ECE 209: *Circuits and Electronics Laboratory*

Notes for Lab 2 (Meters, Measurements, and Errors)

1. The digital voltmeter (DVM)
    - Because voltage is defined at one point **with respect to another point,** then voltmeter must be placed at **two points** in the circuit (i.e., in "parallel" with the device under test).
    - To reduce impact on circuit, voltmeter has **very high** internal resistance (i.e., an **open circuit**).
    - Because voltmeter resistance is very high, if placed in series with a device, it stops all current.
2. The ammeter
    - Because current is defined **at a point,** then ammeter is **inserted** in **series** to do measurement.
    - To reduce impact on circuit, ammeter has **very low** internal resistance (i.e., a **short circuit**).
    - Because ammeter resistance is very low, if it is placed in parallel with a device, current skips the device and usually **fries the ammeter** and possibly other parts of the circuit.
3. The digital multimeter (DMM) or digital volt-ohm meter (DVOM)
    - Combines multiple measurement tools into one unit.
        - Internally, DMM is a **slow** and **high-precision** analog-to-digital converter measuring voltage.
        - Versatile: voltage, current, capacitance, inductance, resistance, temperature, frequency, etc.
            - Convert to ammeter by measuring voltage from *measured* current × *known* resistance.
            - Convert to ohmmeter by measuring voltage from *known* current × *measured* resistance.
            - Measure temperature with a thermocouple.
            - Measure capacitance by finding rise time of a known step across a known resistance.
            - With an on-board DSP, lots of other useful measurements or conversions are possible.
    - High-precision models (e.g., 6.5+ digits) can be PCI cards or larger bench-top units (e.g., function generator size) with computer interfaces. These models have advanced/extensible feature sets.
    - RMS measurements are often AC coupled (i.e., DC offset/average component is stripped out).
        - So RMS measurements may be incorrect when waveform has nonzero offset.
        - Remember that $\text{RMS}^2 = \text{RMS}_{\text{AC}}^2 + \text{DC}^2$.
            - *Calculate* true RMS by measuring DC offset (i.e., *average*) and AC RMS (i.e., RMS_{AC}).
            - Some meters have a *special* setting that does the "AC+DC" RMS calculation for you.
    - Can use **probes** or ***banana connectors*** (the latter is useful for *common ground* connections).
    - For safety, some DMM's have "shutters" to help prevent accidental short-circuiting by ammeter.
    - Bandwidth of these devices is may involve parasitic reactance, but in reality *internal* filters restrict bandwidth **by design**. Typical or guaranteed bandwidth should be specified (usually on device).
        - HP 972A has unity gain up to 20 kHz. HP 974A has unity gain up to 100 kHz.
        - Should not use DMM outside of its specified bandwidth.
4. Introduce and complete the *Meters, Measurements, and Errors* lab.
    - Resistor color codes: Black, Brown, ROYGBV, Gray, White correspond to **digits** 0–9
        - Far-right digit d_t has specifies *tolerance* (different colors and/or separated more).
        - d_1-d_2-d_m-d_t: $d_1 d_2 \times 10^{d_m}$, d_1-d_2-d_3-d_m-d_t: $d_1 d_2 d_3 \times 10^{d_m}$, and so digit d_m is "# of zeros"
        - Brown-Black-Green = 105 = 1000000 = 1 MΩ; Brown-Green-Orange = 153 = 15000 = 15 kΩ
    - See procedure details on the next page.

Part 1 Measure the internal resistance of a DC voltmeter

- V_s is is supply voltage. V_m is measured voltage across R_2 ($V_m \approx V_s/2$).

1. Connect V_s to R_1. Connect R_1 to R_2. Connect R_2 to $0\,\text{V}$ (ground).
2. Temporarily **DISCONNECT** breadboard from V_s DC supply. **THEN** measure resistance across R_1 and R_2. Record these values in your table. They should be $\sim 1\,\text{M}\Omega$.
3. Set the HP 974A (**NOT** the 972A) digital multimeter (DMM) to measure DC voltage. Press the Range button until the number in the upper-right of the screen indicates the appropriate range for your measurement (5 V for the first trial and 50 V for the second trial).
4. Use the DVM to measure V_m across R_2. It should be $\sim V_s/2$. Record your value in the table.
5. For your lab report, plug your measured V_m, V_s, R_1, and R_2 into the equation

$$V_m = \frac{R_2 \| R_v}{R_1 + R_2 \| R_V} \qquad \text{where} \qquad R_2 \| R_V = \left(\frac{1}{R_2} + \frac{1}{R_v} \right)^{-1} = \frac{R_2 R_v}{R_1 + R_v} \tag{1}$$

and **solve** for R_v. Compare this "calculated R_v" to the "given R_v" from the table. Use the percent error formula

$$\%\ \text{error} = \frac{\text{Measured } R_v - \text{Given } R_v}{\text{Given } R_v} \times 100\%.$$

Note that Equation (1) is the V_m/V_s "transfer function" of the circuit in Figure 2(b) from your book.

- Do these steps for **BOTH** the 4 V (5 V DVM range) and 20 V (50 V DVM range) input cases.

Part 2 Measure the internal resistance of a DC ammeter.

- $500\,\Omega$ potentiometers (screw swings middle "wiper" pin) and screwdrivers ("probe tool") are in cabinet.
- Must be in ammeter mode to open and close shutter.

