Lab 2: DC Measurements

OBJECTIVES
- Understand the galvanometer and its limitations.
- Use circuit laws to build a suitable ammeter and voltmeter from the galvanometer.
- Understand the loading effect meters have on a circuit.

MATERIALS
- The lab assignment (this document).
- Your lab parts.
- Pre-lab questions including Multisim.
- Decade resistor box.
- Read section 3.5 in the textbook.

INTRODUCTION
The moving coil galvanometer (also known as a d’Arsonval meter) shown in Fig. 1, contains a pivoted coil of fine wire through which a current passes. The magnetic interaction between the magnetic field set up by this current and the magnetic field of a permanent magnet housed in the meter casing results in movement of the coil against a hair-spring (torsion spring). The resulting displacement is shown by the meter needle against a scale.

The current that causes full-scale deflection (needle deflects to the maximum extent of the meter) is labeled on the galvanometer. Meter movements are usually rated by current and resistance. For our meters, this full-scale current is 1.0 mA and the meter resistance is approximately 50 Ω.

The current through the meter is proportional to the deflection. If the meter deflects 40% of the full-scale (or to 0.4 on the meter), the measured current is value of 40% of 1.0 mA, i.e., 0.4 mA. The galvanometer also has an internal resistance. If the resistance is known, the galvanometer can be used to measure voltage by utilizing Ohm’s law. The full-scale voltage is found by multiplying the full-scale current by the meter resistance. If the full-scale voltage is 10 mV and the needle deflects to 0.2, the measured voltage is 2 mV.

Ammeter
The galvanometer, by itself, is not a very effective ammeter because its range is small (the full-scale current is only 1.0 mA). It also has a relatively high meter resistance, which changes the circuit it is measuring. Both problems can be mitigated with a shunt resistor. The shunt is a small resistor placed in parallel with the galvanometer. Because its resistance is much lower than that of the galvanometer, most current passes through the shunt and we don’t overshoot the full-scale current of the galvanometer. (Going beyond the full-scale value of the galvanometer may damage the device.)

An improved ammeter that can be made with the galvanometer and a shunt resistor as shown in Fig. 2. The current to be measured is $I$. We design the ammeter by choosing the desired current range and then
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determining which shunt resistance is necessary to achieve this maximum $I$. The development of the equation for the ammeter relies on the following two equations:

$$I = I_m + I_{sh}, \quad V = R_mI_m = R_{sh}I_{sh}$$

The first equation is an application of KCL. The second equation comes from the fact that the voltage across parallel elements is the same. The maximum current we can measure, $I$, occurs when the meter current, $I_m$, is full-scale.

$$R_mI_{m(fs)} = R_{sh}I_{sh} = R_{sh}(I - I_{m(fs)})$$

Solving for the shunt resistance:

$$R_{sh} = \frac{R_mI_{m(fs)}}{I - I_{m(fs)}} = \frac{R_m}{\frac{I}{I_{m(fs)}} - 1}$$

This equation is the ammeter equation, which provides the necessary shunt resistance for a meter of range $I$. The full-scale current is known to be 1.0 mA, but the galvanometer resistance must be measured.

For example, suppose a 0.1 mA, 20 $\Omega$ galvanometer is to be converted to an ammeter with a range of 0 to 10 mA. Here, $I = 10$ mA, $I_{m(fs)} = 0.1$ mA, and $R_m = 20$ $\Omega$. The value of $R_{sh}$ is calculated as follows:

$$R_{sh} = \frac{20 \Omega}{\frac{10 \text{ mA}}{0.1 \text{ mA}} - 1} = 0.202 \Omega$$

Voltmeter

The galvanometer, by itself, is not also not a very effective voltmeter because its resistance is too low to approximate the infinite resistance of an ideal voltmeter. The small range is also inhibitive. We can make a better voltmeter by adding a large resistance in series with the galvanometer. This resistor is called a multiplier resistor. The voltmeter constructed from the galvanometer and a multiplier resistor is shown in Fig. 3. Using Ohm’s law results in the following equation:

$$V = I_m(R_{mult} + R_m)$$

Since the voltmeter is a series circuit, the current that passes through it is limited to the full-scale galvanometer current. We extend this range by increasing the resistance. Solving for the multiplier resistance and substituting the full-scale current, we get an equation for the maximum voltage that can be obtained.
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\[ R_{\text{mult}} = \frac{V}{I_m(f_s)} - R_m \]

This is the voltmeter equation. It provides the multiplier resistance necessary to create a voltmeter capable of measuring up to a voltage \( V \). As with the ammeter, the galvanometer resistance, \( R_m \), needs to be determined.

To measure a voltage, the terminals of the circuit in Fig. 3 may be connected in parallel with the element to be measured, just as we would with the digital multimeter. The deflection of the needle corresponds to a fraction of the full-scale value, \( V = I_m R_m \).

