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Title: Experiment #29: Kirchhoff's Laws
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Experiment #29: Kirchhoff's Laws

Who is this Kirchhoff guy and why are his laws so important? They form the basis of understanding circuits, even as simple rules of thumb. In this experiment, I'll introduce the two laws and show you how they're used—without a bar exam!

Terms to Learn

- *Branch*—a circuit path with two terminals through which current can flow
- *Node*—the junction of two or more branches
- *Loop*—any closed path through a circuit that visits nodes and branches only once

Introduction

Circuit analysis (an intimidating pair of words) is founded on Gustav Kirchhoff's Current and Voltage Laws, which he announced in 1845 as an extension of Georg Ohm's pioneering research. These two laws are consequences of the law of energy conservation. In an electronic circuit, just like anyplace else, electrical energy produced must be equal to energy consumed.

To understand the laws, it is important to use the right terms to describe a circuit. First, a *branch* is a circuit path with two terminals through which current can flow—a wire, a resistor, a coil or a box containing some arbitrary circuit. A *node* occurs where more than one branch comes together. A *loop* is a complete path through a circuit, beginning and ending at the same node, but not visiting a node or branch more than once.

Kirchhoff's Current Law (KCL)

Kirchhoff's Current Law is the easiest to understand and it is applied at nodes, where currents combine, as shown in Figure 1. Even the simple connection between R3 and R4 is a two-branch node. (Don't confuse schematic connection "dots" with nodes because there may be more than one dot for a single node as shown at the bottom of the figure.)

KCL says that the sum of currents entering and leaving a node must equal zero. That seems reasonable, since electrons don't pile up at a circuit junction! KCL is a way of stating that energy must be conserved or balanced. The energy it takes to push currents through circuit branches into a node must equal the energy consumed in the branches through which the currents flow out of the node.

As an equation, KCL can be written as *incoming currents = outgoing currents* or *incoming currents – outgoing currents = zero*. You can assign a positive value to either incoming or outgoing current, so that currents flowing into and out of the node have opposite signs. Current is the same everywhere in the branch—you can't reverse current from one end of a branch to the other or change its value.

An example will help. Figure 2 shows a simple circuit with an arbitrary current assigned in each of the five branches. I1 through I5 are called *branch currents*. The three nodes are labeled 1, 2, and 3. We don't know which way the actual branch currents flow because we don't know whether V is positive or negative. The assigned direction doesn't matter! If we draw the arrow in the wrong direction, the calculated value for the branch current turns out to be negative.

Let's "do a KCL" for all three nodes. Ignore the green loop markings for now. At node 1, I1 is assumed to flow in and I2 and I4 to flow out. At node 2, I4 flows in and I3 and I5 flow out. At node 3, I2, I3, and I5 flow in and I1 flows out. If we decide that current flowing into a node is positive:

Node 1: I1 = I2 + I4
Node 2: I4 = I3 + I5
Node 3: I2 + I3 + I5 = I1

KCL is used when analyzing parallel connections in a circuit, such as when figuring out how current divides between two unequal resistances or determining the effect of combining currents.

Kirchhoff's Voltage Law (KVL)

KVL is also a consequence of the law of conservation of

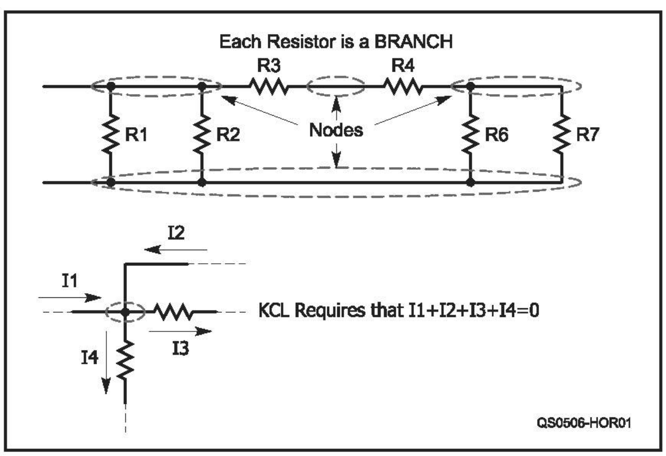

Figure 1—KCL requires the sum of currents at a node equal zero.

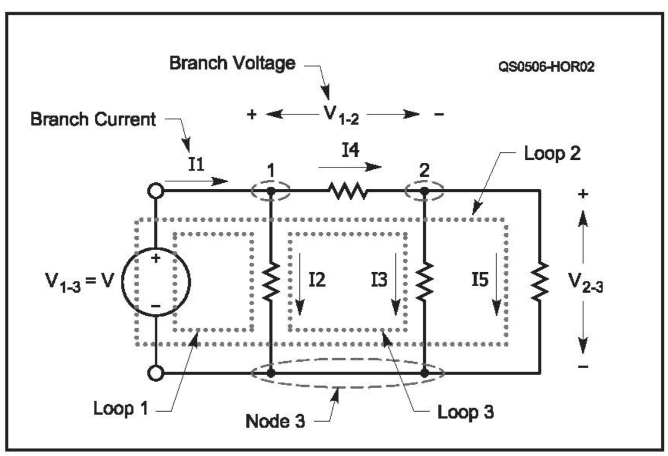

Figure 2—This circuit illustrates nodes, branches and loops—the keys to analyzing circuits.

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energy. The opposite of KCL, KVL is applied to loops and states that *the sum of branch voltages around a loop is equal to zero*. A *branch voltage* is the voltage from one end of the branch to the other, such as V1-2 between nodes 1 and 2 in Figure 2. For example, if we follow loop 1 from the power supply's positive terminal at node 1, through the branch for I2, and back to the supply's negative terminal at node 3, the voltages must all sum to zero. It would be the same if, instead, we followed loop 2 through I4, then I5, and back to the negative terminal.

