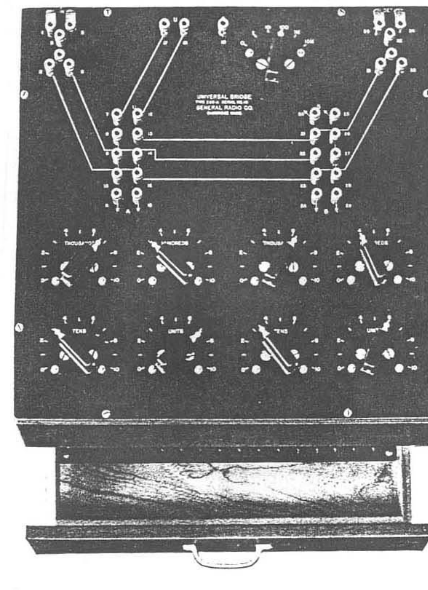
2.26 Megohm Bridge
GR Type 544 1933

2.4 Early Ac Bridges

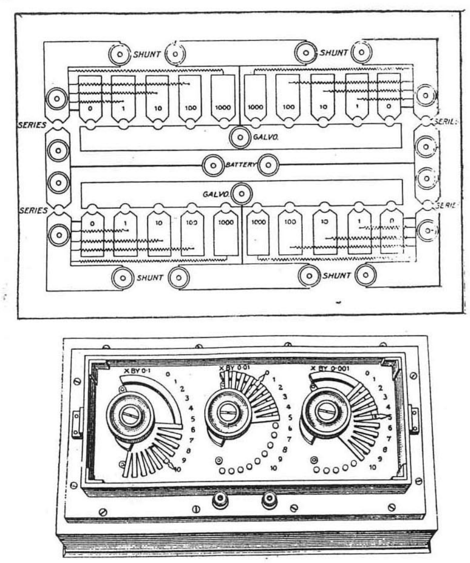
While L&N had the most complete line of dc bridges, GR, the General Radio Co., founded by Melville Eastham in 1915, became the leader in ac bridges. They made several early "decade bridges", the Type 160 (figure 2-27) in 1918[30], the Type 193 in 1919[31] and the Type 293 in 1932[32]. These included switched ratio arms and a resistance decade but required an external standard of resistance, capacitance or inductance. The 293 had a drawer for these external plug-in parts (figure 2-28). An L-C bridge made by Tinsley had resistances of 0, 1, 10, 100, 1000 ohms or an open circuit in each of the four



2-27 Decade Bridge
GR Type 160 1915



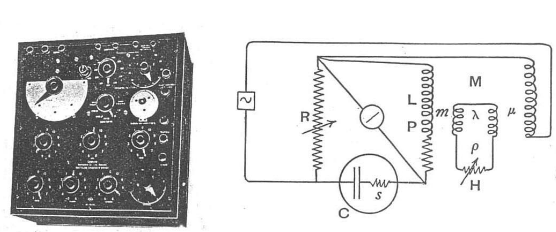
2-28 'Universal' Bridge
GR Type 293 1932



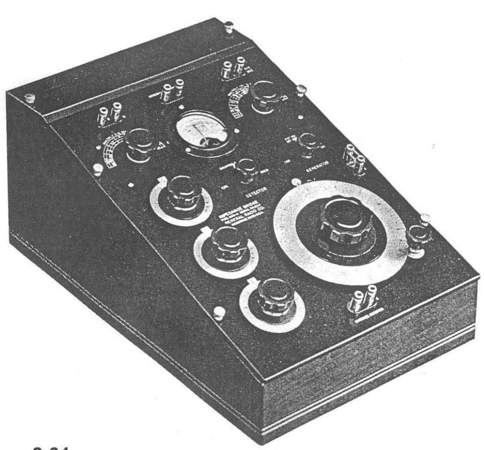
2-29 L-C Bridge and 'Slide Condenser'
H. Tinsley & Co. 1920

arms, but each arm also had terminals where external standards or decade adjustments, such as the "slide condenser", could be connected (figure 2-29). This unique variable capacitance put from zero to ten equal capacitors in parallel using ten contact arms. This avoided the discontinuities of the usual four-capacitor decade box.

