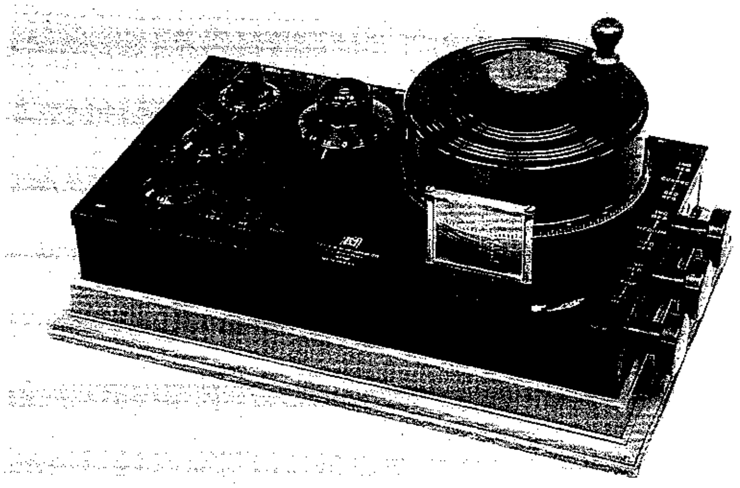
The potentiometer and its potential

For a decade, the word potentiometer meant more than just a volume control. Harold Kirkham explores the potentiometer, and its use as a remarkably precise voltmeter having the capability to read to within a few parts per million.

When we say that there is a potential difference of so many volts between two points in a circuit, we are really saying that the potential is so many times bigger than the volt – a quantity that is known exactly. Forget, for the present, the fact that the volt itself has been changed many times, and as recently as 1990.

An analogue voltmeter obscures the situation somewhat, because an analogue voltmeter is essentially a calibrated spring. The comparison is made at the level of the force of a magnetic field and the force of a spring. A digital voltmeter, on the other hand, makes the comparative nature of the measurement obvious, since there is, buried in the internal circuitry, a reference voltage of some kind.

The digital voltmeter compares the reference voltage and the unknown, to produce a reading directly in volts. At the end of the last century, before there was any such thing as electronics, the potentiometer, along with a reference voltage and a galvanometer, did much the same thing.



This Leeds and Northrup version of the potentiometer is an adaptation of the Crompton arrangement, one of a series (K1 through K5) sold as recently as the 1980s. This one is a K2, dating about from the 1940s. It has three ranges, with full-scale readings of 1.6V, 0.16V and, believe it or not, 0.016V.

Reference voltage sources

A number of devices have served as reference voltages over the years. Since it was patented by Edward Weston – who had emigrated from Britain, and started a company in New sey – in 1892, the Weston cell has been the voltage reference of choice.

This cell **Fig. 1** consisted of mercury as the positive element and cadmium amalgam – a solution of one part of cadmium in seven parts of mercury – as the negative element. These materials could be obtained with a high degree of purity, which is an important factor in a cell whose voltage was to be as permanent as possible.

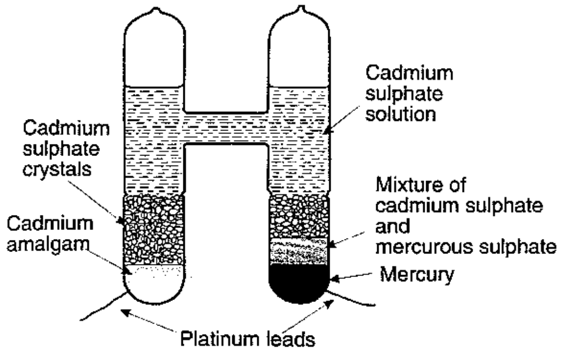


Fig. 1. The Weston cell has crystals of cadmium sulphate to ure a saturated electrolyte. A cell like this, kept in a constant temperature oil bath, has a lifetime of many years.

The electrolyte was a saturated solution of cadmium sulphate, with cadmium sulphate crystals added to ensure saturation. A depolariser, mercurous sulphate, was added. The connections to an external circuit were made by platinum wires sealed into the glass container.