1. Connect V_s to R, R to Ammeter current input (open shutter), and ammeter ground to 0 V.
2. Measure current I, which should be near $(12\,\text{V})/(15\,\text{k}\Omega) = 0.8\,\text{mA}$. If ammeter beeps or reads 0 mA, try a different ammeter (i.e., the internal fuse is blown).
3. Connect **middle** potentiometer pin to junction between R and ammeter. Connect **either one of the outside** potnetiometer pins to 0 V.
4. Adjust potentiometer screw until ammeter reads **half** of the old current (i.e., $I/2$, or around 0.4 mA).
5. **Remove** potentiometer and measure resistance between the two pins that you used (alligator clips may help). The resistance will match ammeter's R_a (typically between $10\,\Omega$ and $15\,\Omega$).
6. Close shutter and put ammeter back in voltage mode.

Part 3 Frequency response of AC voltmeters.

- Make sure your table has both HP 972A and HP 974A; switch tables otherwise.

1. Use banana connectors with alligator clips to connect DMM to function generator's cable. Set generator for `HIGH Z` mode. The ▷ button doubles as a Vrms button to make setting amplitude easy.
2. Set DMM to measure AC (RMS) voltage. Use Range button for 5 V (or 4 V) range. If measurement is noisy, try a different function generator. In **worst-case scenario,** turn on Average feature of DMM. For low frequencies, DVM RMS should match function generator RMS *almost perfectly.*
3. Record data for **BOTH** HP 972A (20 kHz bandwidth) and HP 974A (100 kHz bandwidth). Make sure to use the correct data table. See next page for instructions on how to process and display these data.

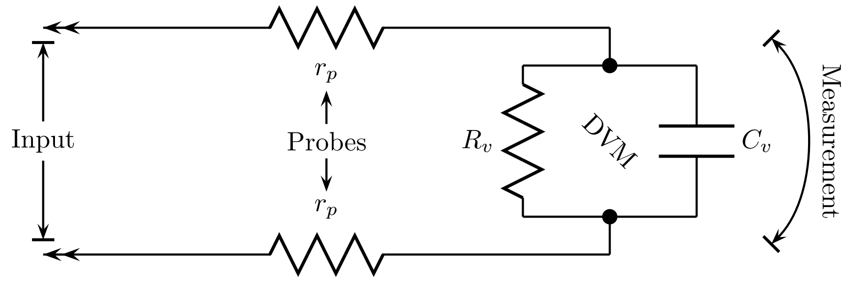
Lab report data

- ⋆ Lab book's lab 2 appendix has information about MATLAB `semilogx` plots.

```
f = [1 2 10 20 30 40 50 60 70 80 90 100]*1000; % Data vectors
rms = [1.998 1.99 1.789 1.414 1.109 0.894 0.743 0.633 0.549 0.485 0.434 0.392];
gain = rms/2;                                   % Gain = rms/input (input = 2 Vrms)
gaindB = 20*log10( gain );                      % Convert to deciBels (dB)
semilogx( f, gaindB, '.-' );                    % semilog plot (1/f (dB) looks linear)
grid on;                                        % Turn plot grid on
xlabel( 'Frequency (Hz)' );                     % X label (with units)
ylabel( 'Gain (dB)' );                          % Y label (with units)
title( 'Gain magnitude for HP 972A DVM' );      % Title
```

NOTE: If the plotted response looks like a first-order step response, you can estimate its corner frequency f_c as the frequency where the magnitude response plot hits $-3\,\text{dB}$.

- In theory, we can model the DVM as resistance R_v (from Part 1) in parallel with capacitance C_v.
- Under this theory, the low-pass filter is formed where the two probes, which each have resistance $r_p \approx 0.8\,\Omega$, meet the DVM. So the attenuation is mostly from dissipation across $2r_p$.



  - The time constant of such a filter is the product of its single capacitor C_v and the equivalent resistance from one end of the capacitor to the other when the inputs are shorted.
  - That is, the time constant

$$\tau \triangleq (R_v \| 2r_p) C_v = \frac{2R_v r_p}{R_v + 2r_p} C_v.$$

  - Because $R_v \gg r_p$, then

$$R_v \| 2r_p \approx 2r_p \qquad \text{and} \qquad \tau \approx 2r_p C_v.$$

- Under this theory and assuming $R_v \gg r_p$, the corner frequency

$$f_c = \frac{1}{2\pi\tau} \approx \frac{1}{4\pi r_p C_v}$$

  where the probe resistance $r_p \approx 0.08\,\Omega$, and the DVM capacitance C_v is unknown.
  - So you can use f_c, R_v, and our estimated r_p to estimate the DVM capacitance C_v. That is,

$$C_v \approx \frac{1}{4\pi r_p f_c} \approx \frac{1}{\pi (0.32\,\Omega) f_c}.$$

- **FLAW IN MODEL:** If you estimate C_v this way, your value will be **very large** (e.g., several tens of μF — that's HUGE! A ***parasitic*** capacitance would never be that large in this application).
  - Small-signal electronics have parasitic capacitances in units of pF ($1\,\text{uF} = 1{,}000{,}000\,\text{pF}$).
  - In reality, the DVM's equivalent circuit is more complex than a parallel R_v–C_v combination.
  - In fact, the probe resistance r_p has little to do with the bandwidth of the DVM. The bandwidth is actually set by ***design*** with internal analog filters.
  - Current draw of *real* DVM does not increase until *very* high frequency.