Circuit Analysis Laboratory Workbook

Synthesis Lectures on Electrical Engineering

Editor
Richard C. Dorf, ***University of California, Davis***

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Teri L. Piatt and Kyle E. Laferty
2017

Understanding Circuits: Learning Problem Solving Using Circuit Analysis
Khalid Sayood
2006

Learning Programming Using MATLAB
Khalid Sayood
2006

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SYNTHESIS LECTURES ON ELECTRICAL ENGINEERING #4

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ABSTRACT

This workbook integrates theory with the concept of engineering design and teaches troubleshooting and analytical problem-solving skills. It is intended to either accompany or follow a first circuits course, and it assumes no previous experience with breadboarding or other lab equipment. This workbook uses only those components that are traditionally covered in a first circuits course (e.g., voltage sources, resistors, potentiometers, capacitors, and op amps) and gives students clear design goals, requirements, and constraints. Because we are using only components students have already learned how to analyze, they are able to tackle the design exercises, first working through the theory and math, then drawing and simulating their designs, and finally building and testing their designs on a breadboard.

KEYWORDS

circuits, circuit design, analog circuit lab, electronics, electronic circuits, electrical engineering, circuits labs, operational amplifiers (op amps), analog circuits, circuit analysis lab, circuit analysis

Contents

Preface

Philosophy This workbook integrates the theory covered in a first circuits course with the concept of engineering design and teaches troubleshooting and analytical problem-solving skills. Traditionally, circuits labs give step-by-step instructions for building a circuit and taking measurements from a given schematic to demonstrate physically the theory learned in class, point out differences between measured values and theoretical calculations, and teach measurement techniques.

In contrast, this workbook asks students to use the theory they are learning in class to design circuits that are simple and functional. In doing so, they learn design techniques, develop their analytical problem-solving skills, and gain a better understanding of theoretical principles. So, instead of demonstrating theory, these labs ask students to apply theoretical principles to a design problem.

Approach This workbook uses only those components that are traditionally covered in a first circuits course and gives students clear design goals, requirements, and constraints. It begins with very simple design exercises and progresses to fairly complex circuits, all while using only basic components, such as resistors, potentiometers, capacitors, and operational amplifiers. Because we are using only components students have already learned how to analyze, they are able to complete the design exercises, first working through the theory and math, then drawing and simulating their designs, and finally building and testing their designs in the lab.

Since they are not merely wiring a given circuit, they must understand the theoretical concepts in order to complete their designs. The process of troubleshooting their circuits then teaches them both analytical problem-solving skills and the difference between theory (circuit works on paper) and real life (wired circuit is not accurate).

Audience This workbook is meant to accompany a first course in linear, analog circuit analysis that covers topics such as Kirchhoff's laws, Ohm's law, node analysis, equivalent circuits (e.g., Thevenin), superposition, first- and second-order circuits, and AC steady-state analysis. Components covered include resistors, capacitors, inductors, operational amplifiers, and voltage sources (DC and AC).

Background We are assuming students have no previous experience using breadboards, multimeters, or other lab equipment.

Student Workload We are assuming that students will spend 1-2 hours on each pre-lab and will have the pre-lab completed before their scheduled lab period. If students are prepared, the in-lab portions and post-lab questions can be completed in a 2-hour lab period.

TA Workload We have found it helpful for the TAs to spend 10-15 minutes at the beginning of the lab period giving a short lecture or demonstration to the class. This should include a demonstration on how to use a new piece of equipment, safety reminders, reviews of measurement techniques (e.g., measuring voltage versus measuring current), and a list of troubleshooting ideas (we have provided some in Appendix C).

Some of the in-lab exercises begin with a statement like,"Your TA will demonstrate how to use the function generator." This is another way we have deviated from a traditional circuits lab: we do not have pictures of equipment with detailed wiring diagrams. Students watch their TA give a demonstration, see the diagrams the TA draws on the board, and then they are ready to tackle that week's circuit build.

In addition, the TAs are also expected to supervise students' work throughout the lab period, and each lab has at least one "TA Verification" space for the TA to sign off on students' work.