Voltage of the cell when constructed in accordance with the standard specification was 1.01859V at 20°C. The voltage at a temperature near 20°C could be estimated readily since the cell output decreased by 40ppm/°C.

Great care had to be taken to ensure that no appreciable current was taken from the standard cell, as the output was only constant on open circuit. Standard cells were thus only used in null methods of measurement, such as the potentiometer.

Potentiometer principles

In the potentiometer, **Fig. 2**, battery B sends a current through a slide-wire of uniform cross-section. Resistor R is a regulating resistance to control the current in the slide wire. It is desired to measure the voltage of the battery B_1, connected in series with a key and a galvanometer. A galvanometer was a device to indicate, rather than measure, current. It can be thought of as a sensitive centre-reading microammeter, except that many galvanometers would produce large deflections with less than a microamp. Typically,

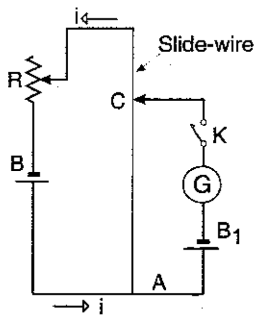


Fig. 2. The elementary potentiometer consists of a reference cell, galvanometer and key connected to the moving terminal of a slide-wire. A battery supplies the current.

only the zero or centre was marked on the scale.

Suppose that r is the resistance per unit length of the slide-wire, and that i is the current in it when the key K is open. Then, if the length AC is l, the voltage drop across AC is irl.

If key K is closed, current flows through the galvanometer in the direction of A to C, if the voltage drop across the length l of the slide wire is greater than the voltage of the battery B_1. Sliding contact C is adjusted until there is no deflection of the galvanometer. Length AC_1 is measured. This length can be called l_1, corresponding to battery B_1.

Battery B_1 is replaced by B_2, and contact C again adjusted until no current flows through G. With length AC_2 at l_2, writing the voltages of the batteries as E_1 and E_2, both of which must be less than the voltage of the supply battery B, gives,

$$E_1 = irl_1$$

$$E_2 = irl_2$$

so,

$$\frac{E_1}{E_2} = \frac{l_1}{l_2}$$

A scale is provided on the potentiometer so that l_1 and l_2 may be read off. If one of the two batteries, say B_2, is a standard cell of known voltage, the voltage of battery B_1 is given by,

$$E_1 = \frac{l_1}{l_2} \times E_2$$

Note that when the potentiometer is balanced, no current passes through the battery under test, so the potentiometer effectively presents a very high resistance. Neither the standard cell nor the circuit being measured is loaded by the potentiometer.

The potentiometer works because it is possible to produce very uniform resistance wire. Of course, that uniformity would be spoiled if the user savaged the wire with a screwdriver as a sliding contact – as I remember doing to a slide-wire in an early physics class. Ordinarily, however, the various lengths could be measured with less than 1% uncertainty. Nonetheless, the approach so far described would be somewhat cumbersome.

Direct reading potentiometer

Col. Rookes Evelyn Crompton – founder of the company bearing his name – first modified the simple slide-wire form of potentiometer to provide improved resolution, and make the device direct reading, **Fig. 3**.

A graduated slide-wire AC was connected in series with 15 coils (resistors), each of which had a resistance exactly equal to that of the slide-wire, of the order of 10Ω. There were two moving contacts, sliding over the slide-wire and the studs of the resistance coils. Supply battery B was 2V, and R_1 and R_2 were variable resistances for the coarse and fine adjustment of the potentiometer current.

Galvanometer G was in series with key K, and a switch by means of which either the standard cell S or the battery whose voltage was to be measured could be connected.

In use, the potentiometer was first 'standardised,' i.e. made direct reading, by adjustment of the current from the supply battery as follows. A standard cell was connected to the ter-

Null versus deflection

In the 1880s, physicists were trying to 'determine' the ampere and the ohm, based on definitions originating in the centimetre-gramme-second system – itself not yet completely adopted for scientific use. These definitions led to apparatus that occupied a considerable amount of time and energy to set up and to use.

