ENGR 1181  |  Lab 3: Circuits

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Preparation Material
• **Overview of Circuits Lab:**

The Circuits Lab introduces basic concepts of electric circuits such as series and parallel circuit, used in many engineering applications.

Students will review this document and then take the Carmen quiz before arriving at lab.

**Learning Objectives – students will be able to:**

1. Recognize and assemble series and parallel circuits.
2. Construct electric circuits using a breadboard
3. Develop techniques to measure voltage, current and resistance
4. Apply Ohm’s Law, Power Law, Kirchhoff’s Current Law and Kirchhoff’s Voltage Law
5. Calculate the equivalent resistance of electric circuit
6. Demonstrate the proper circuit configuration for a given scenario

1. **Circuits in Technology**

Electric circuits are usually laid out on printed circuit boards. The board is made of an electrically-insulating material. Much of the "wiring" on a printed circuit board is made from insulated metal paths printed on the board, rather than actual wires. That is why they are called "printed" circuit boards.

Figure 1 shows the front and back of the printed circuit board inside an iPod Touch. Combinations of resistors, capacitors, diodes, integrated circuits are connected by electrical paths on the boards. The pins on the components are connected together by wire traces on the board.

2. **Measuring Electrical Circuits**

**Current**

Electrical current is the flow of electric charge via electrons, similar to water flowing through a pipe. The amount of water flowing through a pipe can be measured in gallons per minute. Electrical current is defined as the amount of charge that moves past a location in the wire per unit time (1 ampere [1A] = 1 coulomb per second [C/s]).
Voltage

Voltage (Electrical Potential) is a measure of the electrical force between two points which causes current to flow. Just as pressure causes water to flow through a pipe, a voltage difference causes electrons to flow through a wire. Voltage is always measured relative to a reference point in volts [V].

Figure 2 shows a digital voltmeter being used to measure the voltage difference (5.23 Volts) across a 1000 Ohm resistor. In this case, the voltage and current through the resistor are constant, therefore we call this a direct current (DC) circuit.

Resistance

Resistance is the opposition to the flow of current through a conductor. A resistor is one of the many examples of an electronic component that resists the flow of current. When a voltage $V$ (in Volts) is applied across a resistor, it causes the current $I$ (Amperes, A) to flow through the resistor, and we can calculate resistance $R$ using Ohm's Law: $V = I \cdot R$. The unit of resistance is the Ohm and is sometimes given the Greek letter symbol $\Omega$:

$$R = \frac{V}{I} \quad \{ \Omega \: or \: Ohms \}$$ (1)
Light Emitting Diode (LED)

An LED is a device that emits light when current flows through it. It can be used as a light source, or as an indicator. What makes it unique from other components is that current can only flow through it in the direction of the arrow. Therefore, an LED is a polarized component and must always be inserted into a circuit board with the correct orientation.

When you build a LED circuit in lab, you plug the LED into a circuit board with the positive wire connected to the positive side of the battery. Figure 3 shows two different types of LEDs. In this lab you will be using the LED on the left due to its durability. However, in future labs you will use the type of LED on the right. The longer wire denotes the positive lead and the shorter lead (negative) goes to ground. Figure 4 is an example of an LED in a schematic.

Electrical Circuit Schematics

A schematic is an engineering drawing of an electrical circuit. Each symbol on the schematic represents a component in the circuit. Figure 5 shows the symbols for various electrical components.

The lines in the schematic represent the wires or metal paths on the circuit board that connect the components together. Metals like copper and aluminum, which have very low resistance, are used for circuit connections because they are good conductors of electricity.
3. Electric Circuit Laws

**Ohm’s Law**

The voltage difference $V$ (Volts) across a resistor is equal to the product of the current $I$ (Amperes, A) and the resistance $R$ (Ohms, $\Omega$):

$$\text{Ohm's Law} \quad V = I \times R \quad (\text{Volts}) = (\text{Amps}) \times (\text{Ohms}) \quad (2)$$

**Power Law**

The power dissipated $P$ (Watts) in a component with resistance $R$ is equal to product of the voltage $V$ (Volts) across the component and the current $I$ (Amperes) flowing through it:

$$\text{Power Law} \quad P = I \times V \quad (\text{Watts}) = (\text{Amps}) \times (\text{Volts}) \quad (3a)$$

Using Ohm’s Law,

$$\text{Power Law} \quad P = I^2 \times R = \frac{V^2}{R} \quad (\text{Watts}) = (\text{Amps})^2 \times (\text{Ohms}) \quad (3b)$$

**Calculation of current, voltage and power**

Use the Ohm’s Law to solve sample problems:

Consider the resistor schematic (Figure 6) that has a resistor $R = 10\, k\Omega$ and a voltage input $V = 10$ volts.

