Appendix A: RESISTOR COLOR CODES

Rev.: 7/29/14 DJD

The standard method of labeling resistors is shown in ***Figure A.1***. There are four colored bands: the three that are often grouped together give the resistance value; the fourth gives the ***tolerance***. In ***Figure A.1***, from left to right:

- the **first two bands** represent the ***1st*** and ***2nd digit*** of the ***nominal*** ("in name only") ***value*** of the resistor.
- the **third band** is the ***multiplier band***, which gives the number of zeros that follow the first two digits (or the exponent on the 10 in scientific notation).
- the **fourth band**, often offset from the others, is the ***tolerance band***. The manufacturer states that the resistor's actual value is within a certain percentage of its nominal value.

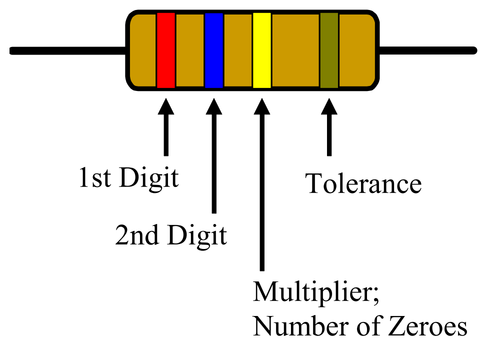


Figure A.1 Four-band Resistor Color Code. With the tolerance band on the right, the first three bands are read from left to right to give the value of the resistance.

The values that correspond to the color bands are given in ***Table A-1***. The color code (0, 1, 2…; Black, Brown, Red...) can be remembered with a mnemonic. Many mnemonics can be found with an internet search. I came up with a modification of the rainbow mnemonic:

"BB ROY G BiV without the i, GW."

"a BB shot out Roy G. BiV's eye. Gee Whiz!"

A way to remember that Black is 0 and White is 9: black is the absence of light so it is "nothing" or zero; white is all colors of light, so it is the largest number, 9.

Table A-1 Four-Band Resistor Color Code.

Color of Band	Value of first two digits (1^{st}, 2^{nd} band)	Multiplier (3^{rd} band)		Tolerance (4^{th} band)
		Multiply first two digits by	Zeroes after first two digits	
Black	0	$10^0 = 1$	0	-
Brown	1	$10^1 = 10$	1	1%
Red	2	$10^2 = 100$	2	2%
Orange	3	1000	3	3%
Yellow	4	10^4	4	-
Green	5	10^5	5	-
Blue	6	10^6	6	-
Violet	7	10^7	7	-
Gray	8	10^8	8	-
White	9	10^9	9	-
Gold*	-	$10^{-1} = 0.1$	-	5%
Silver	-	0.01	-	10%
None	-	-	-	20%

*Note: Most resistors in the ENGR 171 lab have a tolerance of 5% (gold).

Reading the Code

What is the value and tolerance of a resistor with color bands: Yellow / Violet / Red / Silver ?

First, find the ***tolerance band***, which is generally gold or silver. **Place the tolerance band on the right**.

From the left, the first band is **Yellow: 4**; the second is **Violet: 7**. The first two digits of the resistance are: **47**. The third band gives the multiplier (number of zeroes after the first two digits). Here, **Red: 2**. The resistance is:

$$47\times10^2\ \Omega = 4700\ \Omega = 4.7\ k\Omega$$

Silver indicates a tolerance of 10%. Thus, the resistor has a value of:

$$\boxed{4700\,\Omega \pm 10\%}$$

With a 10% tolerance, the actual value may range between 4230 and 5170 Ω.

I expect every ENGR 171 student to know the standard 4-band resistor code from memory.

Power Rating

Resistors have a ***power rating*** P_{max} (for DC current and voltage, the power dissipated by a resistor is: $P = i^2R = V^2/R$). If a resistor must dissipate more power than its *power rating* for some time, it will overheat, burn and smoke. Common resistors typically have power ratings of ¼ W or ½ W.

The power rating is related to the surface area of the resistor. A resistor removes energy from a circuit via heat. The more surface area, the greater the resistor's ability to dissipate heat. A ½ W resistor is therefore larger (has more surface area) than a ¼ W resister. If the resistor cannot dissipate heat to the surroundings fast enough, it will fail.

Circuits are usually designed so that at maximum power, a resistor only needs to dissipate half of its power rating (a *Factor of Safety* of 2).

The resistors generally used in ENGR 171 are rated at ¼ W.

Advanced Resistor Codes – More Bands

Some resistors have more than four bands. These resistors have better properties than standard resistors (and cost more). The additional bands include:

Third Digit Band (a **five-band resistor**)

A resistor with 1% tolerance has four bands grouped together to specify its magnitude: three to specify the first three digits, and the fourth to specify the multiplier. These resistors have special thermal properties to provide the tight 1% tolerance.

Quality Band

If there is a band beyond (to the right of) the *tolerance band*, it is the *quality band*. The quality band represents the "percent failure rate per 1000 hours." This rating is for the maximum wattage being continuously applied to the resistor.

Quality band colors are Brown (1%); Red (0.1%); Orange (0.01%) and Yellow (0.001%).

Standard Values for Resistors

Standard resistance values come in seemingly odd values. The ***standard values*** for the **first two digits** of 20%, 10% and 5% resistors are as follows:

20% tolerance:

10, 15, 22, 33, 47, 68, 100

10% tolerance:

10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82, 100

5% tolerance:

10, 11, 12, 13, 15, 16, 18, 20, 22, 24, 27, 30, 33, 36, 39, 43, 47, 51, 56, 62, 68, 75, 82, 91, 100

Consider the nominal 4700 Ω, 10% tolerance resistor; it can vary in actual value from 4230 to 5170 Ω. The next standard resistor down from 4700 is 3900 Ω (3510 to 4290 Ω), and the next standard resistor up is 5600 Ω (5040 to 6160 Ω). The range of the 4700 Ω resistor overlaps with the ranges of its two "nearest neighbors." This overlap effect allows for the seemingly strange intervals of standard resistances. An overlap occurs for most, but not all, nearest neighbor resistors.

When a designer specifies a resistor in a system that is to be massed-produced, he or she must take into account that actual resistors will only be within tolerance of their nominal values; resistor values will not be exact.

If you want a particular nominal resistance not listed in the standard values, use a combination of standard resistors. If you need an exact resistance in lab, use a potentiometer as a variable resistor. ■

Sources:

Electrical Engineering Faculty, Cal Poly SLO, *Electric Circuit I Laboratory* manual, El Corral Publications, Winter 2001.

Tsividis, Yannis, *A First Lab in Circuits and Electronics*, Appendix A: Component Value Codes, John Wiley and Sons, 2002, pp. 122-3.

"Resistor Color Codes," http://wiki.xtronics.com/index.php/Resistor_Codes, accessed June 25, 2010.