Most of those concerned came to believe that any method that did not require such effort must necessarily be inferior. The orthodox view was that the measurement of electrical quantities was supposed to involve skill and exertion, using complicated apparatus.

As an example, consider the tangent galvanometer, a device to indicate current. The current is passed through a circular coil, at the centre of which is freely suspended a very small magnetic needle – essentially a compass. Initially, the apparatus is set up with the plane of the coil aligned with the local Earth's field. Deflection of the needle is then given by,

$$I = \frac{Hr}{2\pi N}\tan\theta$$

where r is the radius of the galvanometer coil of N turns, H is the horizontal component of the Earth's magnetic field, and I the current.

Consider the difficulties. First, the Earth's field must be determined, and must not be disturbed by the fields of other current-carrying conductors. Second, the coil must be of known radius, and must be exactly vertical. The needle must be infinitely short, and at the centre of the coil.

The tangent galvanometer was far from direct reading, and needed considerable skill to use. There was a general feeling that, for precision work, only the zero point on an electrical instrument could be relied upon. All the well-known bridge methods – and the potentiometer – are nulling methods, requiring an accurate fix on only the zero of the instrument.

This view that the direct methods were inherently inferior was deeply held. Imagine the consternation when Professors William Ayrton and John Perry of the London City and Guilds College, Finsbury, introduced a series of direct reading electrical instruments, beginning in 1880. These first instruments were not very accurate – perhaps ±5% – but they were linear. They required only a constant multiplier, not a conversion table, to translate the reading in degrees deflection to the current or voltage. They were also easy to use, and could be connected more or less at will into circuits of any kind.

In 1881 Ayrton and Perry introduced the terms ammeter and voltmeter. While Ayrton and Perry instruments rapidly dominated the growing world of commercial electricity, they were looked down on by physicists as being both direct reading and pre-calibrated by an instrument maker, a middle-man upon whose skill physics was reluctant to rely.

It seems to have been overlooked that both the ruler and the stopwatch were direct-reading, pre-calibrated instruments. Potentiometric measurements were, being null measurements, quite acceptable.

By 1884, Ayrton and Perry had labelled the scales of their instruments directly in volts and amps. In 1894, Ayrton and another colleague, H. C. Haycraft, presented a paper called 'A Student's Simple Apparatus for Determining the Mechanical Equivalent of Heat' at the Physical Society in London. This paper showed that by using an industrial strength current of about 30A, measured by a direct-reading ammeter with $^1/_3$% accuracy, and a voltage of about 9V, measured by a direct-reading voltmeter with an accuracy of $^1/_5$%, the mechanical equivalent of heat (Joules' constant) could be determined in about ten minutes.

The world of physics was, to put it mildly, quite agitated. E. H. Griffiths, a Cambridge Fellow, had spent the five years before 1893 making 100 separate evaluations to find a value of 778.99 foot-pounds per thermal unit. A year later he had discovered an error in his work, and published a revised value of 779.77. Now here was Perry claiming results of equal precision in a matter of minutes. The indignation of the physicists – particularly Griffiths, as can be imagined, but also George Carey Foster and Charles Vernon Boys – was such that a permanent split occurred between physics and electrical engineering.

This almost religious faith in complex, non-direct methods is only now being abandoned in the physics of international standards. Electrical engineering meanwhile, has, gone on to provide instrumentation of greater and greater accuracy and wider and wider applicability.

nals marked SC and the potentiometer was set to read, directly, the known voltage of the standard cell, corrected to the room temperature if necessary. If a Weston cell was used, contact P_2 would be placed on the stud labelled 1.0 and contact P_1 on 0.01859 on the slide wire.

Resistances R_1 and R_2 were then adjusted until there was no deflection of the galvanometer when the key K was pressed. Leaving resistances R_1 and R_2 at these settings, the switch was changed so as to connect the battery whose voltage was to be measured. P_1 and P_2 were then adjusted until the potentiometer was again balanced. The reading of the potentiometer scale would then give the value of the unknown voltage directly.

