Through the multimeter maze

The basic test instrument — for hobbyist and professional alike — is the multimeter. Here's a look inside the commonest electronic instrument, how to choose one and how to use one.

Roger Harrison

THE MULTIMETER would be just about the most versatile piece of electronic equipment available. Cost-effective too, fortunately for the hobbyist. For developing, building and trouble-shooting projects or other electronic equipment, a multimeter is *indispensible*. For checking voltages around a circuit, supply or device currents and resistors values — no other single item of test equipment will suffice. Every hobbyist, technician or engineer will purchase — *need* to purchase — a multimeter sooner or later. Generally sooner than later, though.

Types

There are two basic types of multimeter — analogue and digital. The analogue type is built around a moving-coil meter, the operation of which is explained in the accompanying box. Digital multimeters, as the title implies, employ a digital counting technique and incorporate a digital readout to display the quantity being measured. The operation of digital type multimeters is explained in a separate box.

Each type has individual merits and disadvantages and what separated them principally in the past was price. Recently, however, the cost of the smaller general purpose digital multimeters has fallen to a level where they now seriously compete with many analogue multimeters.

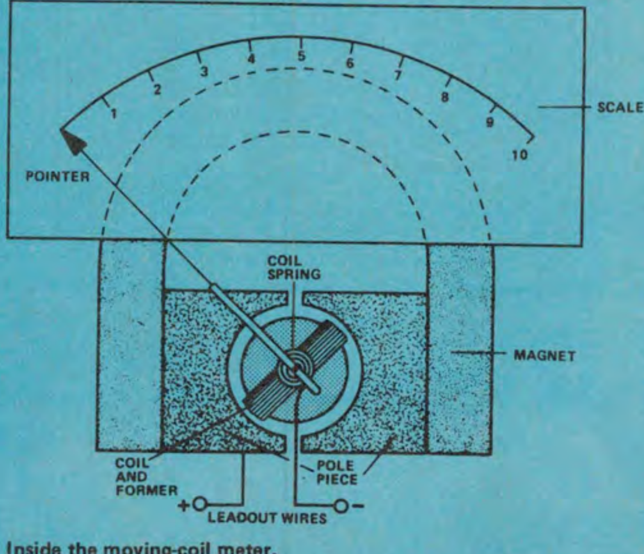
Accuracy

Multimeters of either type will have a certain accuracy specified by the manufacturer. For an analogue type, this may typically be "+/- 3% of full scale" for popular types. This means that on, say, the 100 volt range, the meter reading will be accurate to three volts at any part of the scale. Thus, if you connect the meter to a power supply delivering exactly 100 volts it may read somewhere between 97 volts and 103 volts (over scale) when set on the 100 volt range — an error of only 3% maximum. If you connect it to a power supply set to exactly 30 volts, say, whilst still set to the 100 volt range, it may read somewhere between 27 volts and 33 volts — an error of up to 10%. If measuring 10 volts on the 100 volt range the error may thus be as great as 30%! The lesson to be learned here is to make your measurement with the instrument switched to a range where the reading is towards the full-scale end of the meter.

Most popular analogue multimeters have an accuracy of +/- 3% on the dc ranges and +/- 4% on the ac ranges. The higher cost top-line models typically have an accuracy of +/- 1%. For improved reading accuracy, most analogue meters currently available have what is called a "mirror scale". When the needle of the meter movement is viewed at an angle other than directly overhead a small, but significant, error will be apparent as the scale marking viewed will not be that immediately beneath the needle — this is called "parallax

THE MOVING-COIL METER

THE 'HEART' of the common multi-meter is a moving-coil, or D'Arsonval, type meter. It works as follows: When electricity flows through a wire, a magnetic field is produced in a plane perpendicular to the wire. This magnetic field may be concentrated by winding the wire to form a coil of many turns, and still further by winding the coil around a soft-iron core. If this coil is suspended in a magnetic field (from a permanent magnet) and a current passed through the coil, it will rotate. The force of rotation will be proportional to the current passed through the coil.



Inside the moving-coil meter.

In the moving-coil type of meter, the coil is suspended around a cylinder of soft iron located in a permanent magnetic field. This ensures a magnetic field which is always perpendicular to the plane of the coil. A fine spiral tension-spring restrains the rotation of the coil, providing a linearly increasing restraining torque as the coil rotates when current is passed through it. The coil pivots on two diamond bearings above and below the magnet assembly.

