Introduction to the Electronics Learning Lab Kit Workbook

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This workbook is intended to supplement the paper *Electrify the linear systems problem for our students*. Interested readers can download a pdf copy of this article by visiting the URL below:

http://www.appliedlinearalgebra.com/blog/for-teachers/linear-algebra-laboratory-exercises/electrify-linear-systems

In order to limit the length of this published work, the author makes some assumptions about the reader's familiarity with foundational concepts in electrical engineering and circuit analysis. These foundations are important and deserve special treatment. This workbook provides a crash course in all necessary pre-requisite material for readers who want to use our lab equipment to verify the theory with physical measurements.

Introduction to circuit analysis

This learning activity focuses on an introduction to circuit analysis using the parlance of linear algebra. Students majoring in electrical engineering usually take a selection of courses in circuit analysis at most universities. The study of circuit analysis is a great example of mathematical modeling in practice. By using mathematical models of real electric circuits, an engineer can quickly iterate on her design and devise improvements before needing to physically prototype her work. This ability to iterate using mathematics saves time and money during the design phase of an electronics project.

With this paradigm in mind, our work in circuit analysis focuses on two types of electrical devices: real and ideal. *Real circuit elements* exist in space and time. These real devices are the actual, physical components and interconnections sometimes referred to as the hardware of an electric circuit. Moreover, the electrical behavior of the real circuit devices can be measured using a digital multimeter.

In contrast, *ideal circuit elements* are mathematical models of specialized real circuit devices. These ideal elements, sometimes called *branches*, do not physically exist as tangible objects. Rather, ideal circuit elements exist in our minds as mathematical tools to model the characterisitcs of real circuits. Unlike real circuit elements, the electrical behavior of ideal devices cannot be physically measured using instrumentation. Instead, such behavior is calculated via mathematical algorithms and arithmetic computation.

The major goal of circuit analysis is to use mathematics guided by well-constructed models containing only ideal elements to closely approximate the measured electrical behavior of real components in a physical circuit. In short, we want to replace measurements with algorithms without sacrificing accuracy while analyzing the inner workings of an electric circuit.

In this document, we study all components found in the electronic laboratory learning kit. We also conduct a number of experiments to study the principles of electronics that form the pre-requisite knowledge necessary to fully understand the Linear-Algebraic Nodal Analysis algorithm the we present in our paper (CITE). Finally, we build, measure, and study a large collection of physical electric circuits that contain only resistors, dc voltage sources, and dc current sources.

By building and analyzing the circuits provided in this workbook, we become well-equipped to apply linear algebra to nodal analysis problems in electrical engineering. In doing so, we develop a basic understanding of how to build and measure physical circuits. Of course, our goal is to confirm for ourselves that this stuff works: the math we do accurately models the electrical behavior of the physical circuits we build.

The Electronic Laboratory Kit

In the paper *Electrify the linear-systems problem for our students*, we restrict ourselves to building real circuits containing only three types of real devices including: resistors, direct current (dc) voltage sources, and dc current sources. As part of our service to instructors, we have composed an electronic laboratory learning kit, shown in Figure 1. This laboratory kit includes all the components needed to build the type of circuits that we analyze using the Linear-Algebraic Nodal Analysis algorithm.