Cambridge Instruments, founded in 1881 by Horace Darwin (son of Charles), made two early capacitance bridges using circuits devised by Campbell that used mutual inductances as reactance standards. One of these the Campbell Condenser Bridge[34] (1933) is shown in figure 2-30. It used Campbell's modification of the Carey Foster bridge of figure 1-14 which was direct reading in capacitance and power factor in spite of its complicated balance equation. GR also made two early capacitance bridges, the types 240[35] and 383[36] which used capacitance standards and included buzzer sources and headphones. An option



2-30 Campbell Condenser Bridge
Cambridge Instrument Co.
Before 1935 (Circuit 1917)



2-31 Impedance Bridge
GR Type 650 1933

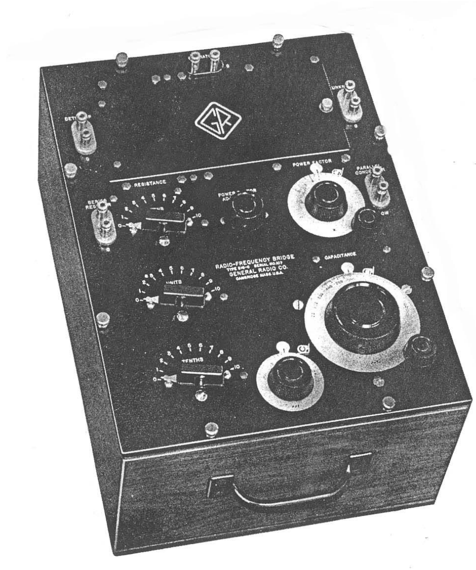
for the later bridge was an ac amplifier with an indicating meter (the type 415) so that balances could be made by visual means instead of earphones.

A major step was made by R.F. Field[37] in 1933 when he combined several bridges circuits to make the first general-purpose "Impedance Bridge", the GR 650-A of figure 2-31, that measured R, C and L, all "direct reading" (a dial reading with a decade multiplier). Any of four bridge circuits could be selected to measure series capacitance (de Sauty-Wien), series or parallel inductance (Maxwell & Hay) or resistance (Wheatstone with either ac or dc excitation). The switched ratio arm and the main rheostat adjustment were common to all circuits. The accuracy of this rheostat was increased by a "justifying" mechanism that consisted of an adjustable cam plate and a roller cam follower on the rotor arm. This compensated rheostat, along with its logarithmic dial, allowed a bridge accuracy of 1% over each 10:1 range. This instrument included batteries and galvanometer for dc and a hummer for a 1 kHz source, but external headphones were used as the ac detector. Later a line-operated, vacuum-tube RC (Twin-T) oscillator and tuned detector unit (type 650-P1) designed by Lamson[38] was available in 1946. This bridge was extremely popular. It was found in most every college electrical engineering or physics laboratory and this encouraged acceptance in industry. The sloping panel 650-A was also long-lived, finally replaced by GR with the Type 1650 twenty-six years latter. Many other companies, at least thirty, made such "Universal" or “RLC” bridges for R, L and C measurements (see Part 3).

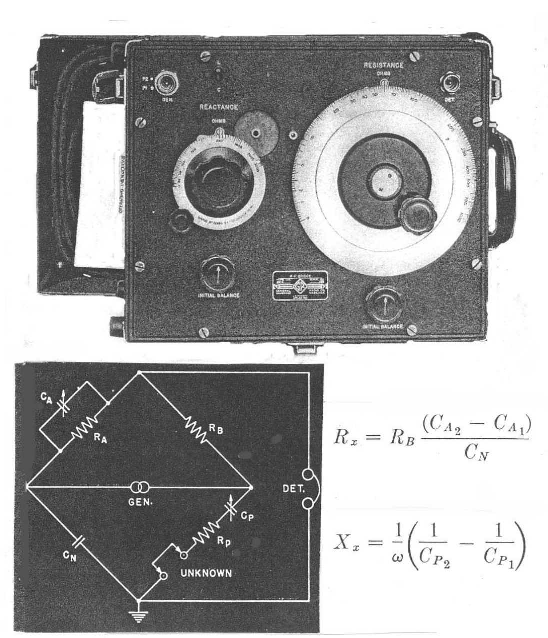
Bridges were being designed for special purposes as well-defined needs appeared, such as testing high-valued electrolytic capacitors. An example of this type was the GR 632-A by Field[39] (1933). This included a 600v dc polarizing supply and a galvanometer for leakage current measurements. This was the archetype for a series of later GR instruments: the type 740 in 1938 by Packard[40], the type 1611 in 1948 by Easton[41] and the type 1617 in 1966 by Hall[42]. These had increasingly high ranges, 250 uF, 1.1 mF, 11 mF and 1.1 F respectively. High-capacitance bridges were made by ESI (model 273), Sprague Electric (1W and 2W series), British Physical Laboratories (CB 154) and others.

Another special-purpose bridge was the "Vacuum-Tube Bridge" used for measuring tube parameters, the Type 361-A in 1928 by Lamson[43], followed by the type 561 by Tuttle[44] in 1932 and the type 1661 by Bosquet[45] in 1959. These were nulled bridges with special circuits that measured plate resistance (r_p), transconductance (g_m) and amplification factor (u). Several other companies made meter-type “tube checkers” that gave indicated only “good” or “bad.”