A pointer is attached to the coil so that, when the coil rotates as a current passes through it, the pointer indicates the value of the current on a calibrated scale.

Moving-coil meters are generally delicate and will change calibration or sustain permanent damage if jarred. Generally it is the fine spiral tension spring that suffers from shock so another suspension torque-restraint system was devised using a thin ribbon or band, called the "taut-band" suspension system. A flat ribbon will provide a restoring torque that increases linearly as the ribbon is twisted. The taut-band replaces the spiral spring and diamond bearings and is considerably more robust, though more costly to manufacture. The taut-band system is also inherently more accurate as there is no 'stiction' — caused by friction in the bearing/suspension system, which results in inaccurate readings on conventional meters.

A multitude of multimeters ! Analogue types lined up at the rear: from left to right, Avometer 8, Dick Smith's Q1140 and the Sanwa N-501. Front row digitals: from left to right, the Fluke 8600A portable bench DMM, Data Precision 935, Fluke 8020A and Tandy's Micronta 22-197. The latter three are low cost hand held models featuring liquid crystal displays.

error". To assist viewing the meter needle from directly overhead a strip of reflecting material is placed between the scales. When the needle and its image are lined up then the meter is being viewed from the correct angle and any parallax error is eliminated.

Digital multimeters are inherently more accurate than analogue types — but that's not necessarily a reason to exclude analogue types when considering the purchase of an instrument! Typically a digital multimeter may be quoted to have an accuracy of "+/- 0.3% of the reading, +/- 0.1% of full scale, +/- one digit", on the dc ranges, slightly worse (big deal!) on the ac ranges. They're not separate accuracy specifications, that's a *complete* specification. It works out like this: say you've selected the 100 volt dc range — if you connect the unit to a power supply of exactly 100 volts, the reading will be within +/- 0.1 volt, plus or minus the last digit. That is, if the unit could resolve down to 0.1 volt the display could indicate "99.9", "100.0" or "100.1", and you couldn't take the last digit as 'gospel'. If the supply you were measuring were set to 30 volts and the multimeter to the 100 volt scale, then the display might read "30.1", "30.0" or "29.9"; and you couldn't trust the last digit, as before.

As with analogue units, you get better accuracy when the reading is made somewhere towards the full scale end of the range selected.

Ranges

As the term 'multimeter' implies, the instrument is designed to measure a multitude of electrical quantities, generally in convenient ranges or steps.

The number of ranges provided on a multimeter depends largely on its price. Typically, the dc voltage ranges will go in decade steps on the cheaper units — 2, 20, 200 volts etc; more expensive units will have anything from five to eight overlapping ranges starting at 2.5 volts (or lower) going to 10, 50, 250 etc. Top-line analogue types may commence as low as 0.3 volts on the dc voltage range, going to 1.2 volts, 3, 12, 30 etc up to 1.2 kV or more. There are usually fewer ac voltage ranges, the lowest being usually two or three volts.

Current ranges on most instruments generally have similar progressions with fewer ranges provided.

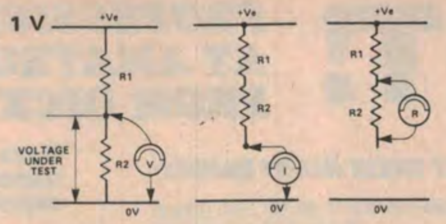
Digital instruments almost universally have a full scale reading based on '2' — 2, 20, 200 etc, as the display will only read up to 1.99, 19.9, etc (depending on resolution). The leading digit of the display (most significant digit) can either be '1' or '0' (the latter is generally suppressed for the sake of clarity) as this turns out to be an economical way to arrange a digital display.

Resistance ranges generally go in decade steps: the less expensive units will typically have a lower resistance range of 1k (analogue types) or 2k (digital types) full scale going to 1M or 2M (respectively) in four ranges altogether. More expensive models may have a lower resistance range of 10 ohms (analogue) or 20 ohms (digital) full scale with decade steps to 100M or 200M (respectively).