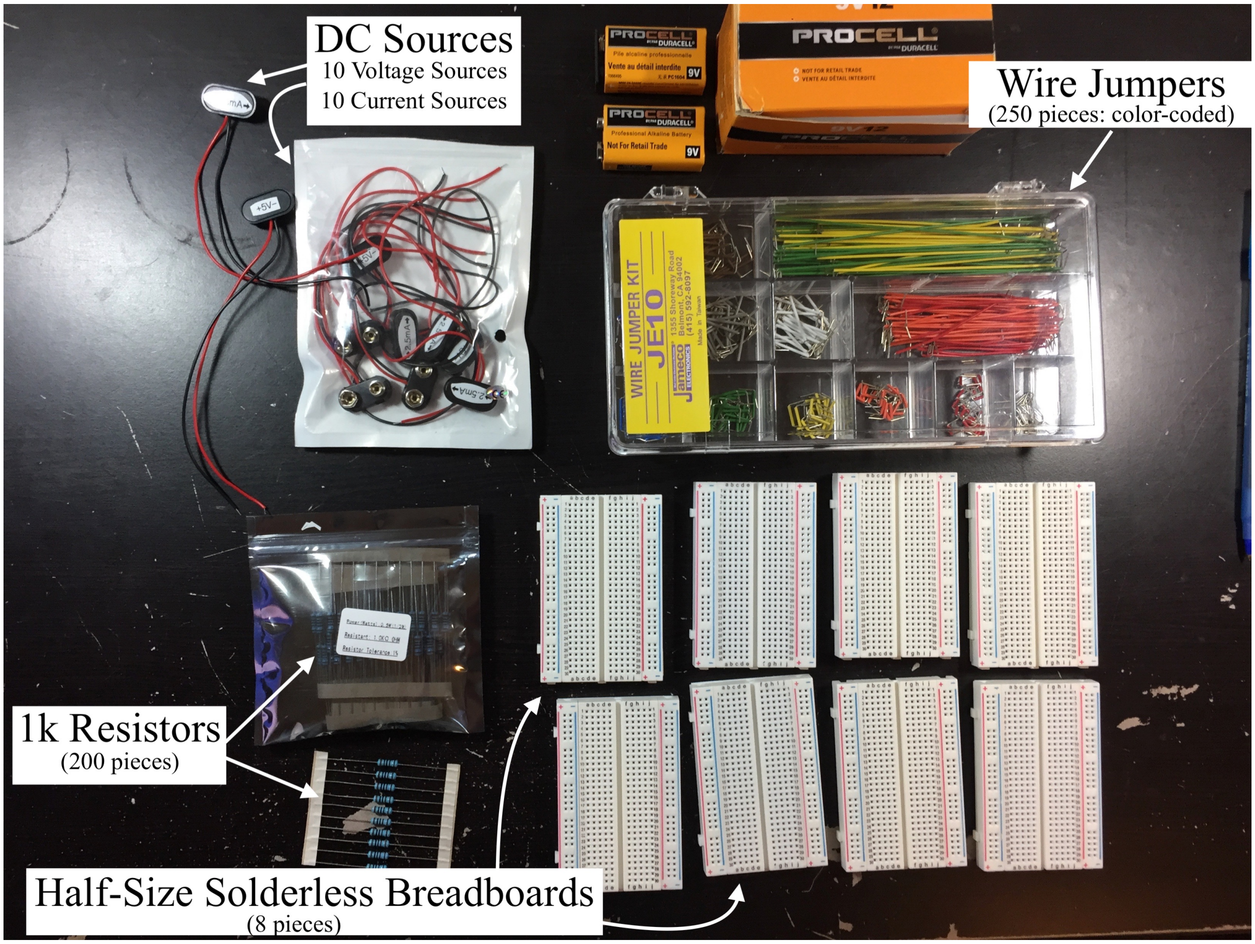

Figure 1: Electronic Learning Kit Parts

Inventory of Parts

The Electronics Learning Lab Kit includes all of the following parts:

- Half-size 2.2"x 3.4"solderless bread board (x8)
- 1k (brn-brn-blk-blk-brn) precision resistors (x200)
- 2.5mA dc current source (x12)
- 5V dc current source (x12)
- 9V batteries (x24)
- 350-Piece Jumper Wire Kit (in 10 colors)

The Solderless Breadboard

When we prototype real circuits, one of the easiest ways to make electrical connections between various electrical components is to use a solderless breadboard. A solderless breadboard provides a small, flexible workspace to connect the leads of our electric components together. In this activity, we use *half-size breadboards* which measure 2.2"x 3.4", as seen in Figures 2A and 2B. Define long edge and short edge.

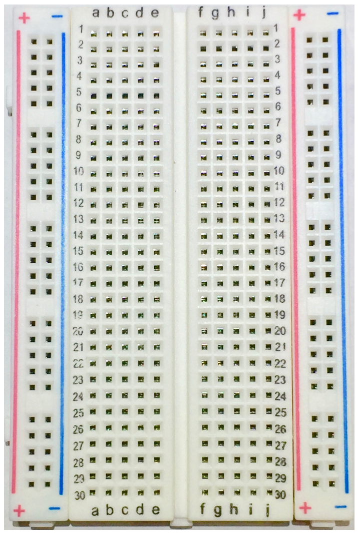

Figure 2A: Photo of real half-size breadboard (front view)