Yet another need was that for RF measurements. It is claimed by GR that their type 516-A was the first commercial “Radio Frequency Bridge”, introduced in 1932, that operated up to 5 MHz. This was designed by C.T. Burke[46] who also designed the improved 516-C introduced the next year. This



2-32 Radio-Frequency Bridge
GR Type 516 1932

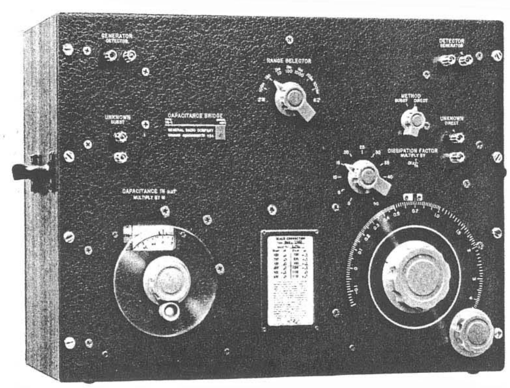


$$R_x = R_B \frac{(C_{A_2} - C_{A_1})}{C_N}$$

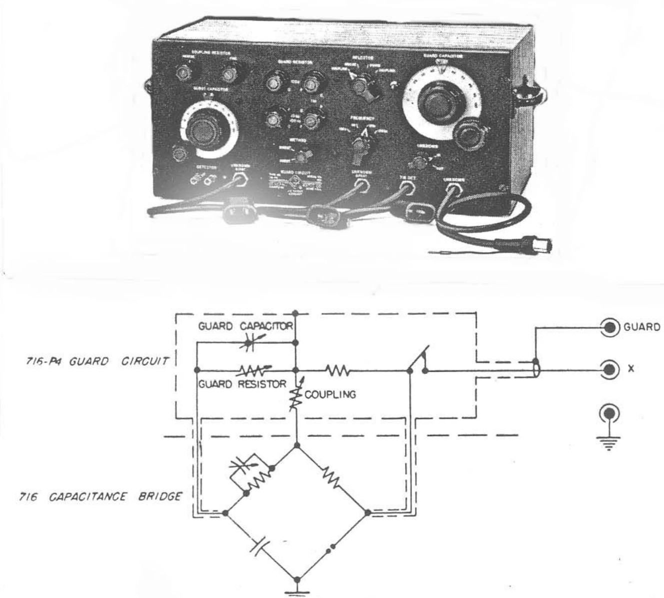
$$X_x = \frac{1}{\omega}\left(\frac{1}{C_{P_2}} - \frac{1}{C_{P_1}}\right)$$

2-33 Radio-Frequency Bridge
GR 916-A 1939

was a 1:1 ratio Schering bridge but with an added resistance adjustment in series with the main capacitor so that it measured resistance as well as capacitance and dissipation factor. Also, it had provision for both for both series and parallel substitution methods, see figure 2-32. This instrument was the forerunner of many later high-frequency Schering bridges made by GR, the type 916-A by D.B. Sinclair[47] in 1940, figure 2-33, followed by the 1601 in 1950[48] and the 1606[49] in 1955, the latter two designed by R.A. Soderman. These used series substitution, the DUT was connected in series with a variable capacitor in one arm and measured by the differences in the two adjustments between their settings with the DUT connected and those made with a short circuit The most precise capacitance bridges of this era also used the Schering circuit. The GR 716-A designed by Field[50] in 1936 used a worm-gear driven precision capacitor and made both direct-reading measurements and parallel substitution measurements (with the DUT placed in parallel with the main capacitor), figure 2-34. The dissipation factor, D, balancing component was also a variable air capacitor and its high resolution allowed precise D adjustments for dielectric measurements. This bridge was modified to -B and -C versions the latter being the workhorse precision capacitance bridge up until the 1960s when it was replaced by transformer-ratio-arm bridges. A 1 MHz version by Easton[51], the 716-CS1, was the premier 1MHz capacitance bridge for many years.



2-34 Capacitance Bridge (Schering) GR Type 716-C 1947 (Type 716-A 1936)



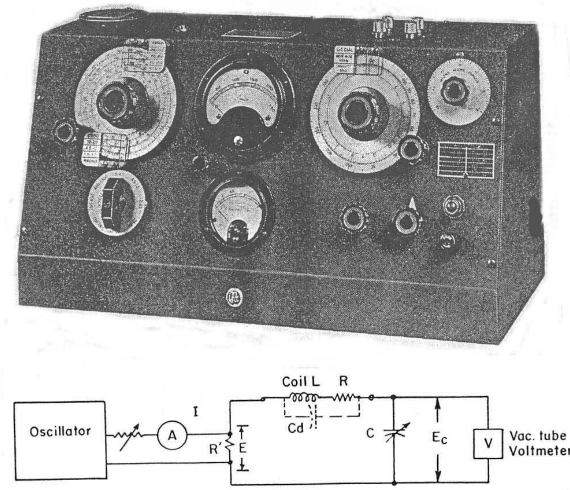
2-35 Guard Circuit for Capacitance Br. GR Type 716-P4 1952

Guarding was necessary for both dielectric measurements and measurements on low-valued, three-terminal capacitance standards, see (figure 1-21). I.G. Easton designed one for the 716-C, the 716-P4[52]. This had not only a "guard" adjustment, but also a "coupling" adjustment (see figure_2.35) that made the guard adjustment less critical. The inherent guarding of transformer-ratio-arm bridges eventually made such guard balances unnecessary.