Sensitivity

The sensitivity of analogue multimeters is expressed in "ohms/volt" and for a typical popular type this may be "20 000 ohms/volt". This means that whenever a voltage reading is being made, the meter resistance will be 20 000 ohms times the full-scale voltage of the range selected. Say you select ▶

the 10 volt range; the resistance across the input terminals of the multimeter will be 200 000 ohms (200k). This is a point to watch when making measurements — and when purchasing a multimeter. The instrument may "load" the circuit you are testing and a false reading will result as you will disturb the operating conditions of the circuit. To take a simple example, say we have a multimeter having a sensitivity of 1000 ohms/volt, and we wish to measure the voltage across R2 in the circuit here with the meter set to the one volt range. By Ohm's law we know the voltage across R2 will be 0.75 volts. Now, the meter will have a resistance of 1000 ohms on the one volt range and this will be in parallel with R2 when we connect the meter, the combined resistance then being 500 ohms. Thus, the voltage read by the meter will be 0.5 volt instead of 0.75 volt — an error of 33% !



The correct way to use a multimeter to measure in-circuit quantities. From left to right: voltage, current and resistance. The internal impedance of the meter is an important consideration , as explained in the text.

It is the *degree* of this shunting, or loading, effect that is important. In theory, it can never be completely avoided as some current must flow into the measuring system from the circuit being measured. However, this can be made vanishingly small by using an instrument having a very high input resistance — or a high sensitivity specification. As a general rule the instrument's resistance should be ten times, or more, than the circuit resistance.

Digital multimeters have a constant input impedance — generally 10M, which rarely presents any loading prob- ▶

RANGE EXTENSION

A MOVING-COIL METER is a dc current-indicating device. They are made with full-scale deflection currents at convenient values, such as 1 mA, 100 uA etc. The current range can be extended by adding a 'shunt' resistor in parallel with the meter, so that most of the current to be measured flows through the shunt and a small amount through the meter.

To measure **dc voltage,** a 'multiplier' resistor is placed in series with the meter so that, at the voltage to be measured, the full-scale current passes through the resistor and the meter. Various switching schemes are arranged so that a number of voltage and current ranges can be covered.

To measure **ac voltage** a rectifier is usually incorporated into the circuit, along with range switching and multiplier resistors. **AC current** is measured usually via a transformer which 'steps-up' the current flowing in a primary winding, the secondary voltage being rectified and applied to the meter. Taps on the transformer primary winding provide different current ranges.

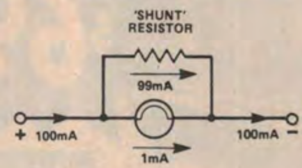
Resistance may be measured by a simple extension of the voltage — or current-measuring principles. The **'series-connected' ohmmeter** is the most common type. The 'range' resistor determines the centre-scale current through the meter. The 'unknown' resistor is connected in series with the range resistor (hence 'series-connected').

The 'set zero' control is adjusted for full-scale deflection of the meter with the X-X terminals shorted together. The unknown resistor is then connected to the X-X terminals and the current through the meter will be directly proportional to the value of the unknown resistor.

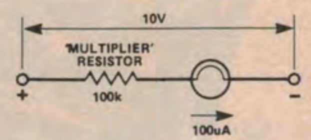
The meter scale is calibrated in resistance, low values to the right — high values to the the left, the scale being logarithmic (see diagram), generally covering four decades. Calibration accuracy is not influenced by minor changes in battery voltage (since you can compensate with the 'set zero' control) and the ranges covered are readily changed by selecting different range resistors.

The **'parallel-connected' or 'shunt' ohmmeter** is used for measuring low and very low values of resistance. The 'set zero' control on this type is adjusted for full-scale deflection on the meter with the switch (SW1) closed and the X-X terminals open circuit. The unknown resistor is then connected across the X-X terminals. The reading obtained will be, again, directly proportional to the value of the unknown resistance.

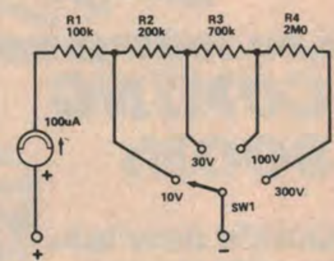
The scale is reverse-reading; that is, lowest values to the left, higher values to the right.