Organization Since these lab exercises are constrained to use only those components students have already learned how to analyze in class, this workbook follows the traditional outline of most circuits textbooks. This means that the first six labs use only voltage supplies and resistive elements (e.g., resistors, potentiometers, and thermistors). We use these early labs to introduce the basics, such as using a breadboard and digital multimeter, identifying resistor values, and wiring resistors in parallel and series. These early labs also introduce the idea of design work, setting out problems that get gradually more difficult and include design requirements and constraints.

The schedule in more detail is as follows.

- Lab 1 has no pre-lab and is meant to be completed the first week of the term.
- Lab 2 is dedicated to students learning the basics of drawing and simulating a circuit using Multisim. This lab is easily skipped, if there is not time or if Multisim skills are not a part of your curriculum. If included, Appendix B gives instructions for basic Multisim work. Also, we usually allow two weeks for this lab, as the pre-lab is time-consumming for those students not already familiar with Multisim.
- Labs 3, 4, and 5 use only resistors, potentiometers, DC voltage supplies, and multimeters. These labs also introduce the concept of design goals and constraints.

- Lab 6 introduces the idea of a resistive sensor (in this case, a thermistor) used in a Wheatstone bridge.
- Lab 7 introduces the use of ICs and operational amplifiers, as many circuit classes do not begin discussing op amps until five or six weeks into the term. All of the remaining labs use op amps in a series of design challenges.
- Lab 8 brings back the Wheatstone bridge from Lab 6, with the new challenge of adding an amplifier and indicator light to improve the circuit's functionality.
- Labs 9 and 10 challenge students to design and build an analog calculator.
- Labs 11 and 12 introduce AC inputs, function generators, and oscilloscopes and ask students to integrate phase shift into their designs (Lab 11) and to design two simple, first-order filters (Lab 12).

Required Lab Equipment Our labs rely on standard circuits lab equipment. Each lab station should have:

- a breadboard,
- a power supply,
- a digital multimeter (for measuring voltage and current),
- a function generator (for producing a sinusoidal and triangle-wave supply voltages), and
- an oscilloscope.

Each lab station should have access to:

- standard $\frac{1}{4}$ W or $\frac{1}{2}$ W resistors, with values from 100 Ω - 1 MΩ,
- at least five 10 kΩ potentiometers,
- operational amplifiers (LM741),
- red and/or green LEDs ,
- capacitors: 10 μF, 0.33 μF, 0.03 μF, 0.02 μF, 0.0075 μF, 0.002 μF,
- two audio jacks (we use Kycon STX-3120 3.5 mm PCB mount),
- ear buds or headphones (students can bring their own), and
- one NTC thermistor (10 kΩ at 25°C; we use Dale/Vishay 01C1002KP, whose data sheet is provided in Appendix F).

In addition, the TAs should have access to a heat gun and a lamp (incandescent bulb). These are used to heat up the thermistors, and alternative means, such as a hair dryer, blowing on the thermistors, or holding them between two fingers, would also be fine.

Teri L. Piatt and Kyle E. Laferty
June 2017

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June 2017

LAB 1

This is my Breadboard

Purpose: In this lab, you will learn to use basic electronic lab equipment, including a breadboard, a power supply, and a digital multimeter.

In the lab: The main equipment used in this lab will be breadboards, power supplies, multimeters, and resistors. *Breadboards* are a prototyping tool used to hold and connect circuit components without solder (see Figure 1.1). Figure 1.2 shows graphically how the breadboard's internal connections are laid out. The top two and bottom two rows of the breadboard shown in Figures 1.1 and 1.2 are connected along the length of the breadboard and are referred to as power rails. Power rails are a way to provide the same supply voltage to multiple, different parts of a circuit and are often labeled with a "+" and "–" symbol at the end of each row. We will be using the power rails for more complex circuits later in the semester.

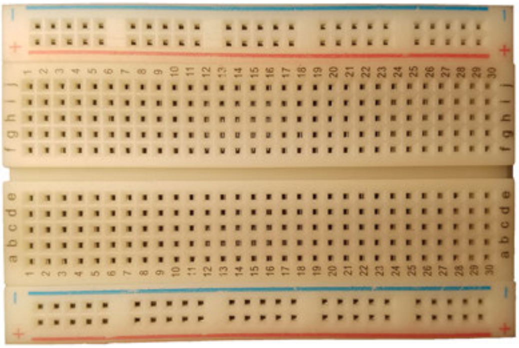

Figure 1.1: A small breadboard [1].