The GR type 667-A (again by Field[53]) was the most popular precision, laboratory inductance bridge from 1934 until it was replaced by the 1632 in 1959. The 667-A was ratio bridge, that is it compared the unknown inductor to an internal standard inductor, a 1 mH, toroidal unit, but it also had a variable inductor in series with the DUT to allow a final balance without a "sliding null" (interaction between the two balances) that made the adjustments slow, sometimes impossible. The later Type 1632 is an Owen Bridge designed by Lamson and Hersh[54]. This also had non-interactive adjustments because both variable components were in the same arm (see figure 1-19.

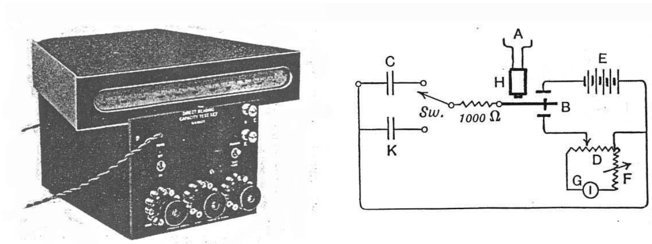
2.5 Other Early Ac Instruments

Perhaps the most famous RF measuring instrument was the Boonton Radio Company's Type 100A "Q Meter" designed by C.J. Franks and W.D. Loughlin and introduced in 1934[55]. This popular instrument went through many revisions over the years with the BRC types 160-A appearing in 1939 (see figure 2-36) and 260-A in 1953 being the best known. Hewlett-Packard, who bought BRC, listed the type 4342A Q meter in its catalogs through 1993. In this circuit the unknown inductor is resonated against a variable capacitor whose dial reads inductance directly at certain frequencies and the inductor's Q value is proportional to the resonant peak voltage and is read on the scale of a vacuum-tube voltmeter.



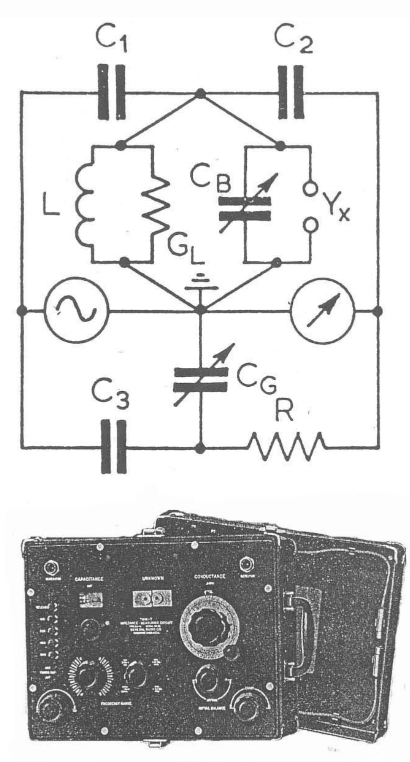
2-36 Q Meter BRC Type 160-A 1939 (Type 100-A 1934)

Capacitance and inductance meters trace back to Maxwell's early ballistic circuit where inductance was determined from a galvanometer deflection and to periodically switched methods using a vibrator or rotating commutator such as one by Fleming and Clinton[56] (1903). A commercial instrument sold by Tinsley was the Gall capacitance meter[57] (1933) of figure 2-37 used a similar principle. Its accuracy was improved by calibration against an internal capacitance standard ("K" in the figure) and it provided several capacitance ranges by adjustment of the resistors in series and in shunt with the meter.



2-37 Gall Capacitance Meter Tinsley & Co. 1933

Also of interest were a bridged-T circuit by Tuttle[58], the GR 721 Coil Comparator of 1937, and a Twin-T by Sinclair[59], the GR 821 Twin-T Measuring Circuit, 1940, see figure 2-38. These were null-type instruments like bridges but had the advantage that the input and output were both grounded so that no isolation transformer was necessary. The latter instrument used variable air capacitors for both balances and used the parallel substitution method. It was direct-reading in capacitance over its frequency range (.46 to 40 MHz) and in G at 1, 3, 10 and 30 MHz and was probably the most accurate instrument for conductance measurements at these frequencies.



2-38 Twin-T Impedance Measuring Circuit GR Type 821 1940

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