**Calculate:** the current flowing through the resistor.

\[
I = \frac{V}{R} = \frac{10 \text{ Volts}}{10 \, k\Omega} = \frac{10 \text{ Volts}}{10,000 \, \Omega} = 0.001 \text{ Amp} = 1 \text{ mA}
\]

![Figure 6: Resistor schematic](image)
For the case of the same resistor, \( R = 10 \, \text{k}\Omega \) but with current of 0.5 mA flowing through,

**Calculate:** Voltage across the resistor

\[
V = I \times R = (0.5 \, \text{mA}) \times (10 \, \text{k}\Omega) = (0.0005 \, \text{A}) \times (10,000 \, \Omega)
\]
\[
V = 5 \, \text{Volts}
\]

Use Ohm’s Law and the Power Law to solve a sample problem. The circuit in Figure 7 has a battery voltage \( V = 15 \, \text{Volts} \) and a resistor \( R = 5 \, \text{Ohms} \).

**Calculate:** Current going through the resistor.

Using Ohm’s Law,

\[
I = \frac{V}{R} = \frac{15 \, \text{Volts}}{5 \, \text{Ohms}} = 3 \, \text{Amps}
\]

**Calculate:** Power dissipated in the resistor.

Using Power Law,

\[
P = V \times I = 15 \, \text{V} \times 3\, \text{A} = 45 \, \text{Watts}
\]

**Kirchhoff’s Voltage Law**

In the circuit of Figure 8, the battery creates an electrons flow through the wires and each resistor in a loop. Electrons carry negative charge and leave the negative terminal of the battery, returning to the positive terminal. However, conventional current is defined as the movement of positive charge, so we define the positive flow of current as the direction shown of the arrow for \( I \).

Since the same current \( I \) flows through each of the resistors, it creates the voltage differences across each resistor, shown by the three voltages \( V_1, V_2 \) and \( V_3 \). Therefore, the battery voltage \( V_{bat} \) is equal to the sum of the voltage difference:

\[
\text{Kirchhoff’s Voltage Law} \quad \quad V_{bat} = V_1 + V_2 + V_3 \quad (4)
\]
Kirchhoff’s Current Law

Since voltage is the same across every resistor connected in parallel, the sum of currents entering into a node is equal to the sum of currents leaving a node. A node in a circuit is the junction of 3 or more wires, usually presented as a dot similarly to Figure 9.

\[
\text{Kirchhoff’s Current Law} \quad I_0 = I_1 + I_2 \tag{5}
\]

![Kirchhoff’s current law sample circuit](image)

Equivalent Resistance

For calculation purposes, several resistors can be replaced by a single “equivalent” resistor \(R_{eq}\).

Resistors Connected in Series

Since the current is the same through all the resistors connected in series, then the equivalence resistance is the sum of all the resistors. Figure 10 is an example of how an equivalent resistance can be found for resistors in series.

\[
R_{eq} \text{ (Series)} = R_1 + R_2 + R_3 \tag{6a}
\]

![Equivalence of resistors in series](image)
Resistors Connected in Parallel

Since voltage is the same across every resistor connected in parallel, the total current is the sum of the currents flowing through the individual resistors. Figure 11 is an example of how an equivalent resistance can be found for resistors in parallel.

Equivalent Resistance (parallel)

\[
\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}
\]  

(6b)

Note that the equivalent resistance is \(1/R_{eq}\), so in order to find \(R_{eq}\), the inverse must be taken.

Calculation of current power dissipated and equivalent resistance

Let us consider an electric circuit schematic (shown in Figure 12) that has a battery voltage of \(V_{BAT} = 15\) Volts connected to resistors \(R_1 = 100\) ohms and \(R_2 = 200\) ohms in parallel.