Ohmmeter

The ohmmeter shown in the below figure is not a precision instrument, but it is useful for the rapid measurement of resistance. It consists of a meter, a series resistor, and a series dc voltage source, as shown in Fig. 4. The unknown resistor \( (R_x) \) to be measured is connected to the ohmmeter circuit as shown. The series resistance \( R_s \) is chosen such that when terminals a and b short-circuited \( (R_x = 0) \), the meter deflects full-scale. When these terminals are open-circuited \( (R_x = \infty) \), the meter shows no deflection. Therefore, a finite nonzero value of \( R_x \) will give a fraction of full-scale deflection. Thus, the meter scale can be calibrated to “read” the resistance \( R_x \). A small variable resistor \( R_v \) is included in the ohmmeter circuit to permit zeroing of the ohmmeter when the a and b terminals are short-circuited. Due to aging of the battery and an increase in its internal resistance, the voltage available at its terminals decreases with time and is offset by reducing the resistance \( R_v \). Because the meter deflection is proportional to the coil current \( I \),

\[ \text{deflection} \propto I = \frac{V_s}{R_x + (R_s + R_v + R_m)} \]

where \( \propto \) indicates “is proportional to.”

Figure 4 – Imprecise ohmmeter made from galvanometer, series resistor, variable resistor, and a dc voltage source.
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PRE-LAB AND QUESTIONS
1. If the galvanometer has a resistance of 2 k\( \Omega \), what shunt resistor would we need to build an ammeter capable of measuring up to 25 mA? For this problem, assume the full-scale galvanometer current, \( I_{m(fs)} = 1.0 \) mA.
2. What is the total ammeter resistance for the above problem?
3. Using the same galvanometer, what multiplier resistance would we need to build a voltmeter with voltmeter resistance of 50 k\( \Omega \)?
4. What is the range of this voltmeter?
5. Build the circuit of Fig. 5 in Multisim. Measure the three branch currents using the Multisim multimeter with ammeter resistance set to 1 n\( \Omega \), and then with the meter resistance equal to your result from part 2. Email the screen capture to your TA BEFORE your lab.
6. Based on the information from part 5, what would the galvanometer read when measuring the current in \( R_3 \)? (Hint: the ratio of the current through \( R_3 \) to the ammeter max current of 25 mA is equal to the ratio of the galvanometer current to galvanometer full-scale current of 1 mA)

LAB PROCEDURE AND QUESTIONS

Measuring Galvanometer Resistance
- In order to design an ammeter or voltmeter from the galvanometer, we must first know its resistance. This will be achieved by substituting current and voltage measurements of the galvanometer into Ohm’s law.
- Our measurement will be less prone to errors if the voltage and current that we use are large because the precision of the multimeter is limited. A shunt resistor is again useful here, because we can feed a large current without damaging the galvanometer.
- Build the circuit in Fig. 6. This is the circuit that will be used to determine galvanometer resistance.

![Figure 5 – Circuit for prelab questions 5 and 6. Three branch currents are shown.](image)
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The voltage across $R_m$ and $R_v$ is the same because they are in parallel. We can derive an equation for meter resistance:

$$V = R_m I_m = R_v I_v$$

$$R_m = \frac{R_v I_v}{I_m} = \frac{R_v (I - I_m)}{I_m}$$

The resistor $R_v$ is a variable resistor. We will use the decade resistor box. Begin with $R_v$ at 0. Slowly increase the resistor until the galvanometer reads exactly 1.0 mA (full-scale deflection). Note this value. CAUTION: Do not overshoot full-scale deflection by increasing $R_v$ too quickly.

We can now solve for meter resistance. $R_v$ is the value set on the decade resistance box, $I$ is the current measured by the DMM ammeter (labeled A in Fig. 6), and $I_m$ is the full-scale galvanometer current 1.0 mA.

After disconnecting your circuit from the galvanometer, use a DMM to measure the galvanometer resistance, $R_m$. Note this value.

Ammeter Constructions and Testing

- Design an ammeter having a range of 0-100 mA. Build the ammeter (circuit in Fig. 2), using the resistance box for $R_{sh}$.
- Build the circuit in Fig. 5 and measure all three branch currents with your constructed ammeter.
- Measure the branch currents with the DMM.
- Explain any differences between the two measurements.

Voltmeter Constructions and Testing

- Design a voltmeter having a range of 0-10 V. Build the voltmeter (circuit in Fig. 3), using the resistance box for $R_{mult}$.
- Build the circuit in Fig. 7. For $R = 330 \, \Omega$, 2.2 k\Omega, and 18 k\Omega, measure the voltage $V_R$ with your constructed voltmeter.
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- Measure the voltage in these three cases with the DMM.
- Compute the percent error between the values obtained with your voltmeter and with the DMM. Explain the trend.

Figure 7 – Circuit for the voltmeter.