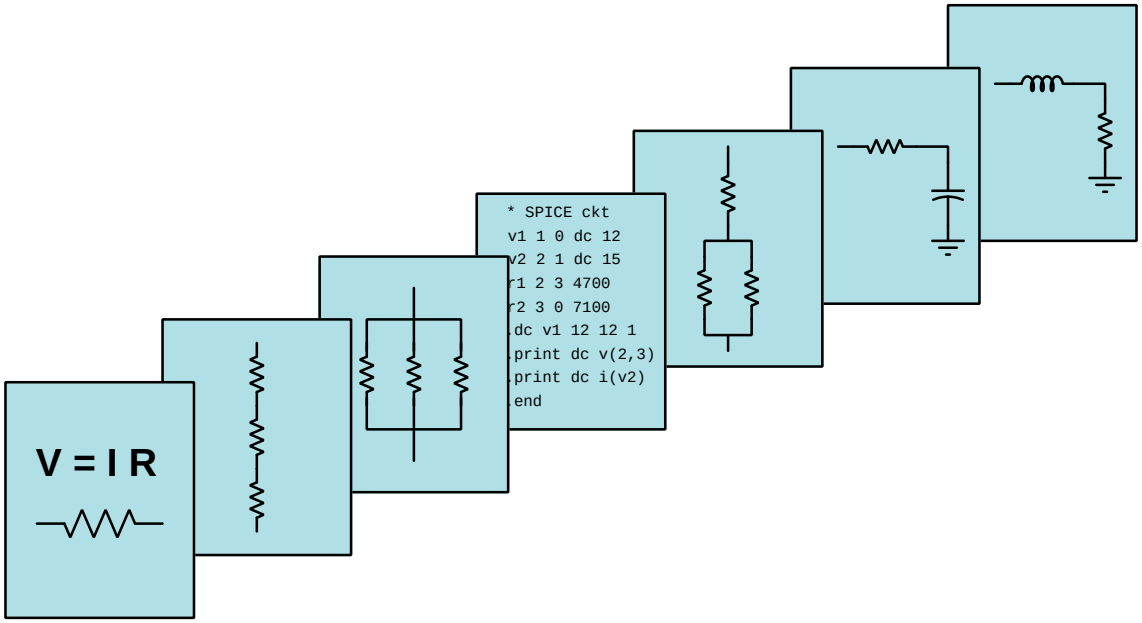
Modular Electronics Learning (ModEL) project



Ohm's and Joule's Laws, Resistor Ratings, and Electrical Safety

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Last update = 26 August 2024

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Chapter 1

Introduction

1.1 Recommendations for students

This module explores two important mathematical relationships for electric circuits: *Ohm's Law* and *Joule's Law*. The first of these relates voltage and current to resistance, while the second relates those quantities to power. After exploring these concepts, the module applies these concepts to the practical matter of electrical safety. Not only are these concepts absolutely essential to master in order to analyze electric circuits, but a firm understanding of them will help keep you safe when performing work around high-energy electric circuits.

Important concepts related to these topics include **energy**, **conductors** versus **insulators**, the relationship of **voltage** to potential energy, the relationship of current to **electric charge**, the effect of **resistance** on energy transfer in a circuit, electrical **sources** versus electrical **loads**, **series** versus **parallel** connections, **algebraic manipulation**, **tolerance** and precision, **color codes**, **algebraic substitution**, **dimensional analysis**, the relationship of **power** to energy, **heat transfer**, electric **shock**, electrical **commonality**, **equipotentiality**, **arc blast**, **arc flash**, and methods to **risk mitigation**.

Here are some good questions to ask of yourself while studying this subject:

- How might an experiment be designed and conducted to demonstrate Ohm's Law? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to demonstrate Joule's Law? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What are some practical applications of Ohm's and Joule's Laws?
- Why is voltage always measured between *two* points?
- How does voltage polarity and current direction relate to energy transfer in a circuit?

