IMPORTANT – SHOW ALL WORK!

1. Determine current through and voltage across each resistor.
   All resistances have units of ohms $\Omega$.

   ![Diagram](image1)

2. Determine voltage across and current through each resistor.
   All resistances have units of ohms $\Omega$.

   ![Diagram](image2)

3. Determine currents $I_1$ and $I_2$, and voltage $V$. All resistances have units of ohms $\Omega$.

   ![Diagram](image3)

4. Determine currents $I_x$ and $I_y$, and voltage $V$. All resistances have units of ohms $\Omega$.

   ![Diagram](image4)
5. Find the equivalent resistance ($R_{eq}$) at terminals A-B for the series, parallel and series-parallel circuits. All resistances have units of ohms $\Omega$.

\begin{align*}
\text{Series Circuit:} & \quad R_{eq} = \underline{\ldots} \\
\text{Parallel Circuit:} & \quad R_{eq} = \underline{\ldots} \\
\text{Series-Parallel Circuit:} & \quad R_{eq} = \underline{\ldots}
\end{align*}
Objective
Experimentally verify the current-voltage characteristics of series and parallel circuits by making measurements of resistance, voltage and current using a digital multi-meter (DMM).

Workbench Equipment
- DC Power Supply, Agilent E3640A
- Digital Multi-meter, Agilent 34401A
- Resistor Box II, 10\(\Omega\)/25\(\Omega\)/40\(\Omega\)/130\(\Omega\)/269\(\Omega\)/562\(\Omega\)

Check-out Equipment, 20-111 window
- Banana to banana, 3 pairs, red/black
- Short leads, quantity 6, 1 bag

Background
A DMM is often used to measure three important circuit quantities; resistance, voltage & current.

Measuring Resistance
Resistance measurements are made with the DMM selected as an ohmmeter. When measuring resistance with an ohmmeter, circuit power must be off. If a circuit is powered while using an ohmmeter, the ohmmeter readings will be inaccurate and even worse the ohmmeter could be severely damaged. Also, when measuring an individual resistance, the individual resistance must be disconnected from the rest of the circuit, otherwise, the total resistance (Req) is measured instead of the individual resistance.

Measuring Voltage
Voltage measurements are made with the DMM selected as a voltmeter. The circuit must be powered when measuring voltage; otherwise the voltmeter will display zero volts. A voltmeter is connected in parallel with a circuit element to measure its voltage. Ideally, a voltmeter has infinite resistance (an open circuit) thereby not taking any current away from the element being measured. A good practical digital voltmeter (DVM) has an internal resistance in the range of 10M\(\Omega\) to 10G\(\Omega\) (10,000,000\(\Omega\) to 10,000,000,000\(\Omega\) ). Thus, a DVM draws relatively low current when connected across circuit elements. This high internal resistance enables the DVM to measure circuit voltages with negligible “loading” (drawn current). Loading is undesirable since it lowers voltage readings and hence introduces measurement error.

Measuring Current
Current measurements are made with the DMM selected as an ammeter. The circuit must be powered when measuring current; otherwise the ammeter will display zero amps. An ammeter is connected in series with a circuit element to measure its current. Ideally, an ammeter has zero resistance (a short circuit) thereby not dropping any voltage, thus not introducing measurement error. A good practical ammeter has a small internal resistance (typically a few ohms) and therefore will decrease the current it’s measuring a tiny amount.
Current –Voltage Characteristic of Series Resistance and Equivalent Series Resistance

Fig. 1-1b illustrates a series configuration of three resistances. At each node (wires between each component), there is only one entering and exiting current. Thus, KCL requires the current I to be identical throughout the circuit. According to KVL, the following relationship must hold:

\[
V = IR_1 + IR_2 + IR_3 = I(R_1 + R_2 + R_3) = IR_{eq}
\]  (1-1)

Therefore, the current is the same through series resistances and voltage across series resistances can differ. To determine the current I, the equivalent resistance \( R_{eq} \) of the series combination of \( R_1, R_2, \) and \( R_3 \) is required. By equation 1-1, \( R_{eq} \) equals the sum of these resistances.

![Fig. 1-1a Series Circuit with Three Resistors](image)

Note: Current limit (CL) is a setting on the Agilent power supply which determines the maximum current available at the power supply output; it’s a safety technique.

Current –Voltage Characteristic of Parallel Resistance and Equivalent Parallel Resistance

Fig. 1-2b illustrates a parallel configuration of three resistances. In this case, all resistors share a common voltage since all resistances are connected to the same two nodes. According to KCL, the voltage source must supply a current equal to the sum of the currents flowing in each resistor:

\[
I_t = I_1 + I_2 + I_3 = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} = V \left( \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) = \frac{V}{R_{eq}}
\]  (1-2)

Thereby, the voltage is the same across parallel resistances and current through parallel resistances can differ. From equation 1-2, equivalent parallel resistance \( R_{eq} \) is

\[
R_{eq} = \left( \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right)^{-1}
\]  (1-3)

If additional resistors are connected in parallel, additional terms \( \frac{1}{R_4}, \frac{1}{R_5}, \text{etc.} \) must be included in equation 1-3 above. For two parallel resistors, the equivalent parallel resistance is:

\[
R_{eq} = \frac{R_1R_2}{R_1 + R_2}
\]  (1-4)
Procedure 1: Multi-meter Measurements of a Series Circuit