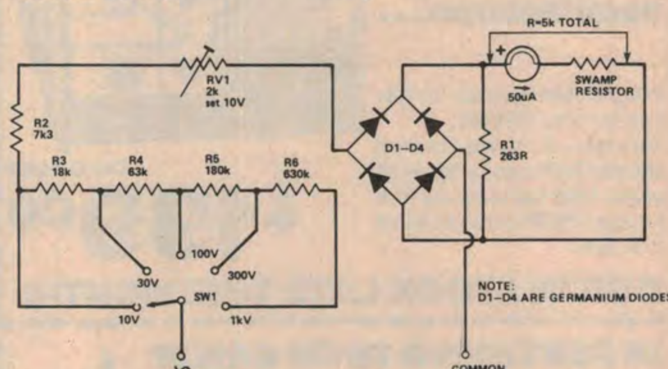
Extending the current range of a meter with a 'shunt' resistor.



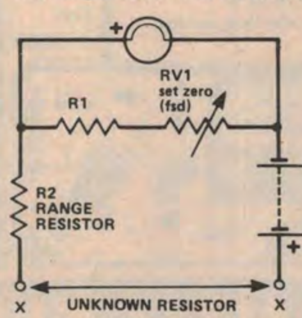
A meter can indicate voltage by adding a 'multiplier'.



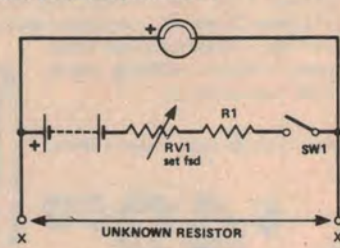
Typical range switching for the voltage ranges in a multimeter. Note how the 'intervals' overlap.



Practical example of an ac voltmeter covering 10 V to 1 kV in five ranges. Note that R1 reduces the sensitivity to 1k/V.



Basic circuit of a 'series-connected' ohmmeter.



Parallel-connected type of ohmmeter is used to measure low and very low values of resistance.

lems, as they employ electronic amplification between the input and the analogue-to-digital conversion.

There are a range of analogue meters available that incorporate electronic amplification — generally using a FET or FET-input op-amp. These have a high input impedance, generally 10M, and similar ranges to other types available. Naturally, they cost more and digital instruments now seriously compete with them.

When measuring current, the internal resistance of the meter is also important. The resistance of the meter, connected in series with the circuit being measured, may introduce an undesirable voltage drop upsetting the circuit operation and resulting in an erroneous reading. In this case, the internal resistance of the meter on the range selected should be one-tenth, or preferably less, than the series circuit resistance.

Protection

No . . . you won't need to pay $100 to the little man who comes around every week so your multimeter will not suffer a terminal fate! Most multimeters include one or more devices to protect the meter movement (at least) and perhaps the internal circuitry from damage in the event of an overload being applied to the input terminals and/or mechanical shock.

Moving-coil meters are delicate instruments and may easily be damaged by overload currents exceeding the full-scale deflection value of the movement by 50% or more. The simplest protection method employed uses two germanium diodes wired 'back-to-back' across the meter terminals. The diodes will conduct when the voltage across the meter terminals rises above about 200-300 millivolts (in either direction), effectively placing a shunt across the meter. Hence, it is called 'shunt diode protection'. Most analogue multimeters incorporate this form of meter movement protection. However, a sufficiently large overload will almost certainly damage the diodes — resulting in damage to the meter. For example: if you have the meter set to the 1 mA range and inadvertently connect it across the 240 Vac mains . . . I recommend you give the instrument an honest burial for it will be *your* fault that the ensuing explosion brought about the instrument's demise.

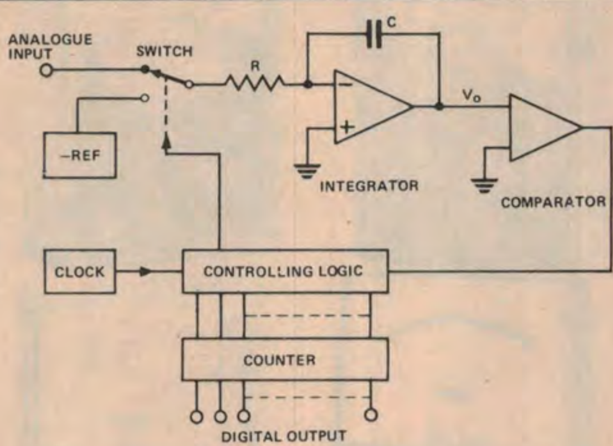
The more expensive analogue instruments may include a device that senses an overload condition and operates a 'cutout' — a device that latches out, disconnecting the input terminals. The famous "AVO" series of multimeters incorporate 'cutout' protection. When an overload occurs, a button on the front panel pops up and the device can only be reset once the overload is removed.