Appendix B: CAPACITOR CODES

Rev.: 7/29/14 DJD

The various methods for labeling capacitor values can be difficult to understand. **When in doubt, measure**. Use the Philips PM 6303 RCL Meter in lab.

Large capacitors (“caps”) have their *values* and *units* printed on them. For example, “10 μF” ($10{\times}10^{-6}$F) on the lower cap in ***Figure B.1***.

Most small capacitors have two or three numbers printed on them, and possibly a letter. Examples include “47”, “0.05K”, “103M”, “101”, “104K” (***Figure B.2***), etc. The digits give the capacitance in ***picofarads*** **pF** (1 pF = 10^{-12} F) or in *microfarads* μF (10^{-6} F), but we are not explicitly told which. In general, the unit is pF (sometimes called “puff”). For “0.05”, experience teaches that 0.05 pF is too small for practical capacitors, so the value is 0.05 μF (50,000 pF).

The letter indicates the ***tolerance*** (***Table B-2***).

Three-Digit Codes

For *three-digit codes* such as “103”, the first two digits are the first two digits of the capacitor value in ***picofarads***. The third digit is the number of zeroes after the first two digits, or the *multiplier*. This is the same system used with four-band resistors (without the colors).

Thus, “103” represents 10 followed by 3 zeros ($10 \times 10^3 = 10{,}000$). So “103” is 10,000 pF = 10 nF = 0.01 μF.

The third-digit multiplier code is given in ***Table B-1***.

Examples of 3-digit Codes:

“224” is $22{\times}10^4$ pF = 220,000 pF = 0.22 μF
“685” is $68{\times}10^5$ pF = 6.8 μF

The 3-digit code is the most common capacitor code you will see in ENGR171.

Two-Digit Codes

Capacitors with two-digit integers are read as picofarads; e.g., “47” printed on a small disk is 47 pF. It is a basically a 3-digit code with “0” for the third number.

Decimal Codes

Decimal numbers such as “0.1” and “0.05” are usually the value in microfarads: 0.1 μF and 0.05 μF.

25 V
47 μF

50 V
10 μF

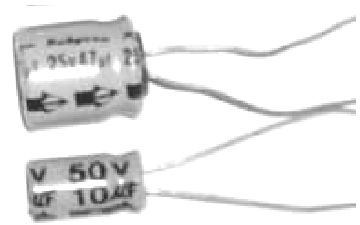


Figure B.1 Electrolytic capacitors tend to be relatively large and cylindrical. Large caps have their value printed on them (here, 47 μF and 10 μF). The polarity of electrolytic caps is indicated on them: the arrows visible on the upper cap point to the negative side. A negative sign is also often printed on the negative side. Additionally, the negative lead (wire) is manufactured shorter than the positive lead.

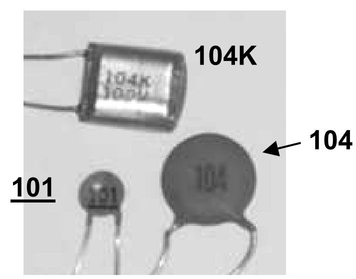


Figure B.2 Caps with 3-digit codes.

Table B-1 *Multiplier*. The third digit in the 3-digit capacitor code indicates the number of zeroes that follow the first two digits. Capacitance in picofarads (pF).

Third Digit	Multiplier
0	$10^0 = 1$
1	$10^1 = 10$
2	$10^2 = 100$
3	$10^3 = 1000$
4	$10^4 = 10{,}000$
5	$10^5 = 100{,}000$
6	Not used
7	Not used
8	$10^{-2} = 0.01$
9	$10^{-1} = 0.1$

Polarity

The polarity of an ***electrolytic capacitor*** is indicated on the capacitor, usually by arrows pointing to the negative side, and/or a negative sign "–" as shown in ***Figure B.1***. An electrolytic capacitor must be connected in a circuit with the correct polarity (proper orientation), otherwise it will not work correctly, and may explode in service.

Another way of identifying the polarity of an electrolytic capacitor is to look at the two leads (wires) of the capacitor. The negative side is manufactured with a shorter lead.

Tolerance

Tolerances are given as letters; a list of a few tolerance codes is given in ***Table B-2***. For "104 K", the capacitance is 0.1 μF ± 10%; the capacitance can vary from 0.09 to 0.11 μF.

In general, the capacitors used in lab have less tolerance than the resistors; capacitor tolerances are more difficult to control.

Maximum Allowable Voltage

The maximum allowable voltage – the ***voltage rating*** of a capacitor – may be printed on the capacitor packaging, as seen in the lower capacitor of ***Figure B.1*** (50 V). For others, the *specification sheet* must be referenced. If the capacitor is subjected to an excessive voltage, it may explode or break down. In design, the voltage rating of a capacitor is usually twice the maximum voltage it is expected to be subjected to in service (a typical engineering *Factor of Safety* of 2).

Capacitor Type

Sometimes the type of capacitor is printed on its casing, but usually not. There are many types of capacitors, each having different strengths and weaknesses. They generally have a ***dielectric*** between their electrodes (the capacitor plates). A dielectric material increases the capacitance of the capacitor (instead of just having air between the electrodes).

Brief descriptions of the types of capacitors can be found at:

http://www.sentex.net/~mec1995/gadgets/caps/caps.html

Very brief descriptions of a few caps that you may come across are given below.

Table B-2 Capacitor Tolerance.

Letter	Tolerance
D	± 0.5%
F	± 1%
G	± 2%
H	± 3%
J	± 5%
K	± 10%
M	± 20%

Electrolytic capacitors (***Figure B.1***) are cylindrical (the parallel plates, separated by a non-conducting paper, are rolled around each other like a cinnamon roll), and are made with an electrolyte (essentially salt in a solvent), with aluminum electrodes. Electrolytic capacitors are one of the most widely-used types of capacitors (look inside a tower computer … but do not break it).

Ceramic disk capacitors are shaped like a disk (***Figure B.2***). They tend to be very small in size and can have very small capacitances. They are also one of the most widely-used types of capacitors.

Polyester film capacitors use a polyester film as a *dielectric*. They tend to be rectangular in shape.

Epoxy capacitors use a polymeric epoxy as a protective coating. They also are rectangular in shape, and often resemble Chiclet gum (DO NOT put them in your mouth!). ■

Sources:

Tsividis, Yannis, *A First Lab in Circuits and Electronics*, Appendix A: Component Value Codes, John Wiley and Sons, 2002, pg.123.

"Capacitor Codes," http://wiki.xtronics.com/index.php/Capacitor_Codes, accessed June 25, 2010.

van Roon, Tony, "Capacitors," http://www.sentex.net/~mec1995/gadgets/caps/caps.html, accessed June 25, 2010.