Once the potentiometer had been standardised, the reading was not only direct, it was semi-digital. Contact P_2 provided a value for the first two digits of the measurement, and the sliding contact added two or three more, depending on how carefully the balancing was done. Standardising was tedious however. Accurate measurements required that the standardisation be performed before and after the measurement – a lot of adjusting.

To simplify operation, a 'standardising device' was used. Remember that the standardisation process really amounted a fine tuning of the current through the potentiometer. Current was adjusted so that the voltage drop across the section of the potentiometer's resistance corresponding to the reading of the standard cell was equal to the cell's voltage. Thereafter, current in the potentiometer was left alone.

A standardising device was simply a series resistor of the same value, adjusted at the factory, so that when this value of current passed through it, the volt-drop would be equal to the voltage of the standard cell. It made no difference where the potentiometer switches or slide-wire were set, since these did not affect the series resistance.

Switches reconfigured the potentiometer circuit to allow the galvanometer to indicate balance in the normal way during standardisation. Usually, the standardising resistor could be trimmed by the user to correct for temperature changes, which affected the Weston cell voltage.

A standardising device of this kind meant that the process of setting up the potentiometer was much simpler and faster, and there was less wear and tear on the moving parts. The setting of the potentiometer made no difference during standardisation. Thus, if many measurements were to be made of similar voltages, they could be performed with little more than small adjustments to the slide wire, and the standardisation could be checked periodically. This was often the case: the two main industrial applications of the potentiometer were the calibration of other direct-reading voltmeters and ammeters, and the calibration of thermocouples.

Range changing

The potentiometer could easily be made to read lower values of voltage by decreasing the current in the series coils and the slide-wire. An arrangement like that shown in **Fig. 4** could reduce the current by a factor of 10 and a factor of 100 while keeping the load seen by the battery constant. In this way, the standardising process would be valid for all the scales.

Voltages higher than a few volts required the use of a device called a volt-box. This was no more than an external voltage divider, arranged to present a suitable voltage, less than 1.6 volts or so, to the potentiometer.

Evolution of the potentiometer

Over the decades, the potentiometer evolved from a simple device consisting of a slide-wire and a galvanometer to become an elegant and accurate system for measuring steady voltages of more or less any magnitude. Several companies included a potentiometer in their product line, and each was different in some way from the others. Some used a parallel standardising device.

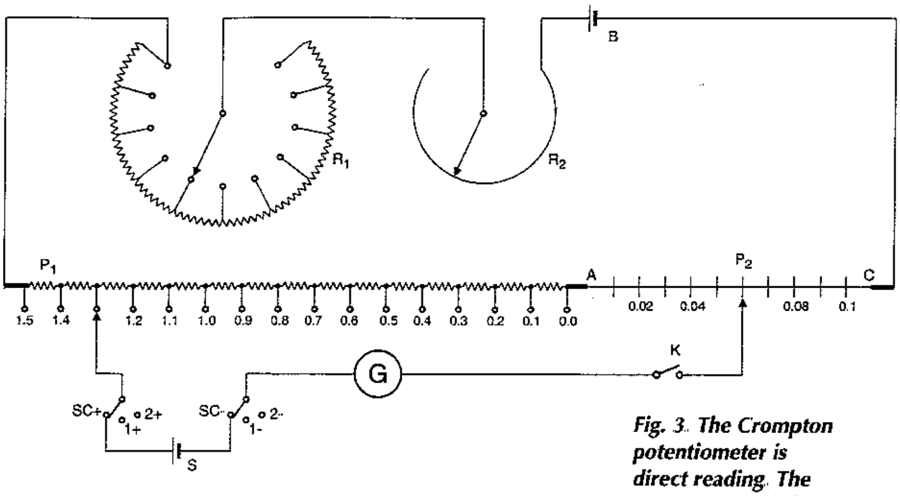


Fig. 3. The Crompton potentiometer is direct reading. The range is extended and the resolution is improved by the series resistors.