- What is the proper way to connect a voltmeter to a circuit, and why?
- What is the proper way to connect an ammeter to a circuit, and why?
- How is algebra useful in the application of Ohm's and Joule's Laws?
- What information must we know in order to compute either voltage, current, or resistance using Ohm's Law?
- What information must we know in order to compute either voltage, current, resistance, or power using Joule's Law?
- What factors must be considered in the design and fabrication of a resistor?
- How is the basic resistor color code formatted to represent resistance values and tolerance?
- What are the highest and lowest resistance values representable by the color code?
- How are energy and power related to each other, yet different?
- What factor(s) affect the power rating of a resistor?
- How does electricity affect the human body?
- How much electricity is dangerous to the human body?
- What factors determine the severity of an electric shock?
- What may be done to ensure safety when performing work on high-energy circuits?
- What are the steps commonly followed in a LOTO procedure, and why is each one important?
- What regulations exist to help ensure electrical safety on worksites?
- Why does certain protective gear help guard against injury from electricity?

You will find helpful example circuits to study in the *Case Tutorial* chapter, and in the *Historical References* chapter you will find sections describing the first explorations into the topics of Ohm's Law (from Ohm himself!) and electrical safety.

Writing an outline to summarize your own understanding of the text (tutorial) is a highly effective way to maximize your reading comprehension. An idea for your outline is to list all versions of the Ohm's Law equation and also the Joule's Law equation. It is important to be able to derive all these forms using algebra, but familiarity with each of the forms is also helpful, and summarizing them all will be an aid to this. Additionally, you may employ any of the strategies listed in the "Reading outline and reflections" subsection of the Conceptual reasoning section of the *Questions* chapter. Also, the list of "Foundational concepts" in the subsection following that is a helpful tool to gauge your own comprehension: can you define each of those concepts in your own words?

1.2 Challenging concepts related to Ohm's and Joule's Laws

The following list cites concepts related to this module's topic that are easily misunderstood, along with suggestions for properly understanding them:

- **Voltage versus Current versus Power** – these are three completely distinct things, each capable of existing without the other. *Voltage* is the amount of potential energy lost or gained by electric charge carriers as they move from one place to another, whereas *current* is the actual motion of electric charge carriers, and *power* is the rate over time which energy transfers from one form to another or from one location to another. An example of voltage existing without either current or power is static electricity. An example of current without either voltage or power is current circulating in a superconducting ring. An example of power without either voltage or current is a steam engine performing work with no electrical involvement at all.

- **Voltage as a relative quantity** – this is arguably one of the most difficult concepts students first encounter when studying electricity: understanding that voltage is a *difference* in energy levels between two locations, and not something that can exist at any single point. In this respect, voltage is similar to *distance* which is always something existing *between* two specified points.

- **Applying equations in context** – a common error among students new to the application of formulae to physical entities is that the formulae in question must be applied in the proper context using conceptual principles. For example, when applying Ohm's Law to a resistance, the voltage must be that across the specific resistance and the current must be that through the specified resistance. One simply cannot take any random voltage or current value they find in a circuit and then simply assume that value or values apply to *any* particular resistance in that circuit. Only by first evaluating the circuit according to trusted concepts may one correctly apply a formula. In a phrase, *always let concepts guide the math, not vice-versa!*

- **Metric prefixes** – metric prefixes such as milli, micro, kilo, etc. are very useful for expressing large and small quantities using reasonable numerical values (e.g. 35 μA rather than 0.000035 A), but it must be borne in mind that these prefixes are powers of ten that *must* be included in any calculations. Foundational formulae such as Ohm's Law, Joule's Law, etc. all assume quantities expressed in *base units*. For example, students you will commonly see mistakes such as calculating 1200 Volts by taking 20 milliAmperes and multiplying by 60 Ohms, whereas the correct result is 1.2 Volts (20 mA $\times$ 60 Ω is actually 0.020 A $\times$ 60 Ω).

- **Engineering mode** – scientific calculators provide a mode called *engineering mode* to express results using powers-of-ten corresponding to common metric prefixes, as well as provide a dedicated key for entering powers of ten (usually labeled `EE`). These are extremely useful in managing metric prefixes, but you will commonly find students resisting their use, insistent upon mentally shifting decimal points to convert between based units and prefixed units. This mental point-shifting is fraught with potential for error, but some students view learning to use their calculators' `EE` buttons and engineering modes as a burden rather than as the aid it really is. Every student eventually comes around, but in the interim it's incumbent upon you as the instructor to demonstrate just how much less error-prone these calculator tools are and to encourage students to acquire and polish the skill of using these tools.