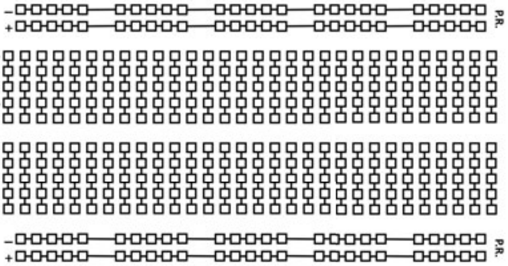

Figure 1.2: A breadboard's internals.

The main part of the breadboard is the middle area, which has rows labeled a–j in Figures 1.1 and 1.2. Both the bottom and top set of five holes in a column are seperately interconnected, and none of the horizontal holes in a row are connected to each other. So, for example, if you place one lead of a component in row "b" and the other lead in row "e" of the same column, then you have effectively wired those two leads to each other, shorting that component. Generally, it is a good idea to build your circuit with the components situated parallel to the power rails.

There are two main types of power sources used in the lab, DC and AC. DC stands for direct current and provides a steady voltage at one value. AC stands for alternating current. The most common type of AC is a sinusoidal signal, but square waves and triangle waves are other examples of AC. Because AC signals can take many forms, the source is often referred to as a function generator. Some schematic symbols for voltage sources are shown in Figure 1.3. Figure 1.4 shows three symbols for another important breadboard connection, *ground*, which is a reference node necessary for a circuit to work properly and where the voltage is always zero.

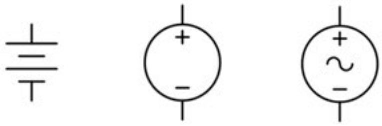

Figure 1.3: Different symbols for voltage sources. The left two are both DC source schematic symbols. The right symbol is an AC source schematic symbol.

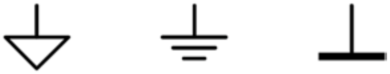

Figure 1.4: Different symbols for ground.

Resistors are the most basic circuit component, and their schematic symbol is shown in Figure 1.5. They *resist* current, and without them a lot of circuits would not work. Different resistors have different resistance values, measured in Ohms (Ω). Engineers use a color code to quickly decipher the value of a resistor (see Table 1.1). A resistor has four color bands encircling it. The first two bands indicate the value of the resistor, and the third color band indicates its order of magnitude. So, if a resistor has color bands of violet, yellow, and red, the resistance value is $74 * 10^2$. This value would be written as 7.4 kΩ. (It is not proper to leave the 10^2 in the answer). The fourth color band indicates the resistor's tolerance. The most common tolerance bands are gold and silver; gold indicates a ±5% tolerance and silver indicates a ±10% tolerance.

Figure 1.5: Resistor schematic symbol.

Table 1.1: Resistor color code

Resistor Color Code									
Black	Brown	Red	Orange	Yellow	Green	Blue	Violet	Grey	White
0	1	2	3	4	5	6	7	8	9

Given the following color bands, find the resistance value:

- Red, Red, Red: ________________
- Brown, Black, Brown: ________________
- Blue, Orange, Green: ________________
- Green, Brown, Orange: ________________
- Brown, Green, Violet: ________________
- White, Brown, Green: ________________
- Gray, Red, Black: ________________
- Yellow, Violet, Red: ________________
- Red, Yellow, Black: ________________

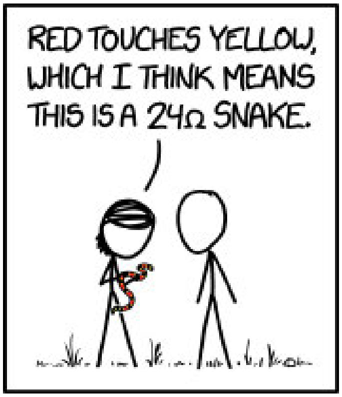

Figure 1.6: Comic relief [2].

Build the circuit shown in Figure 1.7 on your breadboard.