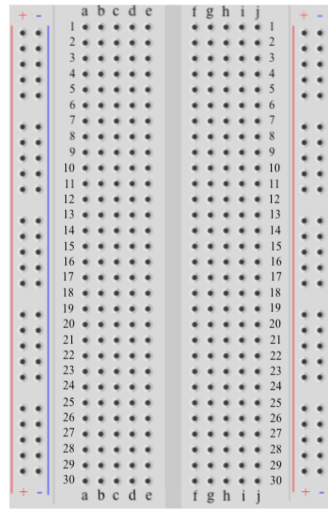

Figure 2B: Computer-generated graphic of half-size breadboard (front view)

Anatomy of the Solderless Breadboard

Half-size breadboards have 400 *connection points*, also known as contact points or tie points, organized into three sections. If we position our breadboard vertically and view the front face, we see a design containing a left power rail, a main section of the breadboard, and a right power rail, as shown in Figure 3A.

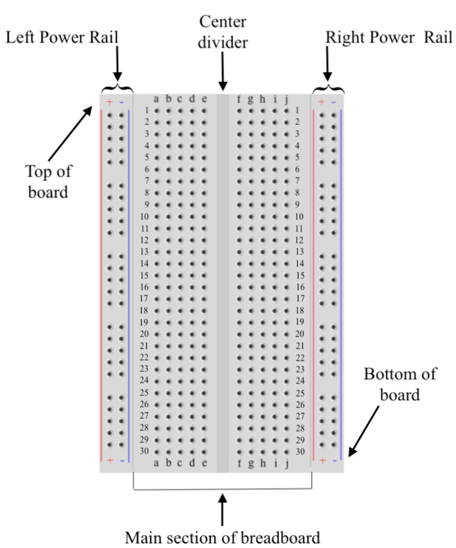

Figure 3A: Three sections of the breadboard as seen from the front to facilitate easy use when prototyping circuits

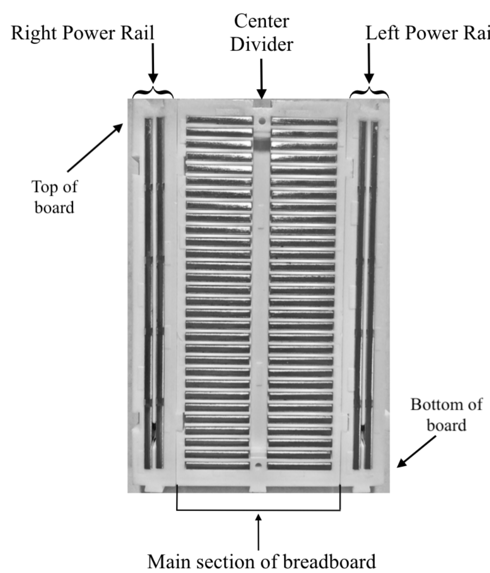

Figure 3B: Three sections of the breadboard as seen from the back to highlight electrical connections within the board

The *main section* of our half-sized breadboard, also known as the terminal strip, has 300 connection points organized into 10 columns and 30 rows. Each individual column is labeled with a unique lowercase English letter and contains 30 individual contact points. The first column is labeled with the letter a, the second column marked with the letter b, and so on until we reach the the tenth which is labeled as column j. The *center divider* runs down the center of the board in between columns e and f. This divider, also called the center line, indicates how the individual contact points are electrically connected.

The rows of our breadboard are tagged with positive integers, starting with row 1 and continuing through row 30. Each row contains 10 individual tie points. We can use this column and row address system to uniquely identify each of the 300 contact points in the main section of our breadboard, as discussed below.

Let's orient the breadboard so that we can read the lower case letters right-side up and refer to this as the vertical orientation of our breadboard. When the board is in this vertical orientation, we define a left- and right-hand side of the board. When the board is positioned as such, there is a power rail to the left of column a and a power rail to the right of column j. We say that the *left power rail* is adjacent to the set of 30 contact points in column a. On the other hand, the *right power rail* is adjacent to column j. The power rails, also known as the bus strips, are designed to provide power to the electrical components inserted into the breadboard.

To understand the electrical connections within each breadboard, let's investigate how these boards are made. We begin by flipping the board over to look at back face the breadboard. On a low-cost breadboards, such as the ones we use in this activity, there is a thin, double-sided adhesive backing intended to fix the board to a solid surface. If we remove this thin piece of tape, we behold the inner workings of the breadboard, as seen in Figure 3B.