Appendix C: PROTO-BOARD (Bread Board)

Rev.: 7/29/14 DJD

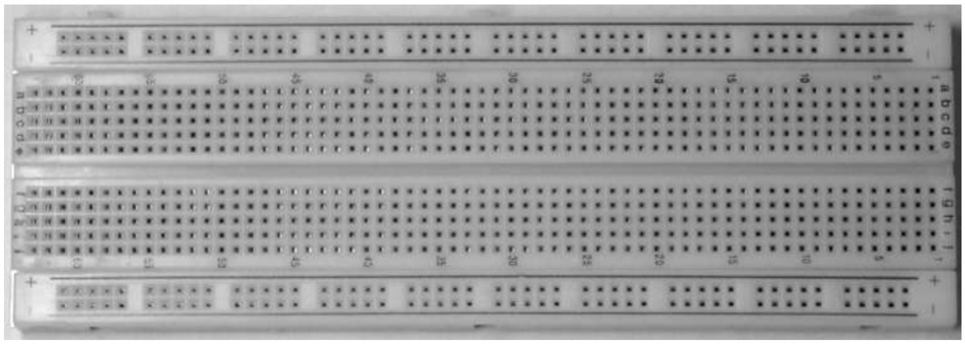


Figure C.1 Proto-board used in ENGR 171.

A ***Proto-Board***, or ***Bread Board***, is used to building temporary circuits (e.g., prototypes). A typical board is shown in ***Figure C.1***. The square ***holes***, or ***sockets***, are 0.1 inches apart, and provide locations to insert the leads (wires) of resistors, capacitors, inductors, op-amps, etc.

The sockets are connected beneath the board surface as shown in the pictorial in ***Figure C.2***. Each socket is represented by a square, and the thin lines between sockets illustrate how they are connected. Sockets that are connected to each other are at the same ***node*** (and thus at the same voltage).

The board in ***Figure C.1*** (the one you probably have in ENGR 171) has red "+" and blue "–" lines printed along each long side. The sockets next to a red "+" line are all connected to each other (***Figure C.2***); those next to a blue "–" line are all connected to each other. These four separate "+" and "–" lines provide convenient interfaces (***buses***) to connect several components or devices to the same voltage. It is suggested to use the topmost "+" bus line for positive input, the very bottom "–" bus line for negative input, and one of the inner bus lines for ***ground***.

Some boards have a printed black line along one side that is broken in the middle; in this case, the ***bus line*** (socket connection) is broken in the middle. Some boards have no printed lines, so it is a good idea to check socket continuity along the sides of the board with an ohmmeter (if two holes are connected, the resistance will be very small (e.g., <10 Ω); if not connected, the ohmmeter will display "OL").

In the central part of the board, the sockets are numbered along the sides (1, 2, 3... 62, 63) and they are lettered along the ends (a, b, c... i, j) allowing a specific hole to be identified (e.g., 53b).

Sockets are connected in groups (sets) of 5. In each numbered row, sockets a, b, c, d, e are connected to each other. Likewise, sockets f, g, h, i, j are connected to each other. Socket set a–e and set f–i are separated by a ***trough***; set a–e is <u>not</u> connected to set f–i (***Figure C.2***).

The numbered rows are <u>not</u> connected to each other (***Figure C.2***).

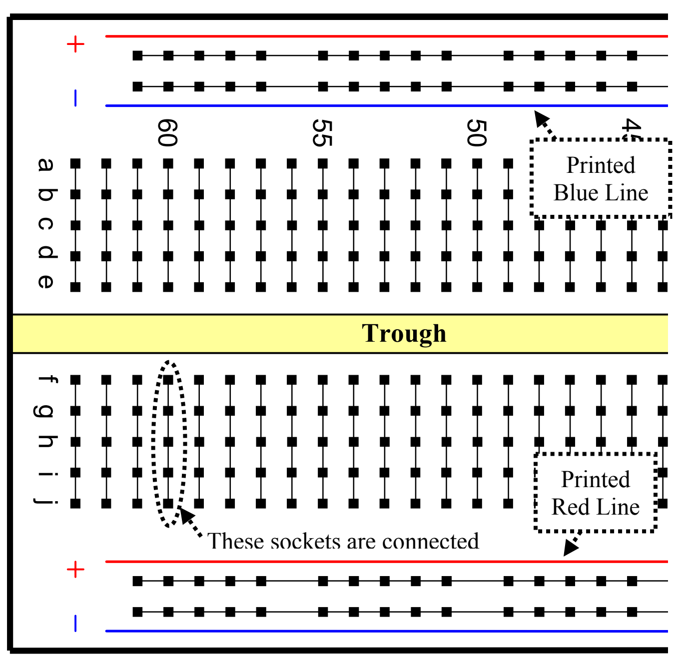


Figure C.2 Pictorial of part of the proto-board of *Figure C.1*. Sub-surface connections between sockets (squares) are indicated by thin lines connecting them. For example, sockets 60f-60j (circled) are connected.

Circuits can be built as shown in ***Figure C.3***. **Try to build a neat circuit** so that you (and your lab partner and instructor) can actually figure out what is going on. **You and your lab partner should check the circuit to ensure it is set up correctly before applying power**. Also check the circuit if you suspect it is not acting as it should.

A sloppy circuit can have errors that are difficult to see (***Figure C.4***). Resistors can be connected in the wrong order. Or, the resistor leads (wires) may touch causing a short-circuit, be placed in the wrong socket, or be pulled out accidentally.

Use **jumper wires** (pre-cut short wires) to connect holes as necessary. They can be used to help separate (spread out) components or blocks of components. In other cases, jumpers may not be required and cause clutter (***Figure C.4***).

Operational amplifiers have 8 terminals (leads). Op amps must be connected **across the trough** so that each lead is connected to a different 5-hole set (***Figure C.5***). If the op-amp is plugged into holes that are all on one side of the trough, the terminals will be short-circuited. ■

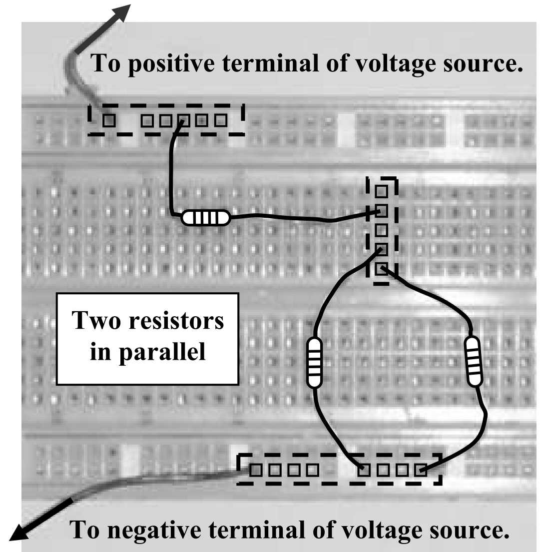


Figure C.3 Try to build neat circuits. Here, resistors are well-spaced, and lay flat on the board. In this figure, squares represent different sockets or holes. Dashed rectangles emphasize the *nodes* – sets of holes that are connected to each other (and thus at the same voltage).