**Calculate:** Current across resistor \(R_1\), power dissipated \(P_{R1}\) across resistor \(R_1\), and equivalent resistance \(R_{eq}\) of the circuit.
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**Calculate:** Current going through $R_1$

Keep in mind that in a parallel circuit the battery voltage across $R_1$ and $R_2$ is the same ($V_{BAT} = 15$ volts). Therefore, using Ohm’s Law for resistor $R_1$

$$I_1 = \frac{V}{R_1} = \frac{15}{100} = 0.15 \text{ Amp} = 150 \text{ mA}$$

**Calculate:** Power dissipated in $R_1$ using the Power Law

$$P_{R_1} = V \times I = 15 \times 0.15 = 2.25 \text{ Watts}$$

**Calculate:** $R_{eq}$ for the circuit. (Hint: Substitute $R_1$ and $R_2$ into Equation 6b)

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{100 \Omega} + \frac{1}{200 \Omega} = 0.015$$

$$R_{eq} = \frac{1}{0.015} = 66.7 \Omega$$

**Resistances in Parallel and Series Together**

When calculating equivalent resistance ($R_{eq}$) in a circuit, a step by step approach is best. First, you must identify each unique group in the circuit. Within each sub-group you should do the following:

1. For each resistor, identify whether the resistor is in series or parallel.
2. If in parallel, then calculate $R_{eq}$ using the parallel method. Otherwise calculate $R_{eq}$ using the series method.
3. Repeat until the sub-group is reduced to a single $R_{eq}$
4. Proceed to the next sub-group using steps until the total $R_{eq}$ is calculated.

See the example shown in Figure 13. A battery is connected to 3 resistors ($R_1$, $R_2$ and $R_3$). Resistors $R_2$ and $R_3$ are connected in series and $R_1$ is connected parallel to resistors $R_2$ and $R_3$. 
In order to solve the overall equivalence resistance, we need to simplify the circuit step by step. The first step will be to combine R₂ and R₃ to create Figure 14. In order to obtain R₂₃, we will use the equivalence resistance equation 6a for resistors R₂ and R₃ connected in series, or $R_{23} = R_2 + R_3$. Then we have R₁ and R₂₃ in parallel and we can use equation 6b to obtain the equivalent resistance $R_{eq}$ to simplify the circuit as shown in Figure 15. The following equation 6c shows the calculation of the total equivalent resistance of the series-parallel circuit,

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_{23}} = \frac{1}{R_1} + \frac{1}{R_2 + R_3}$$

(6c)
4. Equipment

Breadboard

Breadboards (figures 16 and 17) are used to quickly build and test prototype electronic circuits. Circuit components are inserted into the small contact holes on top of the board to make electrical connections to other components. Figure 17 below shows how groups of holes are connected together (by shiny metal strips running vertically and horizontally underneath the holes on the board), allowing circuit connections on the top side of the board to be made easily. At the top left, the first two plastic connectors are wired (left-to-right): 1. to Ground (Black connector), 2. to +5 Volts (Red connector). The next two red connectors will be used to connect Test Probes to the Digital Multimeter (DMM).

Digital Multimeter (DMM)

Digital Multimeters (Figure 18) are designed to measure electrical properties. They are most commonly used for measuring voltage, current, and resistance. Typically, the leads on the Multimeter are color-coded: red is for Positive polarity and black is Negative. There are several settings on the Multimeter that allow it to be versatile. In the Circuits Lab, we will only use the DC Volts setting and the Ohms setting. The DCV setting stands for direct current voltage, which will be used to measure the voltage difference between two points. The Ω (Ohm) setting will be used to measure electrical resistance.
Note: the DMM will not be used to measure CURRENT. Current will be calculated with Ohm's Law from measured voltage and resistance values.

![Digital Multimeter (DMM) with probes attached]

**Figure 18: Digital Multimeter (DMM) with probes attached**

5. **Further preparation assignment**

In order to finish your preparation for Circuits Lab, students are required to:

- Watch the video on how to use the DMM
- Take the Circuits Lab quiz on Carmen
- Complete the Pre-Lab Worksheet below
Lab 3: Circuits Lab - Pre-lab Assignment

Name ________________________________    Team ______   Seat No. _______

This is an individual assignment.

Solve the five problems below and hand it in at the beginning of the Circuits Lab.

Work must be shown or no credit will be given.

Problem 1. Ohm’s Law

For the circuit below, calculate the value of the resistor R which would cause the current of 2.5 mA to flow in the circuit. What voltage would you measure across the resistor? Show your calculations.

\[ R = \ldots \]
\[ V_{\text{res}} = \ldots \]

Problem 2. Kirchhoff’s Voltage Law

For the circuit below, calculate: (1) the equivalent resistance, (2) the current, I, flowing in the circuit, (3) the voltages \( V_1 \) and \( V_2 \), and (4) verify that \( V_1 + V_2 = V_{\text{bat}} \). Show all calculations. (Note: 1 kΩ = 10³ Ω). (5 points)

\[ R_{\text{eq}} = \ldots \]
\[ I = \ldots \]
\[ V_1 = \ldots \]
\[ V_2 = \ldots \]
\[ V_1 + V_2 = \ldots = V_{\text{bat}} \]
Problem 3. Power Law