We note that the individual sections of the breadboard are made from numerous smaller pieces that are assembled together. Each power rail contains three individual pieces. This includes a long thin plastic housing unit along with two separate metal strips that fit snugly into a groves on the back of the plastic casing. Similarly, the main section of the breadboard is composed of the plastic housing and sixty separate pieces of metal.

The different sections of the board can be detached and reattached using small plastic tabs and slots, as displayed in Figures 4A and 4B. Said features are usually located on the long sides of the breadboard though they may be along the short sides as well. These slots and tabs are designed to interlock numerous breadboards together and to allow us to customize our workspace by using any combination of the three sections that we desire.

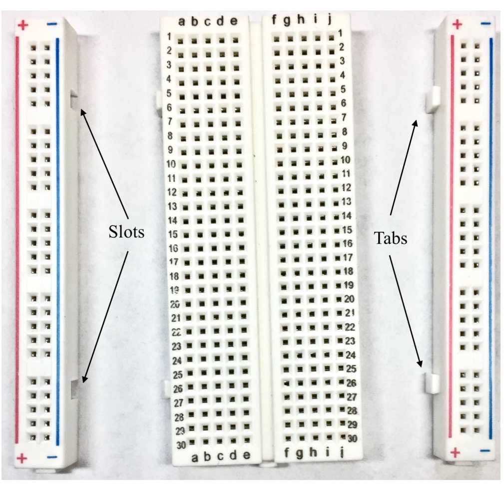

Figure 4A: Front view of three sections of the breadboard detached using slot and tab interlocking feature

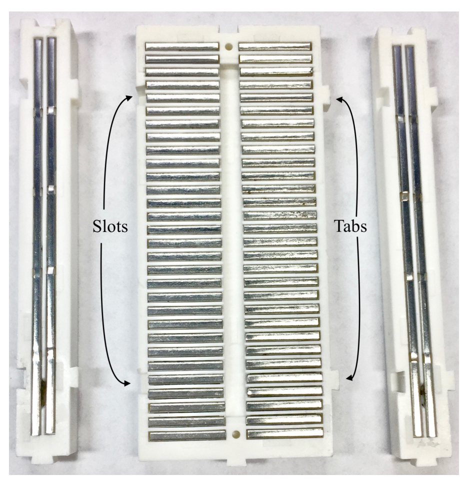

Figure 4B: Rear view of three sections of the breadboard detached using slot and tab interlocking feature

Let's disconnect the power rails and inspect each section of our breadboard separately, starting with the main section. We begin by removing two of the sixty pieces of metal from within the main section's plastic housing unit, as seen in Figure 5. Each of the individual pieces of metal in the main section is known as an *electrical contact strip*. These contact strips fit snugly into the small channels within the plastic housing and can be removed or inserted from the back face of the breadboard. This metal material guarantees each contact strip acts a single conductor. Moreover, each of the sixty contact strips are embedded in a unique channel within the plastic housing and separated from the other contact strips by plastic barriers. Thus, on a standard breadboard, separate contact strips are not electrically connected to each other within the board.

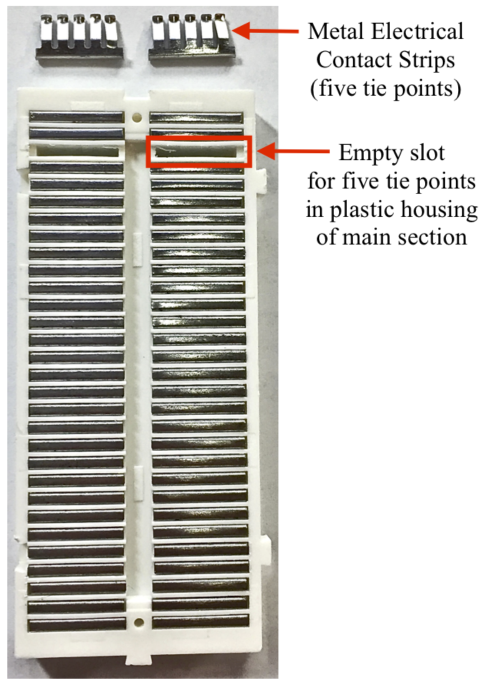

Figure 5: Electrical contact strips removed from the plastic housing
on the main section of our board (as seen from the back face)

If we zoom in on each contact strip, we can figure out the exact electrical connections provided within the board. Each strip has a piece of metal that holds five separate spring contacts together, shown in Figure 6A. When we place the contact strips in the plastic housing unit, the open ends of the spring contacts press up against the small holes on the face of the board. Figure 6B illustrates that each electrical contact strip maps to five tie points in a single row of the breadboard.