Some potentiometers used multiple slide wires, to provide increased resolution. Some included a circuit in parallel with the slide wire that allowed the slide some latitude around zero so that a true zero could be read. The potentiometer from Leeds and Northrup, described below, had only one slide-wire, but it was capable of some very impressive results.

Leeds and Northrup's potentiometer

The body of Leeds and Northrup's potentiometer, shown on the first page, measures by 400mm wide by 230mm deep. The big drum on the right of the potentiometer, called the hood, contains the slide-wire. It is 150mm in diameter, and houses 11 turns of wire of 0.63mm diameter, for a total of over 5m of wire.

Probably, the wire is manganin, so as to reduce the thermoelectric voltages in the system. Controls on the right are the coarse, medium and fine current adjustments. The large knob near the middle is the coarse voltage adjustment, in steps of 0.1V. The three buttons in front of it are low, medium and high sensitivity keys for the galvanometer. The knob at the back, left, is the fine control for standardising: it is set to the voltage from the standard cell, adjusted for temperature. The middle switch on the left is the range selector. The front switch on the left sets the function to measure or standardise. The back has connections for the unknown voltage, the galvanometer and both the reference and the supply battery.

According to the manufacturer, the hood could be set and read to an accuracy of one thousandth of a turn. Its scale has a two hundred tick marks 5mm apart, so this claim is not exaggerated. Thus, in its least sensitive setting, the potentiometer would read to 1.6 volts: each of the 15 switch positions corresponded to 0.1V, and each turn of the hood was 0.01V. Apparently, resolution was 0.01/1000 V, or about 6ppm.

Could the potentiometer really be this good? Consideration

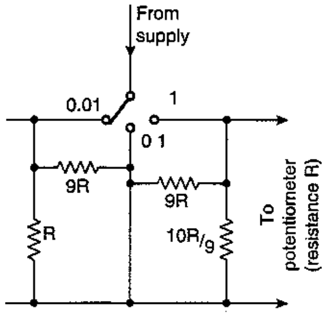


Fig. 4. A resistor network like this is used to produce a lower value of full scale voltage without changing the standardisation.

of the circuit shows that uncertainties in the values of all the coils (resistors) in series with the slide-wire would add directly in rms fashion to the uncertainty of the measurement. There are 15 such coils. In fact, while bridge circuits exist that would enable the manufacturer to produce resistors that were within a few ppm, it is unlikely that the overall uncertainty could be much lower than 10 or 20 ppm. It may be that the uncertainties in the resistance values of the coils are not uncorrelated, leading to somewhat worse performance.

To achieve maximum precision, it was necessary to take precautions to cancel thermal emfs To do this, the potentiometer was operated with the battery disconnected. A wire shorted the terminals normally used for the unknown voltage, and the galvanometer was adjusted to read zero when the key was pressed.

This procedure had the effect of forcing the contribution of the thermal emfs to zero. If the hood had been rotated prior to this adjustment, a 'cooling-off' period was recommended for the slide-wire and its contact.

In use, the potentiometer power came from a 2V battery, or two dry cells. The dry cells were not recommended because their output would fall with use, and frequent standardising would be needed The standard cell and galvanometer were not included as part of the potentiometer.

Present performance

Although I bought my potentiometer as a conversation piece, rather than a precision instrument, I was curious about its capabilities The first difficulty in checking it was finding a standard cell. While I did eventually find one, the first tests I performed used a laboratory power supply instead.

I set the power supply to a value of 1 0186 as indicated on a $4^{1}/_{2}$ digit dvm, and used another laboratory supply, set to 2.0V, to power the potentiometer. For a galvanometer, I used a centre-reading microammeter After standardising the potentiometer, I checked the value of the open circuit voltage of various dry cells and rechargable cells, with the dvm and the potentiometer at the same time.

The readings sometimes differed by one in the last digit, indicating that the error was less than one part in 15,000. It may also be that this error was due to nonlinearity in the dvm. It seemed that better performance would have been possible had I been able to find a more sensitive galvanometer.