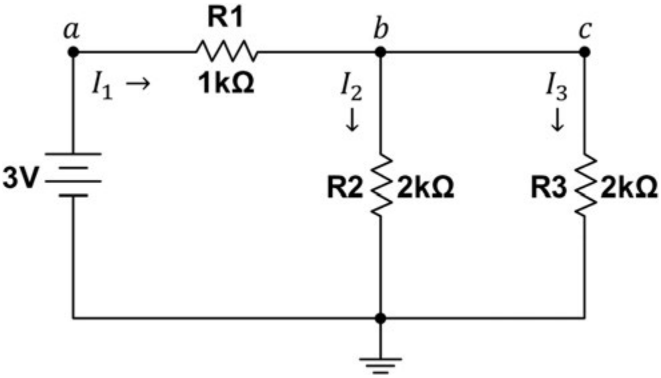

Figure 1.7: Lab 1 circuit.

Use the digital multimeter to measure voltage and current. To measure voltage, set the dial of the multimeter to measure DC voltage. Then put the multimeter's red lead on one terminal of the resistor (or component) and the multimeter's black lead on the other terminal of the resistor (or component). For example, if you want to measure the voltage across R_1, place the red lead at point a and the black lead at point b. This is V_{ab}, and the value displayed will be in volts. Now place the red lead at b and the black lead at a. This is V_{ba}.

To measure current, set the dial of the multimeter to measure mA. Break the circuit at the desired spot, and connect the leads of the multimeter across the open. That is, complete the circuit with the multimeter. The value displayed will be in mA. **NOTE: measuring current has to be done in a very specific way. If you try to measure current the way you measure voltage, you will blow a fuse in the multimeter, and YOU will be responsible for replacing it!** For more instructions on measuring voltage and current, please refer to Appendix A.

Fill in Table 1.2 with your measured values, and demonstrate at least one of your measurements to your TA.

Table 1.2: Data for circuit in Figure 1.7

I_1 (mA)	I_2 (mA)	I_3 (mA)	V_a (V)	V_b (V)	V_c (V)	V_{ab} (V)	V_{bc} (V)	V_{ba} (V)

TA Verification: ________________

Post-lab questions: Answer the questions listed below on a separate piece of paper. Make sure that your handwriting is legible! When you are finished, staple everything together, and turn in this completed lab packet to your TA.

1. Use each resistor's tolerance to calculate the range of potential values for R_1, R_2, and R_3. For example if a resistor is 5.1 kΩ ±10%, then that resistance could potentially be anything from 4590–5610 Ω. Find this range for each resistor in the circuit.
2. Use your current and voltage measurements to calculate the resistance of each resistor (use Ohm's Law).
3. Do these calculated values match each resistor's labeled resistance? If not, do your calculated values fall within the resistor's tolerance range?

LAB 2

Introduction to Multisim

Purpose: In this lab, you will learn how to draw and simulate basic circuits in Multisim.

Pre-lab: Multisim is a powerful circuit design and simulation program. It can help you test and refine your circuit design before you build a prototype. It can also help you understand what's happening in a circuit by allowing you to simulate the circuit and measure voltages, currents, and other values at any point. This reduces or eliminates the need for you to repeatedly solve a complex circuit by hand every time you make a change.

Using the information provided in Appendix B complete the following three drawings, measurements, and calculations.

1. For the circuit shown in Figure 2.1 below, calculate the current, I, in the loop and V_{ab}.

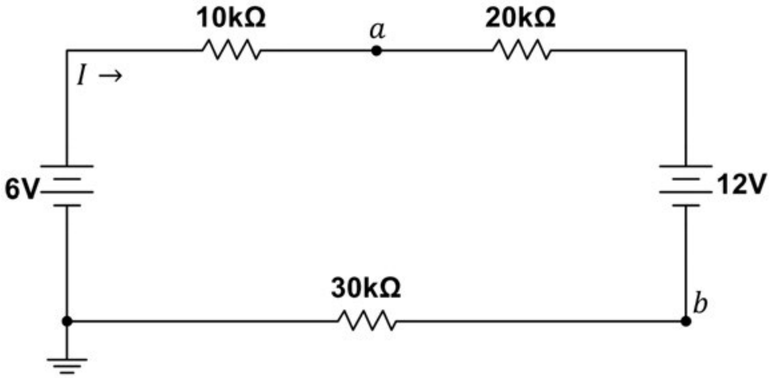

Figure 2.1: Lab 2 pre-lab circuit 1.

Enter your answers here, and show your calculations in the work area:

Calculated I = ________________ Calculated V_{ab} = ________________

Work area:

Use Multisim to draw the schematic shown in Figure 2.1. Simulate your circuit and use a current probe to measure the current in the loop and use the differential voltage probe to measure V_{ab}. Enter those measured values here, and print out your drawing to turn in with this lab.