Figure 6A: Each electrical contact strip contains a set of five spring contacts connected by a longer sheet of metal

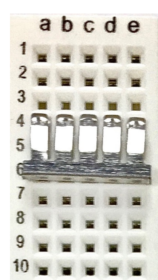

Figure 6B: Electrical contact strips correspond to five connected tie points in a single row of the board

Notice that two separate metal contact strips sit in each row of our breadboard. Thus, electrical connections on the main section of this breadboard come in groups of five tie points. Each set of five contact points is connected within a single row by the short metal contact strips that sit inside the breadboard. The first five connections are in columns a - e and the second five connections are in columns f - j. The center divider of the breadboard indicates that in any given row, the five tie points in columns a - e are not electrically connected with the five tie points in columns f - j of the same row. The contact strips provide this electrical connectivity while the plastic housing provides convenient reference labels as well as electrical separations between the sixty individual metal contact strips contained within.

Now we move onto inspecting the power rails. Each bus strip is composed of a thin plastic housing unit and two electrical contact strips that are much longer than the strips found in the main section. In particular, the electrical contact strips found in each power rail include 25 spring contacts connected together by a long piece of metal, shown in Figure 7.

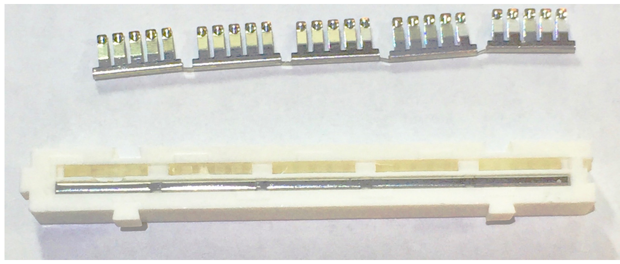

Figure 7: Power rail with one of the strips removes to show how the 25 separate tie points are all connected to a single piece of metal

This assembly guarantees that each group of 25 contact points within a power rail are all electrically connected and function as a single conductor. Now that we understand the electrical connections within the board, let's figure out how to take advantage of the labeling system printed on the face of the plastic housing unit.

The Breadboard Coordinate System

Using the coordinate system provided by the plastic housing, we can identify any of the 400 contact points on our breadboard with a unique label. When referring to contact points found on the main section of the board, we first identify the column letter and then the row number of our target point. In Figure 8A below, we show the location of three separate points: b3, j14, and f 29.

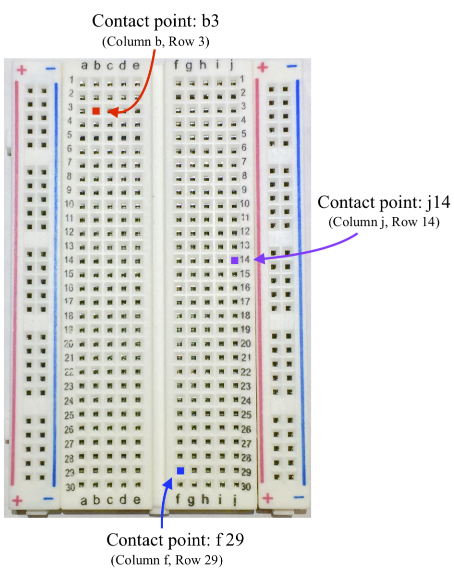

Figure 8A: Addresses of contact points on main section of breadboard start with column letter followed by row number

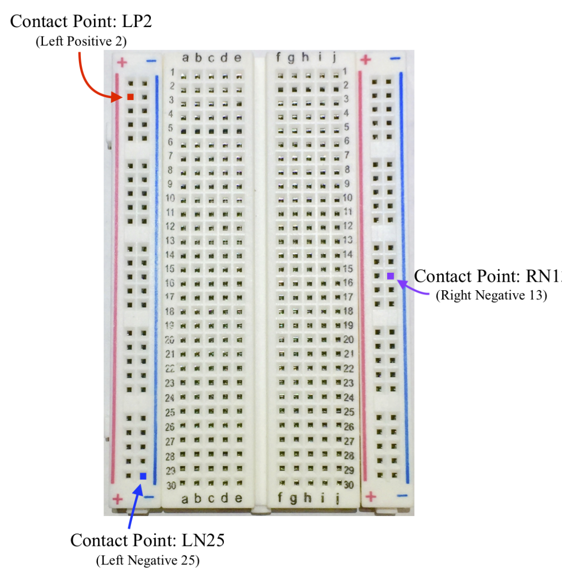

Figure 8B: Addresses of contact points on power rails of breadboard start with power rail location followed by point number