Some manufacturers include an "OFF" position on the range switch of their instruments. This disconnects the input terminals and places a short across the meter. This is to protect the unit against damage from mechanical shock while it is being transported. It works like this: if the meter is jerked suddenly, the meter coil will tend to rotate. As it is suspended in a magnetic field, any movement will generate a ▶

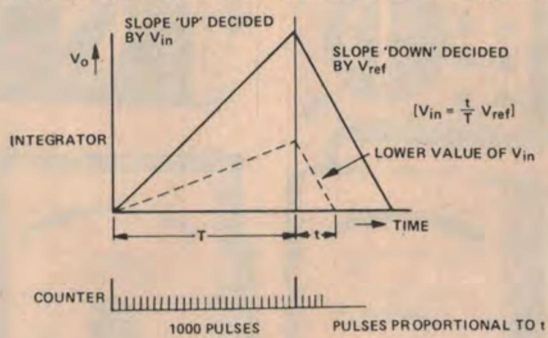
THE DIGITAL MULTIMETER

THE MAJORITY of currently available digital multimeters employ an analogue-to-digital conversion technique called **"dual-slope integration".**

In this method, the analogue input voltage is first converted to a time period which in turn is converted into a binary number by a timer/counting system. Referring to the block diagram here, and the associated timing diagram, the system commences the measurement when the switch connects the analogue signal input to the integrator which commences to 'ramp up'. At the same time the counter begins, from zero, to count the clock pulses. When a predetermined number of pulses (1000 is usually convenient) appear in the counter, the integrator is electronically switched over to the reference voltage. At this point, the integration capacitor, C, has then charged linearly from the input, rising as a ramp voltage to a level decided by the average input signal value over the counter time period (T). As the switch changes to the reference, the counter is reset to zero and commences



Block diagram of the 'dual-slope integration' technique of analogue-to-digital conversion commonly used in digital meters.



Timing diagram for the dual-slope A/D conversion technique.

counting again. The reference, chosen to be of opposite polarity to the input signal, now causes the charged integration capacitor (C) to ramp donward with a fixed slope. When the output of the integrator reaches the zero threshold the counter is stopped and its contents displayed on the digital readout. The count displayed is the ratio of the counts during the 'downward' ramp (over time 't') to the counts during the upward ramp. Thus, when a limit of 1000 counts is chosen for the upward ramp duration a direct reading of input voltage is obtained if the reference voltage is chosen appropriately.

The absolute value of the integration capacitor and the clock frequency are of little significance provided they are stable for the duration of the conversion period.

The relatively long analogue-to-digital (A/D) conversion period has an inherent advantage in that it ignores noise. When noise is integrated over an extended period, its amplitude tends to zero. Thus, dual-slope integration results in excellent accuracy.

Most modern digital multimeters — particularly hand-held types — have most of their internal circuitry located within a single integrated circuit. Range switching is provided in a conventional manner, similar to moving-coil instruments. The more expensive 'top-line' instruments may incorporate input amplifiers to improve sensitivity and provide high constant input impedance.

current in the coil. This current will flow through any load connected to the meter terminals. That current will also set up a magnetic field around the meter's coil that will react with the permanent magnetic field, generating a 'restoring' force that opposes the movement of the meter's coil. A short-circuit across the coil ensures maximum current due to the meter coil's movement and thus maximum restoring force, heavily damping any violent motion of the meter movement due to mechanical shock.

Most popular instruments include a fuse in series with one input terminal to protect the unit from gross overloads.

Choosing

Analogue types range in price from under $10 to over $100. Undoubtedly, price will be the first consideration for the hobbyist. You need to first assess how much money you can afford, or wish to lay out, and then get the meter that best suits your needs or applications from that price range.

The next consideration should be sensitivity. For most hobby applications a sensitivity of 20 000 ohms/volt dc is generally adequate. However, if you intend working with high impedance devices such as MOSFETs and CMOS ICs, then something with a sensitivity of at least 50 000 ohms/volt dc, preferably 100 000 ohms/volt or one of the 500k to 1M ohms/volt types, if you can afford it.