Multisim I = ________________ Multisim V_{ab} = ________________

2. Use Multisim to draw the schematic shown in Figure 2.2. When you simulate the circuit, -12 V should appear on the voltmeter. Print out your drawing to turn in with this lab.

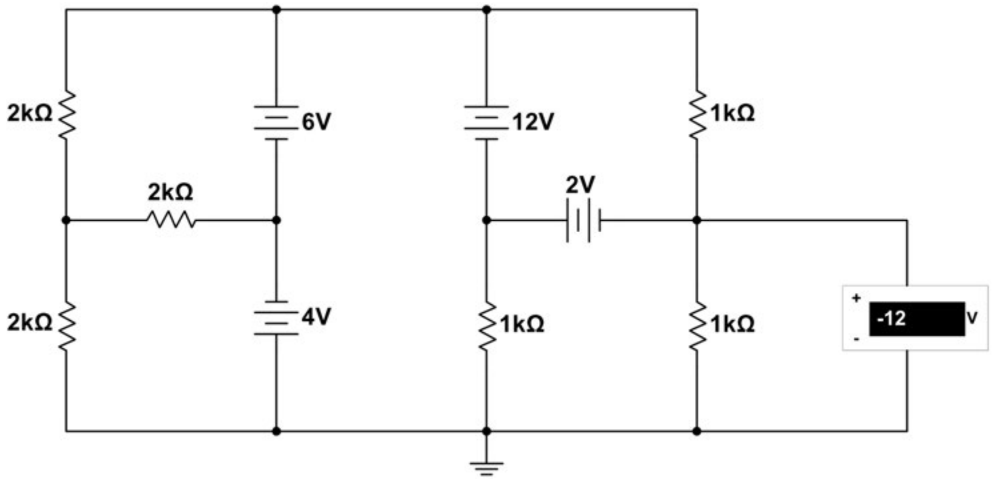

Figure 2.2: Lab 2 pre-lab circuit 2.

3. Use Multisim to draw the circuit shown in Figure 2.3. Then label Figure 2.3 with the direction of each branch current and the polarity for each resistor (you do not need to add these labels to your Multisim drawing). Simulate your circuit, and, using voltage and current probes, fill in the values for each component's voltage and current in Table 2.1.

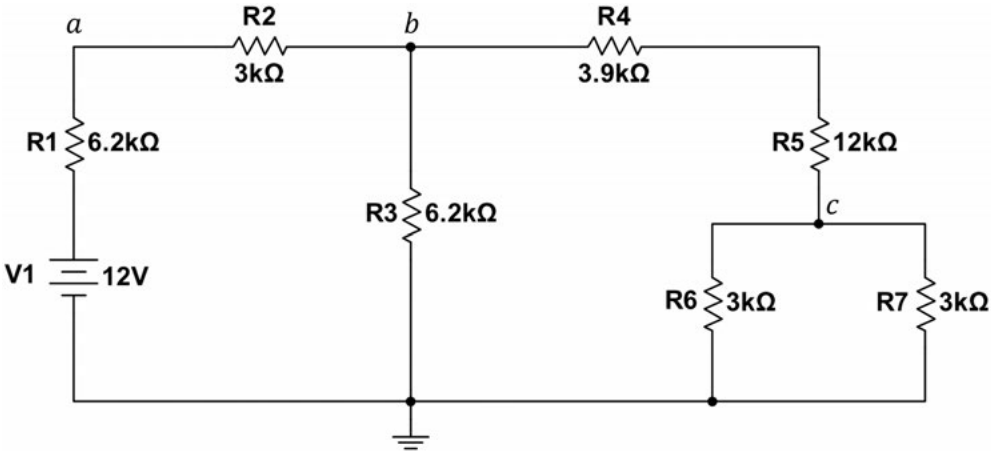

Figure 2.3: Lab 2 pre-lab circuit 3.

Table 2.1: Circuit 3 Multisim measured and calculated values

Component	Voltage (V) (Measured)	Current (mA) (Measured)	Power (mW) (Calculated)	Power (mW) (Measured)
R_1 =				
R_2 =				
R_3 =				
R_4 =				
R_5 =				
R_6 =				
R_7 =				
V_1 =				
		Total Power:		

Once that is complete, use these values to calculate the power *dissipated* by each component. (Pay attention to the direction of the current and remember the passive sign convention.)