Point b3 can be found in column b, row 3. This point is electrically connected the four other contact point that lie on the same electrical contact strip that spans points a3, b3, c3, d3, and e3. If we move to column j, row 14 of the main section we find point j14 which is electrically connected to the electrical contact strip within points f14, g14, h14, i14, and j14. Finally, point f29 is found in column f, row 29 of our board. Although point f29 is electrically connected to all contact points f29 - j29, we notice that the center divider guarantees that point f29 is electrically separate from point e29. When viewing the breadboard vertically as in Figures 8A and 8B, we see that electrical connections in the main section of the board are provided horizontally within a row. For example, in row 8, the contact points in columns a - e provide a set of five electrically connected points with a different set of connect points in columns f - j. The two contact strips that enable these connections are separated by the center divider on the board.

Assuming each power rail is fully assembled, we see that each rail has exactly 50 contact points, grouped into two separate columns of 25 rows each. When viewing the front face of a power rail, one group of 25 connected contact points is labeled with a red + sign and a long red line. The other group of 25 connected points is marked with a blue − sign and a long blue line. These colored lines printed on the front face of the power rails indicate that the 25 contact points in each column are electrically connected, pin to pin, by the long metal strips inside the breadboard.

To refer to contact points on the power rails of the board, we first notice we have four options. In this work, we refer the Left Positive (LP), Left Negative (LN), Right Positive (RP), Right Negative (RN). Within each power rail, there are 25 connected points, oriented vertically along the board in Figure 8B below and grouped into sets of five points. We will call the points on the top of the board LP1 and move down in the column to the last point LP 25 found along that specific power rail. Thus, the addressing convention of the power rails follows the pattern we set for the main section of the board. First we identify which the column label for the specific power rail we want to use and then we specify which the row number of the target point within that column. In Figure 8B, we select three separate points on the power rails: LP2, LN25, and RN13.

Interested readers can find much more comprehensive information online using sites like the electronics literacy sight SparkFun.com (Cite). Show distance between points on breadboard.

Insert Parts Into the Breadboard

To connect a physical components into the breadboard, we insert the metal wires, known as the leads of our component, into any one of the contact points by pushing the lead into the aperture. We can apply a force downward until the lead disappears into the board and stops moving. We want to make sure that the leads poke through the spring contacts and descend until they reach the metal connector at the bottom of each electrical contact strip. Such a configuration guarantees a sturdy hold on the part with the desired electrical connections.

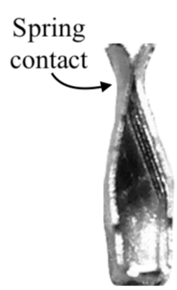

Figure 7: Power rail with one of the strips removes to show how the 25 separate tie points are all connected to a single piece of metal

When connecting several components on the same board, we need to be sure to keep the leads separate. By taking extra care to make sure that leads do not touch each other, we guarantee that the only electrical connections between our real elements occurs via the use of our contact points in the bread board.

Getting Started with Circuit Diagrams

In electrical engineering, we can represent a circuit using such pictures known as *circuit diagrams*. We use these figures to help design and prototype circuits. In our work, we focus on developing two different types of circuit diagrams. First, we present a *wiring diagram* which is a figure drawn to show the connections between components to help readers easily create a working prototype of the circuit with minimum confusion. These wiring diagrams show images of the real components used to build the circuit and demonstrate how to make the proper connections between these components. Wiring diagrams are designed to help novices build the circuit easily but are not very useful to practicing engineers who want to figure out how the electrical properties that enable the circuit to function as intended.

On the other hand, we also depict a *schematic diagram* of each circuit that shows idealized sketches of the individual components used in the circuit and all interconnections between the various components in an understandable way. Good schematic diagrams include names, values, and labels for each component to help convey the intended purpose of each part. Schematic diagrams are used to reveal the inner working of the circuit to other engineers.