"Run-of-the-mill" 20 k/V dc sensitivity multimeters range in price from a little under $20 to a little over $30. Models having a sensitivity of 50 k/V or 100 k/V dc range from about $25 up to $50. The more expensive types will include more ranges and perhaps have additional features such as transistor testing and/or capacitance measurement. Seek out a model having a large scale and good meter protection. A large scale makes for easy reading and good protection is wise insurance. The more expensive models often include an "OFF" position on the range switch that puts a short-circuit across the meter movement to protect it from shock damage. Models incorporating a taut-band suspension meter are less prone to shock and overload damage.

As a minimum requirement, the voltage ranges on your instrument should be from about one volt to at least 300 volts dc, and 10 to 300 volts ac. Resistance measurements should have at least four ranges, preferably more, covering ohms 'X1', 'X10', 'X100' and 'X1000'. The dc current ranges should go down to at least 100 ua and up to 200 mA or more, preferably with an extra input socket providing measurement up to 10A. You'll rarely use the ac current ranges so this is not of too much importance.

Accuracy is not of great importance to the average hobbyist as measurement to better than +/- 5% is rarely required and even the cheapest multimeters advertised quote accuracies these days of +/- 3% on the dc ranges and +/- 4% on the ac ranges. If you envisage a requirement for greater accuracy then go for the higher-priced taut-band suspension models or start looking amongst the digital instruments.

Always look carefully at the construction of an instrument. Seek an instrument with rugged construction as a multimeter is a valuable tool that should remain serviceable for many years.

It can be a waste of money to buy something 'too fancy' for your needs so think carefully beforehand. It is often possible to make test instruments to supplement your multimeter's capabilities for less than the difference in cost between a unit with straightforward ranges and features and a higher cost type with many 'extras'. You also get the satisfaction of building such projects yourself — and there's no price on that!

Digital instruments have to be considered in something of a different fashion to analogue types. Again, price is generally your first consideration. The cheapest digital instruments available at present cost around $70 to $80 . . . and the competition at this end of the market is fierce!

Sensitivity and accuracy are unimportant: resolution and the number of ranges are the two basic deciding factors. Instruments in this price range generally have a 3½-digit display (1999 full-scale reading). Unless you are looking for a mains-operated, bench instrument, the portable models having a liquid crystal display (LCD) have a considerably longer battery life, larger display size and are consequently more practical than those having LED displays — the latter are rapidly disappearing from the market as a result. However, LCD displays have a limited life — generally around five years.

The general comments on ranges that I made with regard to analogue instruments also apply to digital instruments. Maximum input voltages and currents are generally given on the front panel of digital instruments and should be heeded. Most units provide overload protection — a fuse on all the models the author has seen to date. A spare fuse is handy — particularly if one is provided stored in the instrument case.

Most digital instruments will generally provide as many ranges and features as analogue instruments costing about 25-30% less. The chief advantages of digital instruments over analogue instruments are: direct readout (no interpretation of a meter scale required, with the chance of error), better resolution and constant input impedance on the ac and dc voltage ranges. However, an analogue instrument can indicate varying quantities — when adjusting a circuit to provide a "peak" or "minimum" reading where the exact value is not required. You cannot tell on a digital display which way a quantity is changing, unless the change is very slow.

The final choice is up to you — but the author has noted a growing tendency among 'serious' enthusiasts, engineering labs and servicemen to purchase at least one multimeter of each type to take advantage of the special features unique to each!

Using

A multimeter is not only an easy instrument to use but will serve you well for many years if you stick to the following basic rules:

1) Most moving-coil multimeters are designed to operate accurately only when the face of the meter is in one specific orientation — usually horizontal. Digital instruments are not affected this way.
2) When measuring an unknown current or voltage always set the meter to its highest range and switch down through the ranges until the correct range is found — try to obtain a reading that is nearest full scale, switch up one range as a check on accuracy (this also reduces loading problems with analogue meters).
3) When measuring an in-circuit voltage, always connect the meter *across* the voltage source.
4) When measuring an in-circuit current always connect the meter *in series* with the current source.
5) When measuring an in-circuit resistance always disconnect one lead and then connect the meter across the resistance. Always 'zero' an analogue meter on the selected range before making a measurement.
6) When measuring continuity in semiconductors (diodes, transistors etc) always remember that the meter's internal battery has the *positive* connected to the *common* (black lead) terminal.
7) With analogue instruments ensure that, on dc and ac voltage measurements, the input impedance (ohms/V sensitivity multiplied by the voltage range) is at least ten times the circuit impedance being measured. ●