Now add power probes to your Multisim drawing and simulate. Enter these measured power values in Table 2.1. Do the power values shown on the probes match those you calculated using the voltages and currents? According to the power law, the power dissipated = the power supplied in a circuit. Sum the values in the power columns. Does the power law hold true for the power values you calculated and measured?

In the lab: Build circuit 3 (shown in Figure 2.3) on your breadboard. Use the multimeter to measure the voltage across and the current through each component, and enter these measurements in Table 2.2. Use the voltages and currents you measured to calculated the power dissipated by each component, and enter these values in the table, as well. Add the values in the power column.

If you are having problems getting your circuit to work, see Appendix C for some ideas on how to troubleshoot your circuit. Demonstrate your working circuit to your TA.

TA Verification: ________________

Table 2.2: Circuit 3 breadboard measured and calculated values

Component	Voltage (V) (Measured)	Current (mA) (Measured)	Power (mW) (Calculated)
R_1 =			
R_2 =			
R_3 =			
R_4 =			
R_5 =			
R_6 =			
R_7 =			
V_1 =			
		Total Power:	

Post-lab questions: Answer the questions listed below on a separate sheet of paper. Make sure that your handwriting is legible! When you are finished, staple everything together and turn in this completed lab packet to your TA.

1. Why didn't your power values add up to zero?
2. How close were your in-lab measured values (Table 2.2) to your Multisim measured values (Table 2.1)?
3. For the circuit that you built (circuit 3), use your measured data to verify Kirchhoff's current law at nodes a, b, and c. Show your work!

LAB 3

The Resistor Challenge

Purpose: In this lab, you will combine resistors in parallel and series and practice constructing equivalent circuits.

Pre-lab: A complicated network of resistors can be combined into a single equivalent resistance in order to simplify circuit calculations. For resistors that are wired in series, as shown in Figure 3.1, an equivalent resistance can be found as follows:

$$R_{eq} = R_1 + R_2 + R_3. \tag{3.1}$$

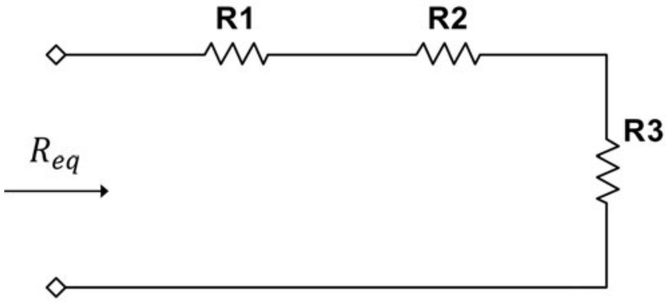

Figure 3.1: Three resistors connected in series.

For resistors that are wired in parallel, as shown in Figure 3.2, an equivalent resistance can be calculated like this:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}. \tag{3.2}$$

Notice that when resistors are combined in series, the equivalent resistance is larger than the individual resistances, and, when resistors are combined in parallel, the equivalent resistance is smaller than the individual resistances. With this in mind, complete the following three design challenges.

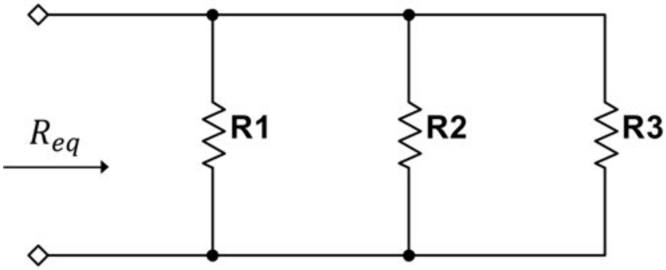

Figure 3.2: Three resistors connected in parallel.

1. Design a circuit with an equivalent resistance of 9 Ω using all three of the following resistor values: 4 Ω, 6 Ω, and 12 Ω. Draw your circuit in the work area.

   Work area:

2. Design a circuit with an equivalent resistance of 8 Ω using all four of the following resistor values: 2 Ω, 3 Ω, 4 Ω, and 12 Ω. Draw your circuit in the work area.