- **Component ratings** – some students tend to confuse a component's maximum *rating* with the calculation of that same variable for a component: for example, assuming a 5-Watt rated resistor must dissipate 5 Watts of power, just as a 5-Ohm resistor should by all rights exhibit 5 Ohms of resistance at all times. Appeals to common every-day life examples are helpful for dispelling this form of misconception, for example citing the maximum speed rating of an automobile's tires (e.g. 120 miles per hour) versus the actual speed that vehicle is traveling at any given moment in time. Certain parameters, like resistance for a resistor or capacitance for a capacitor, are *intrinsic properties* of that component. By contrast, quantities that may freely vary for a component, like voltage, current, and power for a resistor, are subject to maximum safe limits in order to avoid component damage.

- **Hazards of electricity** – an unfortunately common adage about electrical hazards is that "it's current that kills rather than voltage". This originates from the fact that the most consistent data we have on electrical threats to the human body are all measured in Amperes rather than Volts, and this in turn is due to the wide variations we see in contact resistance with human skin. Internal body resistance is much more consistent than skin-contact resistance due to variations in surface sweat, epidermal layer thickness (e.g. callouses), contact pressure, etc. Therefore, the amount of *power* dissipated within the human body (which is the fundamental driver of damage) is based on a quantity of current we can measure and a quantity of voltage (across internal organs) we cannot.

1.3 Recommendations for instructors

This section lists realistic student learning outcomes supported by the content of the module as well as suggested means of assessing (measuring) student learning. The outcomes state what learners should be able to do, and the assessments are specific challenges to prove students have learned.

- **Outcome** – Demonstrate effective technical reading and writing

  Assessment – Students present their outlines of this module's instructional chapters (e.g. Case Tutorial, Tutorial, Historical References, etc.) ideally as an entry to a larger Journal document chronicling their learning. These outlines should exhibit good-faith effort at summarizing major concepts explained in the text.

  Assessment – Students show how voltage, current, resistance, and power values were calculated by the author in the Tutorial chapter's examples.

  Assessment – Students present their "Conceptual Toolbox" Theory Journal entries listing important concepts applied in the Tutorial text(s). A "Conceptual Toolbox" serves as inspiration when solving problems, each concept suggesting a potential problem-solving action. Challenge students to collaboratively generate a Conceptual Toolbox for the day's topic during the class session and then use it when solving problems together, thus fostering the habit of reasoning from principles rather than recalling procedures!

- **Outcome** – Apply the concepts of Ohm's Law and Joule's Law to the calculation of voltage, currents, resistance, and power in simple circuits

  Assessment – Calculate either voltage, current, or resistance given the other two in a simple (one-source, one-load) circuit; e.g. pose problems in the form of the "Voltage, Current, and Resistance calculations" Quantitative Reasoning question.

  Assessment – Calculate either voltage, current, resistance, or power given any two of the other quantities in a simple (one-source, one-load) circuit; e.g. pose problems in the form of the "Power, Voltage, Current, and Resistance calculations" Quantitative Reasoning question.

- **Outcome** – Apply the concepts of the resistor color code and error calculations to resistor values

  Assessment – Predict and then measure the resistance values of randomly-selected resistors, also determining whether or not the measured resistance falls within the specified tolerance.

- **Outcome** – Destructively test a resistor's power rating

  Assessment – Predict the amount of voltage and current necessary to over-heat a chosen resistor, selecting that resistor to keep the requisite voltage low enough to avoid shock hazard as well as choosing a test jig that will not be damaged by the resistor's heat, then measure its temperature when energized and time how long it takes for its resistance to fall outside of the specified tolerance.

- **Outcome** – Demonstrate lock-out/tag-out procedures on a real circuit

Assessment – Build a simple circuit with a source, a load, an on/off control switch, and either a lockable disconnect/breaker or multiple non-locking disconnecting switches, then demonstrate proper LOTO technique.

- **Outcome** – Independent research

  Assessment – Locate datasheets for different types of resistors and properly interpret some of the information contained in those documents including power ratings, resistance tolerance, temperature coefficient, etc.