Later tests with the standard cell gave much the same results. The standard cell, from another antique, was of unknown history. Nevertheless, its open circuit voltage was exactly 1.0186 V, as expected

Evidently, its age notwithstanding, this potentiometer was readily capable of better than 100 ppm uncertainty. A better dvm would be required to check the device's performance more closely

Concluding remarks

It is easy to see why the potentiometer was so favoured by early metrologists. It is relatively easy to use, remarkably stable, and capable of excellent accuracy. Potentiometric methods were used for calibrating transfer standards until quite recently in the national standards laboratories such as the National Physical Laboratory, NIST and the National Research Council of ■

The author would like to thank Tom Gedman of Honeywell-Leeds and Northrup for taking the time to track down for me a copy of the owner's manual for the potentiometer

Standards

Until the French adopted the metric system, their standards for units of measurement had been somewhat vague. The development of this now internationally used system was highly political, and its adoption, beginning in about 1790, was slow and widely resented

Among other things, the adoption of a standard measure reduced the opportunity for the middle-man to profit from the small differences between measures of the same name in different regions of France.

By the mid-1880s, when there arose the need to standardise the units for measuring the electrical quantities, the metric system was quite widespread At the time, what we now call electrical engineering was part of physics.

The physicists thought it made sense to define the amp and the ohm in terms of 'natural' quantities, such as the metre and the kilogramme It seems to have been overlooked that the metre was arbitrarily based on a division of a meridian running through France, and that the estimate of the meridian was rather approximate. The kilogram was 'natural' only because it was based on the weight of a cubic centimetre of water.

The unit of current was defined as 'that current which when passed through a wire of negligible diameter in the arc of a circle of length 1cm and radius 1cm will produce a force of one dyne on a unit magnetic pole placed at the centre.' The ohm was defined as 'that amount of resistance which when subject to a unit current for one second would dissipate one erg.' The volt was a derived unit, based on these two definitions.

Apart from the difficulty of finding a unit magnetic pole, the definition of unit current was far from practical. Wire could scarcely be of negligible diameter compared to 1cm, and the effect of stray fields caused by the wires going to and from such an apparatus as defined could hardly be neglected.

A practical means of determining the ampere derived from the definition was the current balance, originally associated with the name of Lord Rayleigh, in which the force created by the current was 'weighed.' Current balances have been made at the National Physical Laboratory (NPL) in the UK, and at the National Institute of Standards and Technology (formerly the Bureau of Standards) in the US.

Over the years since these quantities were first defined, there have been many revisions. The ampere is still defined by a force; it is now that steady current which will produce between two infinitely long parallel conductors 1 m apart in a vacuum a force of 2×10^{-7}N/m

But the volt is fixed in terms of the voltage across a Josephson junction maintained at the temperature of liquid helium and irradiated with microwave energy of known frequency, and the ohm is fixed by the quantum Hall effect. These represent departures from the earlier practice in two important ways.

First, the units are fixed by what are called 'representations,' something that produces the same kind of effect. The volt is fixed in terms of something that produces a voltage, and the ohm by something with a well-defined resistance, rather than in terms of length, mass and time.

Secondly, the representations automatically provide 'recipes' for practical standards Such standards used to be called secondary standards – the Weston cell used in potentiometric work is an example – and were capable of fixing the quantity with less precision than was desired for a standard unit. This defect no longer applies: the volt is fixed to a few parts in 10^7, i.e. less than 1 part per million, and the ohm to a few parts in 10^8 by the present representations.

The new volt and ohm can be seen as part of a trend toward basing standards on quantum effects and doing so with a recipe that leads to a reproducible result. Thus, the second and the metre are both now based on material spectra.

Work under way to redefine the kilogram – the only standard that is still based on an artifact, in this case a lump of metal. One approach is based on an accurate determination of Avogadro's number, perhaps from the X-ray spectrum of ultra-pure crystalline silicon, something made possible by modern semiconductor technology.

In an ironic twist, another way would be to use the current balance in reverse: rather than have the kilogram fix the ampere, the ampere, which can be derived from the quantum representations of the volt and the ohm, would fix the value of the kilogram