For the circuit in Problem 2, calculate the power dissipated in each resistor, and the total power generated. Show all calculations. (3 points)

\[ P_1 = \quad P_2 = \quad P_{\text{Total}} = \]

Problem 4. Equivalent Resistance

Calculate the total equivalent resistance of the circuit below. Also, calculate the total current supplied by the battery, \( I_0 \). Show all calculations. (3 points)

\[ R_{\text{eq}} = \quad I_0 = \]

Problem 5. Kirchhoff’s Current Law

For the circuit in Problem 4, calculate the currents, \( I_1 \), \( I_2 \), and \( I_3 \). Does \( I_1 + I_2 + I_3 = I_0 \) (from Problem 4)? Show all calculations. (3 points)

\[ I_1 = \quad I_2 = \quad I_3 = \]

Does \( I_1 + I_2 + I_3 = \) \( I_0 \)?
Lab Procedure
Introduction and Background

The holiday season is coming up and The Lights Company is trying to improve their holiday lights. Having received customer complaints during the previous holiday season, the company needs to fix their current holiday light configuration. Majority of the customers reported that their problem with the Holiday lights was if one bulb went out, the rest of the chain died out. Engineers at Bright Lights have to figure out a way to prevent the problem that The Lights Company faces, and if not fixed the upcoming holiday season might result in a loss for The Lights Company.

Your boss has asked you and a team of electrical engineers to figure out a solution to this problem. The Lights Company does not have enough money to go and buy new parts, thus the engineers have to reuse as much of the resistors and LED’s available at the company. The electrical engineers believe that perhaps changing the type of circuit (series or parallel) might solve The Lights Company's problem while not costing too much.

Your team’s task is to determine which circuit type, series or parallel, would be best for The Lights Company, and then report back on solving The Lights Company’s dilemma.
Circuits Lab Setup

Circuit Components

- Banana Plug Wires (1 Black and 1 Red)
- DMM
- +5 Volt Power Module
- Breadboard
  (Pre-Wired)

Breadboard Connections

- +5 Volts Power
- Ground
- DMM Probe Wires
- +5 Volt Switch Box
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Task 1. Basic Setup

1.1 Plug the +5 Volt Modular Power Supply into the power bar on the lab table. Plug the other end (Bayonet connector) into the +5 Volt Switch Box at the top right corner of the Breadboard. Push the switch on the Switch Box to the left to turn +5 Volts Power on to the Breadboard. Notice which light indicates "Power On". Turn the Switch Box "Off".

1.2 Set up the breadboard as shown in Figure 19. Connect the DMM to the Breadboard using the Red and Black Banana Plug Wires exactly as shown. Insert the three Resistor Boards Marked 100 Ohms, 200 Ohms and 300 Ohms into the circuit board exactly as shown.

1.3 Turn the DMM to the Ohms (Ω) setting. Using the DMM Probe Wires, measure the actual resistance of each resistor and record the measured values in the Excel Worksheet.

Figure 19: Task 1 Setup.
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Task 2. Lab Measurement and Calculations using Ohm’s Law and Power Law
2.1 Using wires and the correct resistor, create a circuit according to the schematic (Figure 20).
2.2 Toggle power on.
2.3 Turn DMM dial to the DCV setting.
2.4 Measure and record the power supply voltage ($V_T$) in the Excel Worksheet.
2.5 Measure and record the voltage across $R$ and verify that the two voltages are equal.
2.6 If you have time, calculate the power and current in Task 2 on the lab worksheet. Otherwise these can be calculated after lab. Use Ohm’s law and the Power law for the calculations.

Figure 20: Circuit Diagram for Task 2
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Task 3. Measure the Equivalent Resistance and Voltages of a Simple Series Circuit

3.1 Toggle power off.

3.2 Create a circuit according to the schematic (Figure 21). Note: Lining up the resistors is critical.

3.3 **While the power is still off,** measure and record the equivalent resistance of the circuit.

3.4 Toggle power on.

** *****CURRENT SHOULD NEVER BE MEASURED USING THE DMM *****

3.5 Measure and record $V_1$, $V_2$ and $V_{\text{Total}}$
Check to see if $V_1+V_2=V_{\text{Total}}$

3.6 If you have time, use the measured voltages (Task 3) and resistances (Task 1) to calculate all remaining values on the worksheet. Otherwise complete these after lab.

Task 4. Measure the Equivalent Resistance and Voltages of a Simple Parallel Circuit

4.1 Toggle power off.

4.2 Connect the **nominally-valued** 200 Ohm and the 300 Ohm resistors on the breadboard as shown in Figure 22.

4.3 **While the power is still off,** measure and record the equivalent resistance of the circuit.