Chapter 2

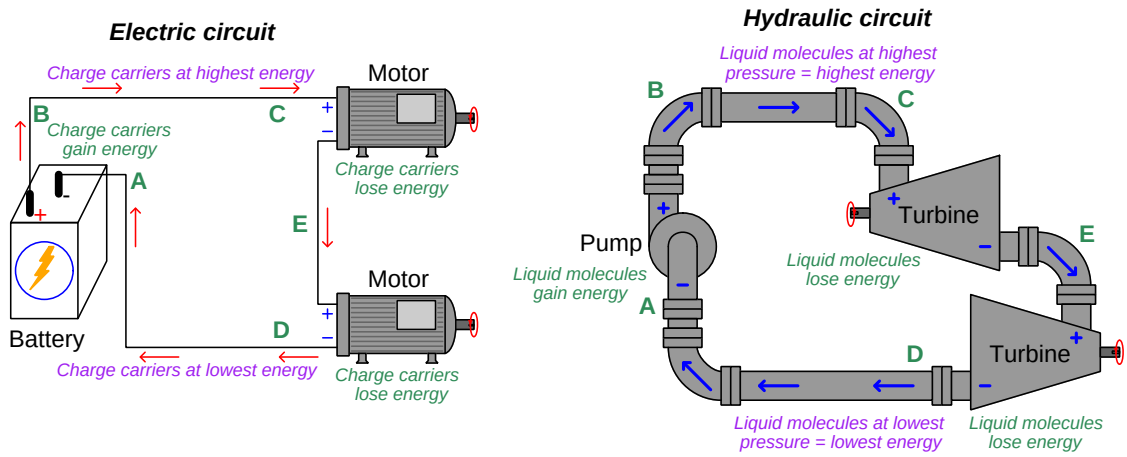
Case Tutorial

The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as a scientific experimenter. Hopefully you will find these cases illuminating, and a good supplement to text-based tutorials.

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

2.1 Example: potential in open and shorted circuits

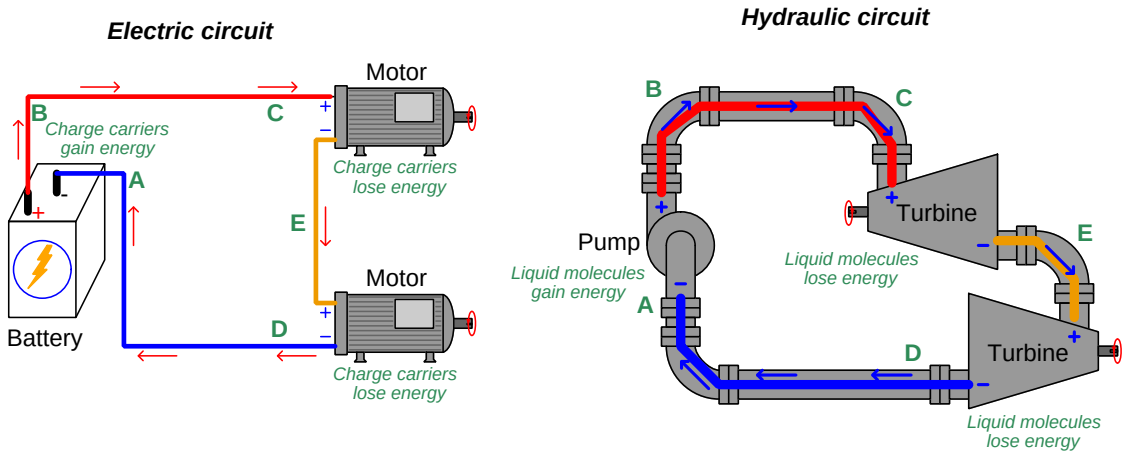
Here we will explore the concept of *potential* in both electric and hydraulic circuits. The following illustrations will be used, each circuit containing one *source* tasked with boosting the potential energy of the flow and two *loads* where that flow releases energy to do useful work:



"Potential" may be thought of as *specific potential energy*, or the amount of potential energy possessed by a certain quantity of mobile fluid particles. In the case of electricity, electric potential is the number of Joules of potential energy carried by one Coulomb (6.2415×10^{18}) of charge carriers. In the case of hydraulic systems, fluid potential is better known as *pressure* and is the number of Joules of potential energy carried by one cubic meter of the fluid.