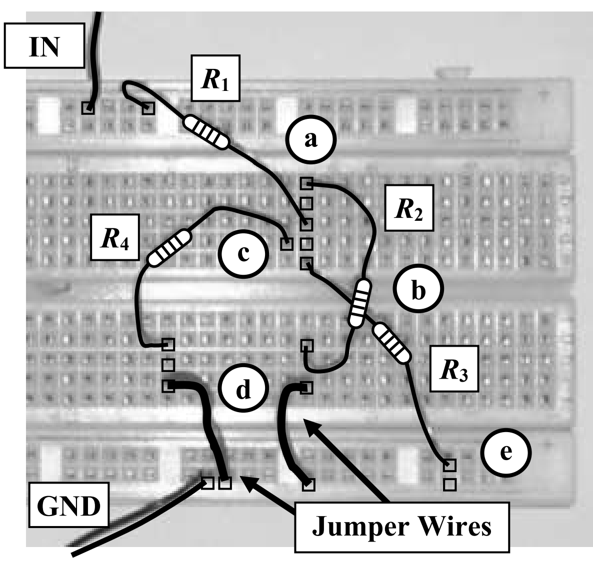


Figure C.4 A few common sources of error and suggestions for neater circuits. In this circuit, resistors R_2, R_3 and R_4 are supposed to be in parallel with each other. **(a)** For a neater circuit, the lead of resistor R_1 might switch sockets (holes) with the lead of R_2. **(b)** Resistors R_2 and R_3 cross; if wires touch, the system may become short-circuited. **(c)** The right lead of resistor R_4 is not connected to another wire/component; it is in the wrong 5-hole set. **(d)** Unnecessary jumper wires; take resistor R_2 and R_4 direct to ground if possible. **(e)** Resistor R_3 is not connected to the correct bus line.

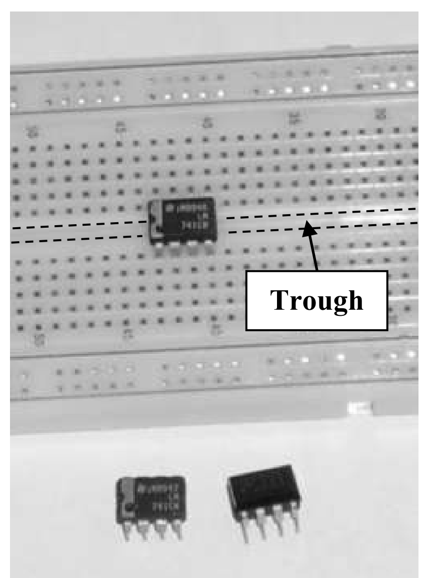


Figure C.5 An op-amp must be placed across the proto-board *trough* (shown dashed) so that each of the op-amp's 8 terminals is connected to a different 5-hole set.

Appendix D: GROUND CONNECTIONS

Rev.: 7/4/11 DJD

from: Tsividis, Yannis, *A First Lab in Circuits and Electronics*, New York: John Wiley & Sons, 2002, pp. 11-13.
Slight reformatting of text and [added comments], and recreation of figures: by D.J. Dal Bello, 2004-05.

Introduction

The issue of ground connections is one that will concern you again and again, in this and other labs. Read this chapter carefully, and try to understand it as much as possible. Not everything in it may make perfect sense in the beginning; some of this material will become clearer as you gain laboratory experience. Nevertheless, it pays to have a preliminary understanding at this point. As you attempt to connect various instruments in future experiments, you may need to return to this chapter for advice.

Producing Positive or Negative Supply Voltages with Respect to Ground

Lab instruments have terminals so that you can connect them to the circuits you are working with. For example, a "***floating***" power supply has plus (+) and minus (–) terminals. The voltage between them is a well-defined quantity, which you can set at will. However, the voltage between one of these terminals and a third point, such as the instrument's metal case (if it has one) or the case of another instrument, may not be well defined and may depend, in fact, on instrument construction and parasitic effects that are not under your control. Parasitic voltages can interfere with proper operation of the circuits you are working with, or can even damage them. Worse, in some cases they can cause an electric shock.

To avoid such situations, instruments have an additional terminal called ***the ground***, often labeled **GND** or indicated by one of the symbols shown in ***Figure D.1***; … . The ground terminal may be connected to the internal chassis of the instrument (it is sometimes referred to as the ***chassis ground***); to the instrument's metal case; and if the power cord of the instrument has three wires, to the ground [third] lead of the cord's plug. When you plug in the instrument, this lead comes in contact with the ground terminal of the power outlet on your bench, which is connected to the ***earth potential*** [earth ground, $V = 0$] for safety and other reasons. In fact, other instruments on your bench [such as the oscilloscope], or other benches, or even elsewhere in the building may have their grounds connected to that same point, through the third wire of their power cords.

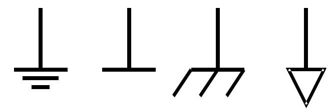


Figure D.1 [Rightmost figure added by DJD].

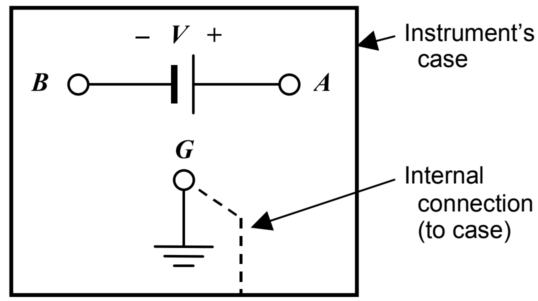


Figure D.2 [*Floating* terminals *A* and *B*, *Ground* terminal *G*].

When you use a power supply with the ***output floating*** (i.e., with neither of the output terminals connected to ground), you get the situation shown in ***Figure D.2***. The circles (A, B, G) indicate terminals for making connections to the instrument's output or ground. In the following discussion V_{XY} will denote the voltage [difference] from a point X to a point Y. In ***Figure D.2***, V_{AB} [$= V_A - V_B$] is the power supply's output voltage V, and it is well defined. However, V_{AG} and V_{BG} are *not* well defined and can cause the problems already mentioned.