We are not yet ready to present either of these types of circuit diagrams. However, as we introduce the circuit elements below, we provide three different visual representations of each circuit element including a digital photo of the real element provided in the learning lab, a computer-generated graphic of the real circuit element to be used in wiring diagrams, and the appropriate circuit schematic of said element to be used in schematic diagrams. Depending on the context, we may use any of these representations for a single circuit element. As noted previously, in the paper *Electrify the linear-systems problem for our students*, we build real circuits containing only three types of real devices including: resistors, direct current (dc) voltage sources, and dc current sources. Let's investigate each of these components separately. We begin with resistors which are electrical components that resist the flow of electrical current.

Resistors

Resistors resist the flow of electrical current through a wire. We can use resistors to decrease current flow or to divide a voltage into a smaller voltage. We can also use resistors to control the gain provided by operational amplifiers or to increase the time necessary to charge a capacitor. Students learn much more about these functions in introductory classes in electrical engineering (CITE).

Figure 9A shows an image of a real resistor. The body of this resistor looks like a miniature hourglass and is engineered to obey Ohm's law. The color bands that run around the body are standardized in industry to encode the resistance value and level of precision of the resistor, as discussed below. The wires that jut out of either sides of the resistor are known as the *leads* (pronounced "leeds") of this real circuit element. To connect this real resistor to other components in a physical circuit, each lead must be connected electrically with the leads of at least one other real circuit elements.

Figure 9A: Photo of real 1k resistor

Figure 9B: Computer graphic of real 1k resistor

Figure 9C: Circuit schematic of ideal resistor

In this work, we present detailed wiring diagrams of each example circuit we present. Our wiring diagrams are computer graphics generated using an open-source, freely available program called Fritzing. Figure 9B presents a computer graphic representation of our 1k resistor from Figure 9A. Finally, in addition to our wiring diagrams, we present an ideal circuit schematic for each and every circuit we study. These schematics are the standard way that practicing electrical engineers communicate circuit designs to each other. As seen in Figure 9C, the schematic for an ideal resistor is a pair of two leads with a set of jagged lines in between. When used in a schematic diagram, we label each resistor with a unique name and indicate the resistance value.

The Resistor Color Code

Resistors resist the flow of electrical current. In fact, we can quantify the amount that a specific resistor impedes the flow of current. This number is called the resistance value of a resistor. The colored bands printed on each real resistor encode the resistance value of that resistor. In Figure 10 below, we provide a detailed guideline to ascertain the resistance values from the colored bands printed on a real resistor. All resistors we use in our learning lab are 5 band resistors. However, in other context it is very common to work with 4 band resistors and thus we include reference to these color codes as well.

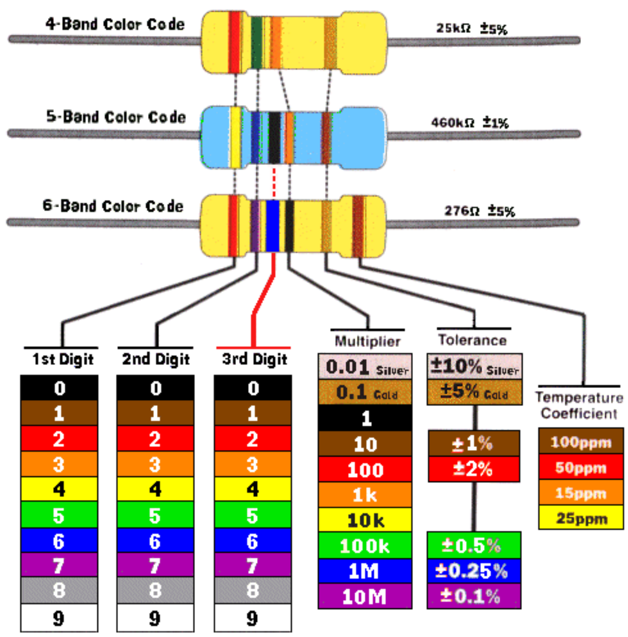

Figure 10: Color Codes for real resistors resistance values

Because these color codes show up in many places in electrical engineering, students have a tradition of using a mnemonics to memorize the resistor color codes. For the sequence of colors:

Black, Brown, Red, Orange, Yellow, Green, Blue, Violet, Gray, White

we might use one of the following mnemonics as a memory tool:

A. Black Bananas Really Offend Your Girlfriend But Violets Get Welcomed.

B. Black Bananas Really Offend Your Guyfriend But Violets Get Welcomed.