Differences of potential may be precisely quantified in any circuit, be it *voltage* for electric circuits or *pressure differential* for hydraulic circuits. The "+" and "−" symbol pairs shown in each illustration represent the high-potential and low-potential sides of each difference. Each component's identity as either a source or a load is clear to see from a comparison of these "+" and "−" polarity marks in conjunction with the direction of flow. Note how each source takes in flow on the low-potential (−) side and outputs flow on the high-potential (+) side as it boosts the potential of the flowstream, while each load does just the opposite as energy is released by the flow.

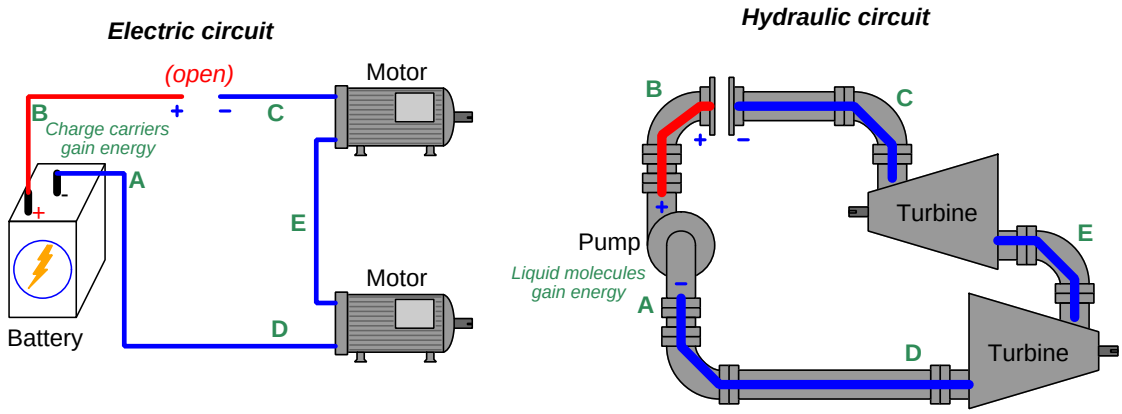
Here we show the circuit illustrations with higher and lower potentials color-coded[1]: red to signify high potential, orange to signify medium potential, and blue to signify low potential. Applying these colors to the original illustrations:



These color-coded potentials are all qualitative in nature. It is really impossible to precisely specify potential at any single location in a circuit, whether electrical or hydraulic, because potential energy depends on *two* conditions: a starting condition and an ending condition. We cannot say with any certainty how much energy is *potentially* released by any given fluid unless we know for certain what its end-state will be. This is why voltage in an electrical circuit is always relative between two points: an expression of how much potential was either gained or lost by charge carriers passing from one location to another. In a similar sense, hydraulic liquid pressure is also relative between two points: even a simple pressure gauge registering liquid pressure inside of a pipe is actually sensing the *difference* in pressure between the fluid within the pipe versus the atmospheric (air) pressure surrounding the pressure gauge. Thus, in both circuits the color-coding merely represents "greater" and "lesser" potential on a relative scale rather than absolute values of potential.

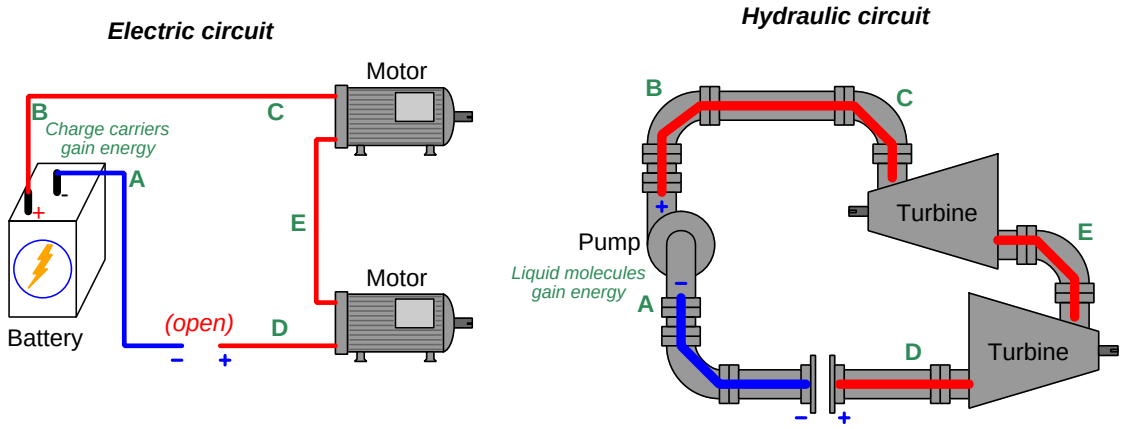
[1] These same colors are often used to signify relative liquid pressures in hydraulic system illustrations.