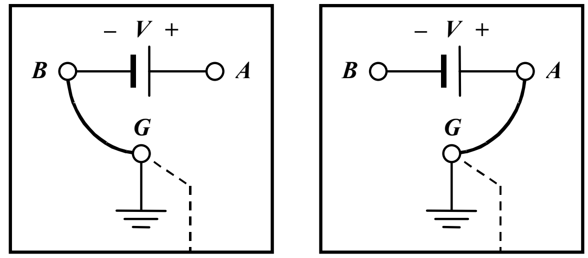
To avoid this, you should strap [connect] one of the two output terminals to the ground terminal [G], as shown, for example, in ***Figure D.3(a)***. Now *all* voltages are well defined: $V_{AB} = V$, $V_{BG} = 0$, and $V_{AG} = V_{AB} + V_{BG} = V + 0 = V$. If we assume that V is a positive quantity, the connection in ***Figure D.3(a)*** develops a positive voltage at terminal A with respect to ground. If you … need a negative voltage with respect to ground instead, you would use the connection in ***Figure D.3(b)***. Here, terminal B has a potential of $-V$ with respect to ground [$V_{BG} = V_{AG} - V_{AB} = 0 - V$]. In some power supplies, ground connects as shown in ***Figure D.3*** are permanent, and you do not have access to them. In other power supplies, it is up to you to make such connections.

Connecting One Grounded Instrument to Another

When more than one instrument or circuit with ground connections is used, one should think carefully. Consider … ***Figure D.4***, where it is attempted to connect the output of one instrument to the input of another. For example, Instrument 1 can be a function generator [providing varying voltages]... Instrument 2 can represent an oscilloscope, or an oscilloscope probe [measuring varying voltages]. At first sight, the connections shown seem to be correct. However, there is a *big* problem. Although not apparent from ***Figure D.4***, the ground terminals are connected not only to the instrument cases but also to the common ground of the power outlet on the bench (through the ground pin on the power plug, as explained earlier). Making these connections explicit, we have the situation shown in ***Figure D.5***. It is now clear that the second instrument's ground connections short the first instrument's output across *CD* (i.e., they place a short circuit across it; you can trace this short circuit along the path *CIHGED*). [Thus output V_{DC} is forced to $V_{DC} = 0$.] Not only will this prevent a voltage from being developed at that output, but also it can damage the instrument. The problem is solved if the connection between the two instruments is modified, so that **the instrument ground is connected to instrument ground**, as shown in ***Figure D.6***.

... one may wonder [why] the connection marked *x* is needed in ***Figure D.6***, given that the two ground terminals are connected together anyway through the power cables, as shown by the heavy lines. The answer is that there may not always be a ground [third] terminal on the power plug, and even if there is one, it may not be reliable; although ideally all ground terminals on power receptacles should be at the same potential, they sometimes are not. In addition, the long ground wires (*IH* and *GH* in ***Figure D.6***) may act as antennas, picking up interference. To be safe, then, use a short connection such as *x* between the ground terminals of the two instruments.

A final word of caution: Since an instrument's case is in contact with ground connections, you need to be sure that cables and devices do not accidentally come into contact with it. If this happens, malfunction or damage can occur.



(a) *(b)*

Figure D.3

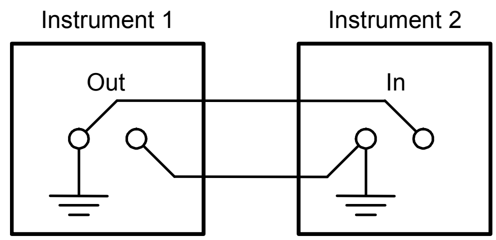


Figure D.4

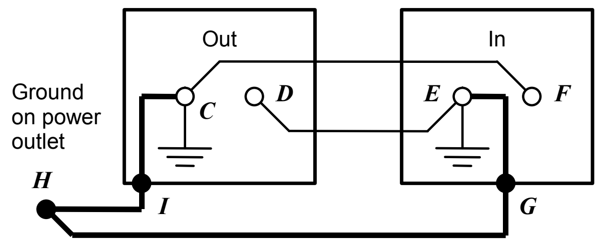


Figure D.5

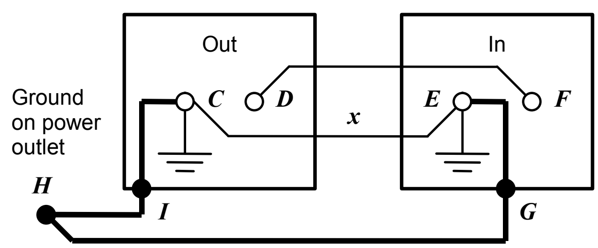


Figure D.6

These guidelines will be sufficient for the purposes of this lab. Grounding is actually a complicated issue, and you should not expect the simple practice discussed above to be adequate in all situations. As you gain experience, you will obtain a better feel for grounding practices. ■

Appendix E: FLUKE 45 DIGITAL MULTIMETER (DMM)

Revised: 7/29/14 DJD

You will make frequent use of the **FLUKE 45 Digital Multimeter**, or DMM (***Figure E.1***). It is called a ***multi*meter** since it can measure several quantities: DC voltage, DC current, AC voltage, AC current, resistance, frequency, and forward voltage drop across a diode. It is a ***voltmeter*** (measures voltage), an ***ammeter*** (current) and an ***ohmmeter*** (resistance), although not all at the same time.

The following pages provide some details on the Fluke 45 DMM to help you. Some advanced applications are given in the *Fluke 45 Quick Reference Guide* pamphlet in the top drawer of the lab benches, or in the *Reference Manual* in the reference manual drawer in M-433.

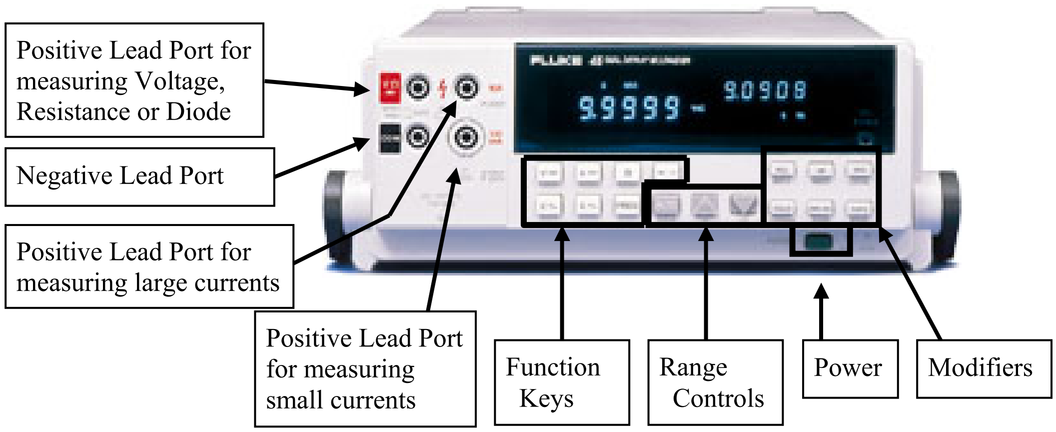


Figure E.1 Fluke 45 Digital Multimeter. On the Function Keys, DC is indicated by two parallel lines (solid and dashed) and AC by a sinusoidal icon. Lead ports are for banana-ended test leads.