4.4 Calculate and record $R_{eq}$ to check value from 4.3. **Use the measured values of $R_2$ and $R_3$ from Task 1.**

4.5 Ask instructional staff to check your setup.

4.6 Toggle power on.

4.7 Use DMM to measure and record voltage across the resistors.

4.8 If you have time calculate all the values in the worksheet. Otherwise complete these after lab.
Task 5. Series-Parallel Circuit

5.1 Toggle power off.

5.2 Connect the nominally-valued 100, 200 and 300 Ohm resistors on the Breadboard as shown in the schematic drawing (Figure 23).

5.3 Measure and record $R_{eq}$ for the total resistance with the DMM.

5.4 Calculate $R_{eq}$ using the measured values of $R_1$, $R_2$ and $R_3$ from Task 1.

5.5 Toggle power on.

5.6 Use the DMM to measure $V_1$, $V_3$ and $V_T$.

5.7 If you have time during lab complete the following calculations, otherwise complete after lab:

- Calculate current $I_1$. Use Ohm's law and the measured value of $R_1$ and $V_1$ from previous tasks for your calculation.
- Calculate currents $I_2$ and $I_3$ by using Ohm's Law for the two parallel paths. Show your work on the worksheet. (Hint: calculate $I_3$ using Ohms law and then $I_2=I_1-I_3$.)
- Use Power law to calculate $P_2$ and $P_3$. Show appropriate calculations.

Task 6. LED Circuit

6.1 Toggle power off.

6.2 Connect the nominally-valued 200 Ohm resistor and the LED in series to make the circuit shown in Figure 24. Determine the correct orientation of the LED using the positive and negative leads.

6.3 Toggle power on.

6.4 Measure and record the voltages $V_R$ and $V_{LED}$.
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6.5 Toggle power off.

6.6 Remove and re-insert the resistor in opposite orientation. Now toggle power on and note the values of \( V_R \) and \( V_{LED} \)

6.7 Does the LED glow when the power is on?

6.8 Toggle power off; Remove and reinsert the LED in opposite orientation. Now toggle power on and note the values of \( V_R \) and \( V_{LED} \)

6.9 Does the LED glow?

6.10 If you have time during lab complete the following calculations, otherwise complete after lab:

- Calculate the current through the resistor (using the measured value of \( R_2 \) from Task 1), \( I_R \) and through the LED, \( I_{LED} \) (Hint: How are the current through the LED and resistor related?)
- Calculate the power dissipated in the LED, \( P_{LED} \).

6.11 Use this activity and the values of \( V_R \) and \( V_{LED} \) to answer the Lab Specific Directions in the Report Guidelines.
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Task 7. Clean-Up Procedure
Place all materials back in their respective containers.

Caution: **DO NOT** Remove the +5Volt Power and Ground wires from the Breadboard

**DO NOT** Remove the DMM Probe Wires from the Breadboard

**DO NOT** Remove the Small Gold Wires from the Breadboard

At the end of the lab, your Breadboard should look exactly like this:

![Breadboard Image]

Task 8. Check-Out Policy
After you have finished the lab and the clean-up procedure, have your instructor or GTA sign the “End-of-Lab Signoff” line at the end of the rubric. You will lose 5 points if this is not signed by your Instructor/TA.
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General Guidelines

Write an Executive Summary
For details on content and formatting, see the Technical Communications Guide on Executive Summary specifications.

Lab Specific Directions
- In addition to requirements listed in the Technical Communications Guide, be sure to briefly address the following questions. Answer within your summary, not with numbers or bullets.
  - For the circuit shown in Figure 25 below, explain how the equivalent resistance, $R_{eq}$, can be calculated, in a step by step approach. No equations need to be provided for this part. Simply include the thought process involved in the simplification steps for calculating $R_{eq}$.

![Figure 25: Parallel and Series Resistor Circuit](image)

- Justify why the LED glowed in just one case and not the other in Task 6. Use the recorded values of $V_R$ and $V_{LED}$ in the two steps of task 6 to support your justification.
- Which circuit configuration would be better for The Lights Company (series or parallel) as discussed in the Introduction? Explain your choice and why the other circuit configuration would not solve the company’s problem. (Questions for thought: If there were more LEDs what would happen if one went out in series, in parallel? Are there any situations that could lead to fire hazards from too large of a current?)
- Include all the calculations from tasks 5.7 and 6.10.
- Lastly, attach in the appendix the lab worksheet and sample calculations.