- Measure the resistance of the following individual resistors with the DMM set as an ohmmeter; 10Ω, 25Ω and 40Ω. Record these values in Table 1-1.
- Construct the circuit of Fig. 1-1a and measure the total series resistance, Req. Compare (% Error) calculated Req (use measured R values) to measured Req in Table 1-1.
  \( \% \text{ Error} = \left( \frac{\text{Meas} - \text{Calc}}{\text{Calc}} \right) \times 100 \)
- Set current limit of E3640A Agilent power supply to 0.5A & set voltage output to 15V = Vt.
- Construct the circuit of Fig. 1-1b by connecting Vt to the circuit of the previous step.
- Measure the voltage across each resistor with a DVM; record in Table 1-1. Check to make sure these measured resistor voltages make sense, hint: KVL.
- Measure current through each series resistor with the DMM set as an ammeter. Compare calculated I (use Ohm’s law with measured values) to measured I. Record in Table 1-1.

<table>
<thead>
<tr>
<th>Nominal R (Ω)</th>
<th>Measured R (Ω)</th>
<th>Calculated Req (Ω)</th>
<th>Measured Req (Ω)</th>
<th>% Error</th>
<th>Nominal R (Ω)</th>
<th>V_R (V)</th>
<th>I_R (mA)</th>
<th>Calculated I (mA)</th>
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Table 1-1 Multi-meter Measurements of a Series Circuit

Procedure 2: Multi-meter Measurements of a Parallel Circuit

- Again measure the resistance of the individual resistors, 10Ω, 25Ω and 40Ω, for accuracy.
  - Resistor measured values most likely have changed from previous measurement due to heat; record these values in Table 1-2.
- Construct the circuit of Fig. 1-2a (R1 = 10Ω, R2 = 25Ω, R3 = 40Ω) and measure the total series resistance, Req. As in Proc. 2, compare calculated Req to measured Req in Table 1-2.
- **Change voltage output from 15V to 2V = Vt.** Make certain CL is still set to 0.5A.
- Construct the circuit of Fig. 1-2b by connecting Vt to the circuit of Fig. 1-2a.
- Measure the current through each resistor with an ammeter; record in Table 1-2. Check to make sure these measured resistor currents make sense, hint: KCL.
- Measure voltage across each parallel resistor with a DVM. Compare calculated V (use Ohm’s law with measured values) to measured V. Record in Table 1-2.

<table>
<thead>
<tr>
<th>Nominal R (Ω)</th>
<th>Measured R (Ω)</th>
<th>Calculated Req (Ω)</th>
<th>Measured Req (Ω)</th>
<th>% Error</th>
<th>Nominal R (Ω)</th>
<th>I_R (mA)</th>
<th>V_R (V)</th>
<th>Calculated V (V)</th>
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</tbody>
</table>

Table 1-2 Multi-meter Measurements of a Parallel Circuit
Procedure 3: Multi-meter Measurements of Series-Parallel Circuit I

![Fig. 1-3a]

![Fig. 1-3b]

**Fig. 1-3 Series-Parallel Circuit I**

- Again measure the resistance of the individual resistors, 10Ω, 25Ω and 40Ω, for accuracy. Record these values in Table 1-3.
- Construct the circuit of Fig. 1-3a and measure the total series resistance, Req between nodes ab. Compare calculated Req (use measured R values) to measured Req in Table 1-3.
- Construct the circuit of Fig. 1-3b by connecting 5V source to nodes ab of circuit Fig. 1-3a. Make certain CL is still set to 0.5A.
- Measure current I0, I1, I2 and I3 with an ammeter; record in Table 1-3. Check to make sure these measured currents make sense, hint: KCL.
- Measure the voltage across each resistor with a DVM; record in Table 1-3. Check to make sure these measured voltages make sense, hint: KVL.

<table>
<thead>
<tr>
<th>Nominal R (Ω)</th>
<th>Measured R (Ω)</th>
<th>Calculated Req (Ω)</th>
<th>Measured Req (Ω)</th>
<th>% Error</th>
<th>I#</th>
<th>Measured I# (mA)</th>
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**Table 1-3 Multi-meter Measurements of a Series-Parallel Circuit I**

Procedure 4: Multi-meter Measurements of Series-Parallel Circuit II

![Fig. 1-4a]

![Fig. 1-4b]

**Fig. 1-4 Series-Parallel Circuit II**

- Repeat steps of procedure 3 for the circuit of Fig 1-4; record data in Table 1-4.
Table 1-4 Multi-meter Measurements of a Series-Parallel Circuit II

<table>
<thead>
<tr>
<th>Nominal R (Ω)</th>
<th>Measured R (Ω)</th>
<th>Calculated Req (Ω)</th>
<th>Measured Req (Ω)</th>
<th>% Error</th>
<th>I#</th>
<th>Measured I# (mA)</th>
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<th>Measured V (V)</th>
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</tbody>
</table>

**Discussion**

1. Why is an ideal internal resistance of zero ohms desirable for an ammeter?  
   Explain, by giving a numerical example, the undesirable effect which would occur if an ammeter with high internal resistance was used.

2. Why is an ideal internal resistance of infinite ohms desirable for a voltmeter?  
   Explain, by giving a numerical example, the undesirable effect which would occur if a voltmeter with low internal resistance was used.

   Note: Use a circuit with at least two series resistors where the voltmeter is connected across one resistor.

3. For series elements _____________ is the same and ____________ can differ.

4. For parallel elements _____________ is the same and ____________ can differ.

5. Derive equation 1-4 from equation 1-3.