Function Keys

Press the appropriate *Function Key* to measure a particular quantity; e.g., the DC voltage key to measure DC voltages. An AC measurement gives the *root-mean-square* value (r.m.s.), which is the subject of one of the ENGR 171 experiments.

Range

A ***range***, or ***scale***, is the region of values in which the DMM is trying to take measurements. On the Fluke 45 DMM, the "300 mV range" gives readings up to 300 mV (0.00001 to 0.29999 V). The "3 V range" gives values up to 3 V (0.0001 to 2.9999 V).

Likewise, for resistance, the "300 Ω range" goes from 0.01 to 299.99 Ω, while the "3 kΩ range" goes from 0.1 to 2999.9 Ω.

The Fluke 45 DMM is what is called a 4-1/2 digit, 30,000 count DMM. The term "4-1/2 digit" refers to a meter that gives measurements with four full digits ranging from 0 to 9, plus the leading "half digit" which is a zero, 1 or 2. Thus all numbers from 0 to 29,999 are represented. The "count" refers to the size of each ***range***. Here, there are 30,000 "tick marks" or *counts* in each range.

The range values can be found in the "Fluke 45 Quick Reference Guide" in the top drawer of the lab benches, and in ***Table E-1*** at the end of this article.

When taking measurements, **record as many digits as the display reads**. **Do not round off** unless the last digit drifts with time.

Range Controls

- The **up arrow** $\boxed{\blacktriangle}$ increases the range (scale). For example, from the 300 mV range to the 3 V range.
- The **down arrow** $\boxed{\blacktriangledown}$ decreases the range.
- The $\boxed{\text{AUTO}}$ key lets the Fluke *autorange*, or automatically select the best range; the display window will read "AUTO." To turn autorange off, press the $\boxed{\text{AUTO}}$ key again.

The range is adjusted to get measurements of better ***resolution***. For the best resolution, use the smallest range larger than the value you are measuring; e.g., if measuring a 150 Ω resistor, use the 300 Ω range. The 3 kΩ and 3 MΩ scales will give readings, but not to the same number of meaningful digits. For example, a 150 Ω resistor was measured on the Fluke 45 DMM at three different ranges:

300 Ω range:	147.16 Ω
3 kΩ range:	0.1472 kΩ
3MΩ range:	0.0002 MΩ.

The 300 Ω range gave the best *resolution* for the 150 Ω resistor.

Always start at the highest scale (range) first. Trying to measure a value larger than the range setting may damage the DMM's internal circuitry.

Making Measurements

Always use appropriate meter leads. For the Fluke, one end of each lead is a banana plug, and the other can be an alligator clip, a mini-grabber, or a straight probe. Alligator clips can be connected to short ***jumper wires*** that can easily be inserted into proto-board sockets; mini-grabbers can be clamped directly to component wires.

The positive (red) test lead plugs into one of the positive (red) ports: [V,Ω,→], [10 A] or [100 mA] port. The negative (black) test lead plugs into the negative or common [COM] (black) port.

Again, always start at the highest scale (range) first. Trying to measure a value larger than the range setting may damage the DMM's internal circuitry.

If you try to measure a resistance larger than the current range, the DMM will read "OL" meaning "overload" (some call it "over limit" or "open line").

In analog (dial) meters, trying to measure a resistor larger than the DMM's range setting results in *pegging*. As the dial tries to turn to a value beyond its maximum for the selected range, the dial slams into the peg intended to limit its motion. This mechanically damages the DMM.

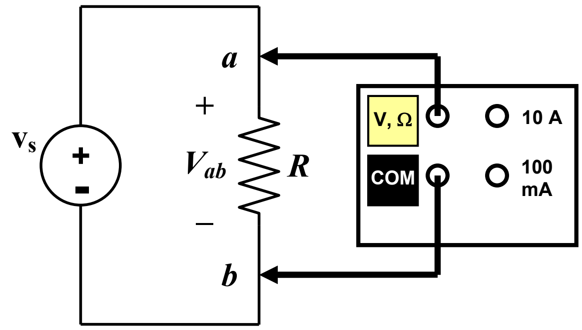


Figure E.2 Connection for using the DMM as a **voltmeter**, measuring voltage drop V_{ab} from *Node a* to *Node b* ($V_{ab} = V_a - V_b$).

Voltage Measurements

Voltage measurements are made *<u>in parallel</u>* with the component(s) whose voltage is being measured (e.g., the resistor in ***Figure E.2***). **In *parallel*, the component and the DMM have the same *voltage drop***. As a ***voltmeter***, the DMM presents a **high resistance** so that the current through the component being measured is practically unaltered (see *current dividers* in the textbook).

<u>The voltmeter is connected across (in parallel with) the component</u>. The assumed positive (higher voltage) terminal of the component (***Node a*** in ***Figure E.2***) is connected to the positive port [V,Ω,→] of the DMM. The assumed negative terminal (***Node b***) is connected to the negative port [COM].

Voltage has polarity. If the measured voltage drop from ***Node a*** to ***Node b*** is **positive**, then the higher voltage is indeed at the component terminal connected to the [V,Ω,→] port; i.e., $V_a > V_b$ ($V_{ab} = V_a - V_b > 0$).

If the measured voltage drop from ***a*** to ***b*** is **negative**, then the higher voltage is actually at the component terminal connected to the [COM] port; i.e., $V_b > V_a$ ($V_{ab} = V_a - V_b < 0$).

DC and AC Voltage Measurements

DC (constant) measurements are made by pressing the Function Key for DC voltage $\boxed{V =}$. If the voltage across the element varies periodically, the DC measurement gives the ***average value*** of the signal. If the signal is a pure sine wave, e.g., $v(t) = V_m \sin\omega t$, then the DMM displays the average value (i.e., zero, 0). However, if the sine wave is offset, e.g., $v(t) = V_o + V_m \sin\omega t$, then the average value V_o is displayed.

AC (time-varying) measurements are made by pressing the Function Key for AC voltage $\boxed{\text{V} \sim}$. This measures the ***root-mean-square*** (***r.m.s.***) value of **<u>only</u> the time-varying part of the signal**. For a sine wave, $v(t) = V_o + V_m \sin\omega t$, the value displayed is $0.707V_m$, regardless of V_o.

To measure the ***<u>total</u> root-mean-square*** (***r.m.s.***) value of a time-varying signal **due to both its constant <u>and</u> time-varying parts, press both** $\boxed{\text{V} =}$ and $\boxed{\text{V} \sim}$ **at the same time**. The r.m.s. value of the total signal is displayed.