Why does this conserve energy? Take the perspective of a single electron leaving the positive terminal of the power supply that gives the electron all of its energy. If the electron chooses to follow branch current I2, all of its energy is dissipated by that resistor before returning to the supply. It might also follow loop 2 and spend its energy in those resistors. In either case, the energy imparted by the supply has to be sufficient for the electron to "make it home." If the electron didn't expend all of its energy, it would arrive home with energy to spare, increasing the energy stored in the supply! KVL describes how energy is exactly balanced between *sources* (that supply energy) and *sinks* (that consume or dissipate energy).

As with KCL, you must keep polarities straight. By convention, voltages across an energy sink (such as a resistor) are assumed to be positive in the direction of the current—voltage is plus to minus across a resistor in the direction of current flow. Voltages through an energy source (such as a power supply) are negative in the direction of the current. Just as for KCL, if you don't know a voltage's polarity, you're allowed to guess and, if you're wrong, it turns out to be negative.

Let's do another example. In Figure 2, "doing a KVL" around loops 1, 2, and 3, the equations are:

Loop 1: $I2 \times R2 - V = 0$ or $I2 \times R2 = V$

Loop 2: $I4 \times R4 + I5 \times R5 - V = 0$ or $I4 \times R4 + I5 \times R5 = V$

We can move the energy sources to the other side of the equal sign and treat them as positive quantities, which is a little more convenient.

Loop 3: $I4 \times R4 + I3 \times R3 - I2 \times R2 = 0$

Note that there is no energy (voltage) source in loop 3. Furthermore, we encounter the voltage across R2 as negative to positive because of the assigned direction of I2. Bonus—there are three more possible loops in the circuit. Can you find them?

KVL is used when analyzing (or troubleshooting!) circuits using their voltages. For example, when looking at the collector circuit of a common-emitter amplifier, the resulting KVL equation balancing energy sources and sinks is $V_{CC} = I_C R_C + V_{CE} + I_E R_E$.

Extending the Laws to AC Circuits

KCL and KVL work just as well when resistance is replaced by impedance, which includes both resistance and reactance. Impedance generally changes with frequency, so the equations for circuit voltages and currents will also depend on frequency.

For example, if a resistor and capacitor are connected in parallel, KCL will show that at dc, all the current goes through the resistor, gradually shifting to the capacitor as frequency increases. In the series connection of a resistor and inductor, KVL will show that the voltage across the resistor is a maximum at dc and gradually drops as frequency increases.

Exercising Kirchhoff's Laws

Now test KCL and KVL in a real circuit! The solutions for this circuit are found on the Hands-On Radio Web page: **www.arrl.org/tis/info/HTML/Hands-On-Radio**.

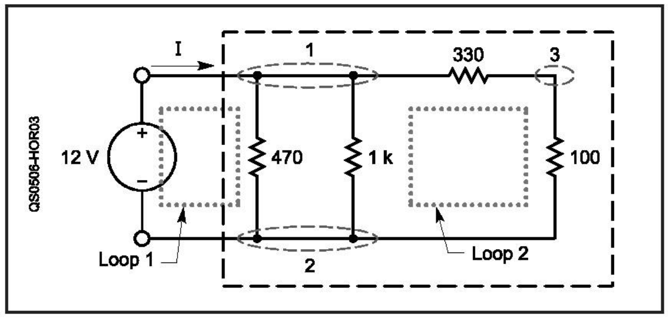

Figure 3—Build this circuit to test your understanding of KCL and KVL.

- Using the circuit of Figure 3, combine the values of the series and parallel resistors until you have one single equivalent resistance, R_{EQ} replacing everything inside the dashed line.
- Solve for $I = V / R_{EQ} = 12\ V / R_{EQ}$.
- What current flows in the 470 Ω and 1 kΩ resistors with 12 V across them?
- What current flows through the series combination of the 330 Ω and 100 Ω resistors?
- Build the circuit of resistors (no power supply yet) on your prototype board and measure the resistance from node 1 to node 2 to see if your calculated value of R_{EQ} is correct.
- Apply 12 V as shown and measure the power supply current, I. Compare the value to your calculated value.
- Measure all of the currents going into and out of the three nodes and confirm that KCL works. Either measure the currents directly, using the current scale of your meter, or indirectly, by measuring voltage across the resistors and using Ohm's Law.
- Measure all of the voltages in the two loops and confirm that KVL works. Don't forget to always measure voltage in the same "direction" around the loop.
- Experiment by changing the resistor values, then doing the calculations and measurements again. Identify the two remaining loops and "do a KVL" around them. Try replacing the 330 Ω resistor with a diode!

Shopping List

- 100 Ω, 330 Ω, 470 Ω, and 1 kΩ 1/4 W resistors

Suggested Reading

The section on series and parallel resistances in Chapter 4 of *The ARRL Handbook* (2005) covers Kirchhoff's Laws and also has all the equations for combining series and parallel resistances if you're a little rusty on those. While you're at it, browse through the following section on Thevenin equivalents—we'll be tackling those in the future. Rick, KB1HUE, also contributes the following Web site reference, which, if you have a Macintosh (or Mac simulator software), will provide hours of fun: **www.inform.umd.edu/EdRes/Topic/Chemistry/ChemConference/Software/ElectroSim/index.html**.

Next Month

We'll learn about another special type of IC—the charge pump. These handy critters can turn positive into negative or even double a voltage, just with a clever arrangement of switches and a couple of capacitors.