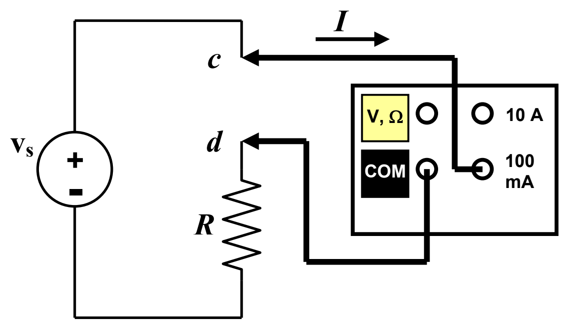


Figure E.3 Connection for using the DMM as an **ammeter**, measuring current *I* through the circuit branch between *Nodes c* and *d*. Use the 100 mA port for currents less than 100 mA.

Current Measurements

Current measurements are made *<u>in series</u>* with the component whose current is being measured (***Figure E.3***). **In *series*, the component and DMM have the same current.** As an ***ammeter***, the DMM presents a **very small resistance** – it acts as a short – so that the current through the component is practically unaltered by the measuring device (see *voltage dividers* in the textbook).

<u>The ammeter is inserted into the circuit</u> by "breaking" the circuit, and inserting the ammeter into the "break". In other words, "**Break and Replace**". When the circuit is broken at a node, two new nodes are created – the ammeter is inserted between these two nodes.

In ***Figure E.3***, ***Nodes c*** and ***d*** were originally the same node; the circuit is broken at ***c-d***, and the ammeter placed between ***c*** and ***d***. Alternatively, imagine a *short* circuit (wire) between ***Nodes c*** and ***d***; then replace the *short* with the ammeter.

Current *I* is taken to enter the Fluke at the [10 A] or [100 mA] port (depending on if the current is large or small), and leaves through the [COM] port. Currents in ENGR 171 are less than 100 mA, so the lower current input port is used.

In ***Figure E.3***, current is assumed to flow from ***Node c*** to ***Node d***, from the [100 mA] port to the [COM] port.

If the measured current is **positive**, then the current physically flows from the [100 mA] port to the [COM] port (from ***c*** to ***d*** in ***Figure E.3***).

If the measured current is **negative**, then current physically flows in the opposite direction assumed (from ***d*** to ***c***).

Measuring current is more difficult than measuring voltage because the circuit must be "broken" and the ammeter correctly inserted into the circuit without change the circuit architecture.

The water analogy of electric circuits might be helpful. To measure water flow through a pipe, a meter must be inserted into the pipe. The pipe is cut; water that would flow out of the pipe must be directed into the meter, and then out of the meter back into the downstream pipe. To measure electric current, the wire ("pipe") must be broken; the current that would "flow out" of the wire must be directed into the meter, and then out of the meter back into the wire.

Three important points to remember:

1. **The current to be measured must be forced to go through the ammeter.**
2. **Do not change the circuit**. The components must be connected the same way as they were without the ammeter; the currents through each component must remain the same. Recall that the ammeter acts as a short.
3. **Do not connect the ammeter in parallel**.
   - this provides an alternate (new) path for the current to flow through, thus changing the circuit.
   - since the ammeter acts as a short, the current in this new path can be large – exceeding 100 mA – and blowing the fuse in the DMM (the fuse protects the DMM circuitry from being overloaded).

Resistance Measurements

Resistance measurements **are made** ***in parallel*** with the resistor being measured (***Figure E.4***). One lead of the resistor is connected to the [V, Ω, →] port, while the other is connected to the [COM] port. ***Resistors are not polarity sensitive***, so the resistor can be connected in either direction.

The DMM applies a calibrated voltage, and measures the current caused by the voltage. The ratio of the voltage to current is the resistance.

Two important points to remember when measuring resistances:

1. **Do not supply power to the circuit when measuring resistances**.
   - the external power may damage the calibrated voltage source in the DMM.
   - the external voltage will affect the current measured by the DMM, giving faulty readings.
2. **Isolate the resistor** (**remove it**) from the circuit to ensure that you are not measuring a parallel combination of some other resistances, as illustrated in ***Figure E.5***. (Note: the resistor does not need to be removed from the proto-board, but must be removed from the circuit).

■

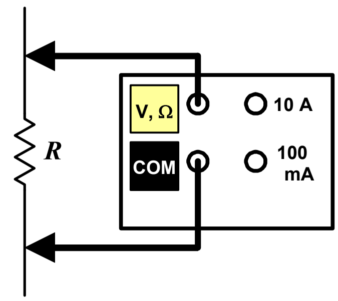


Figure E.4 Connection for using the DMM as an **ohmmeter**, measuring the resistance of resistor *R*.

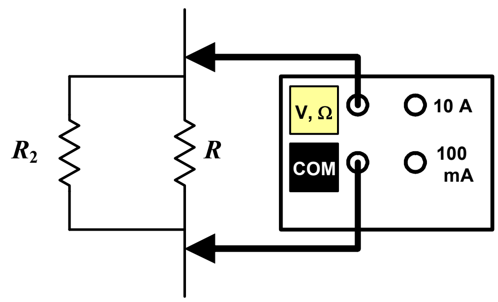


Figure E.5 Measuring the resistance of the parallel combination of *R* and R_2. To measure *R* alone, remove it from the circuit (here, disconnected from R_2.

Table E-1 Typical Fluke 45 Ranges and Full-Scale Values, partial list (adapted from Tables 3-2 through 3-4, *Fluke 45 Dual Display Users Manual*).

Voltage Range (full scale)	Current Range (full scale)	Resistance Range (full scale)
300 mV (300.00 mV)*	30 mA (30.000 mA)	300 Ω (300.00 Ω)
3 V (3.0000 V)	100 mA (100.00 mA)	3 kΩ (3.0000 kΩ)
30 V (30.000 V)	10 A (10.000 A)	30 kΩ (30.000 kΩ)
300 V (300.00 V)	-	300 kΩ (300.00 kΩ)
1000 V (1000.0 V)	-	3 MΩ (3.0000 MΩ)
-	-	30 MΩ (30.000 MΩ)
-	-	300 MΩ (300.00 MΩ)

* Voltages are measured from 0 mV to 299.99 mV.

Measure Voltage *in Parallel*.
Measure Current *in Series*.

For measuring current, you may have heard: "Break and Replace".

Voltage, ***Current*** and ***Diode*** measurements are ***polarity sensitive***. It matters which component terminal is connected to which DMM port.

Reference:

The Fluke Corporation, *Fluke 45 User's Manual*, 1999.

Appendix E1: DIGITAL MULTIMETERS (DMMs): *Accuracy* and *Resolution*

Taken directly from the Cal Poly EE241 circuits lab manual, 2001.

Emphasis, [notes, clarifications, additions in square brackets], footnotes, and other minor editing by D. J. Dal Bello, 2004-05, 2010-11, 2014.

Note: the text was originally written assuming a 3-1/2 digit, 2000-count DMM (i.e., a range from 0 to 2000 Ω). AHC's Fluke 45 DMM is a 4-1/2 digit, 30,000-count DMM (e.g., 0 to 30,000 Ω). The ideas are the same.

A digital multimeter (DMM) is one of the most versatile instruments in an electronics laboratory. It is relatively inexpensive, accurate, and easy to use. DMMs usually measure DC and AC voltages, AC and DC currents, resistance, forward voltage drops in diodes, and sometimes conductance.

There are pitfalls in the use of DMMs. Students often believe that the numbers shown on a display are precisely accurate. This is never true, and often the relative error can be quite big when measuring small values on the selected range.

It is extremely important to distinguish between ***accuracy*** and ***resolution***. [*Accuracy* is how close you are to the actual value. *Resolution*, or *precision*, is how well you can distinguish two different, but nearby, signals or values; e.g., the distance between marks on a ruler].

A 3-1/2 digit[1] meter can count up to 2000 in displaying the measured parameter, whether it be voltage, current, or resistance. The ***resolution*** for such a meter is one count or ±1 part in 2000[2]. So, for example, if you are measuring DC voltage on the 2 V ***range***, the meter will measure from 0.001 V to 1.999 V. The **resolution** is then "one count" or 0.001 V [±0.0005 V].

The ***accuracy*** of a DMM, however, is another matter. It is always worse than the resolution. Accuracy is specified as **a percentage of the <u>reading</u> plus or minus 1 or 2 counts of the least significant digit**.[3] In an analog meter [a meter with a dial or needle] the accuracy is specified as a percentage of the full scale value of the range of the meter setting. Therefore, **digital instruments** have an additional advantage: their accuracy is mostly independent of the meter range. The accuracy is not completely independent of the range because of the 1 or 2 count uncertainty in the least significant digit.

As an example, suppose you measure 1.324 V on the 2 V DC range of a [3 1/2 digit] meter with a DC accuracy of 0.25% ± 1 count[4]. The error would then be:

$$(0.0025)(1.324\text{ V}) + 0.001\text{ V} = 4\text{ mV}$$

As a percentage error, this would be:

$$\frac{0.0043}{1.324}(100\%) = 0.33\%$$

A more extreme example. Suppose on the 2 V DC range you measure 0.032 V. The error would be [to one significant figure]:

$$(0.0025)(0.032\text{ V}) + 0.001\text{ V} = 1\text{ mV}$$

The *percentage error* would then be:

$$\frac{0.001}{0.032}(100\%) = 3.4\%$$

This is worse than a good quality analog meter, and much worse than the stated accuracy of the digital meter. [This problem is caused by trying to measure a quantity that is near the bottom of the range].

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[1] "3-1/2 digit" refers to a meter that gives 3 full digits ranging from 0 to 9, plus the leading "half digit" that is either a blank or a one (1)… thus all numbers from 0 to 1999.

AHC's Fluke 45 reads to 2999.9; it is a "4-1/2 digit, 30,000 count" DMM – 4 full digits, plus the leading "half digit": blank, 1 or 2.

[2] The last digit has an uncertainty of ±0.0005 V, which is 0.5 parts in 1000, or 1 part in 2000.

AHC's Fluke has a resolution of 1 part in 30,000; assume ±0.5 of the last digit.

[3] It would seem that the *accuracy* should be ±(0.25% + 1 count), not (0.25% ± 1 count).

[4] Nominally, AHC's Fluke has a DC voltage accuracy of 0.025% + 2 counts; its resistance accuracy is 0.05% + 2 counts.

A **remedy for this problem would be to switch to the next lowest scale**, [from the 2-V range (±0.001 V for the 3-1/2 digit meter), to the] 200-mV [range (±0.0001 V)]. The reading error would still be 0.25%, but the least significant digit of uncertainty is now 0.1 mV = 0.0001 V. You would then measure something like: 0.0320 V. The error would then be:

$$(0.0025)(0.0320\ \mathrm{V}) + 0.0001\ \mathrm{V} = 0.2\ \mathrm{mV}$$

and the percent error is:

$$\frac{0.0002}{0.0320}(100\%) = 0.6\%$$

To obtain the most accurate reading, choose the lowest range possible.

[Note: If it exists, the next lowest scale, 20 mV, would be unable to measure the 32 mV, since 32 is greater than 20 mV. The DMM will display “OL” for “overload”.]

Other hidden sources of error in DMMs are noise, variations with temperature, and errors due to lack of calibration. The most accurate measurements that can be made on a DMM are DC voltages. All other measurements are less accurate, with AC current being the least accurate. When a single accuracy figure [rating] is given for a meter, it is always for DC voltage. Always read the complete specifications if measurements other than DC voltage are to be made.

AC Signals

Another thing to keep in mind is that most DMMs measure the average value of AC signals. This value is converted to the equivalent r.m.s. [root-mean-square] value **as if the signal were a sine wave**. Therefore, for non-sinusoidal waveforms, the readings will be very inaccurate. Analog meters measure AC signals the same way.

Some higher quality DMMs have a true r.m.s. capability which allows for the computation of the actual r.m.s. value [no matter what the waveform; AHC’s Fluke can measure true r.m.s.]. There are limitations to this technique. The crest factor usually cannot be greater than about 5 to obtain accurate readings. The bandwidth of AC measurements is also quite limited. Most DMMs can measure AC voltages with their highest accuracy in the approximate range of 40 Hz to 5 kHz. Above 10 kHz, most DMMs are unusable.

[You will generally use the **oscilloscope** to measure AC voltages].

Analog Meters

Are analog [needle or dial] meters obsolete? Almost. Their only advantage is that they can show trends. It is easier to see a needle move than it is to keep track of numbers changing on a display. To accommodate this feature, some digital instruments have an analog display in addition to the digital display. Analog meters find use in specialized measurement situations, such as high voltage, low current, or high resistance.

The severest limitation of analog meters is their accuracy, which is never better than 2%. Digital meters can have more than 5-1/2 digits, giving a resolution of 5 parts per million[5]. ■

References:

Electrical Engineering Department Faculty, Cal Poly, SLO. *Electric Circuit I Laboratory Manual*, Winter 2001.

The Fluke Corporation, *Fluke 45 User’s Manual*, 1999.

[5] A 5-1/2 digit, 20,000 count DMM has 6 total digits; the leading half digit, plus 5 full digits. The last digit has an uncertainty of 0.5 the last digit, i.e.,: 100,000±0.5, which is 5 parts in 1,000,000, or 1 part in 200,000.