Now we will place an "open" (i.e. a blockage to flow) on the upper portion of each circuit:



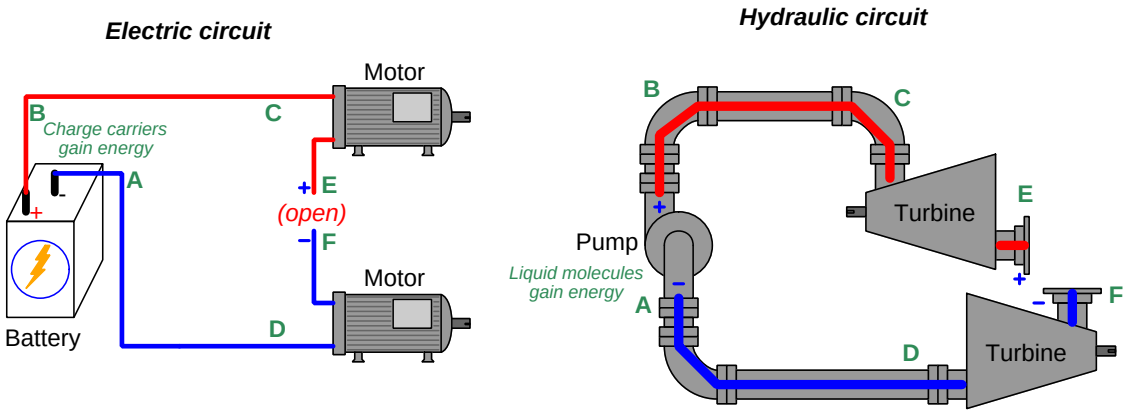
Note how the only portion with high potential lies between the "+" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (low). No longer will a difference of potential develop across each load, since the flow ceases everywhere as a result of the "open", but a potential difference does exist across the "open".

Next we will place an "open" on the lower portion of each circuit:



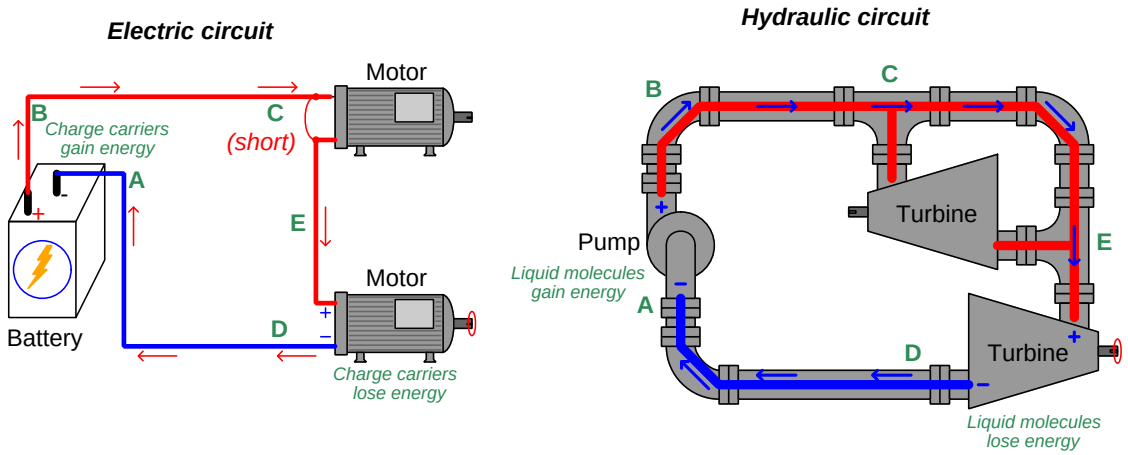
Note how the only portion with low potential lies between the "−" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (high). Each load experiences zero difference of potential across it, since the flow ceases everywhere as a result of the "open", but a potential difference does exist across the "open".

Our last "open" will be placed between the two loads in each circuit:



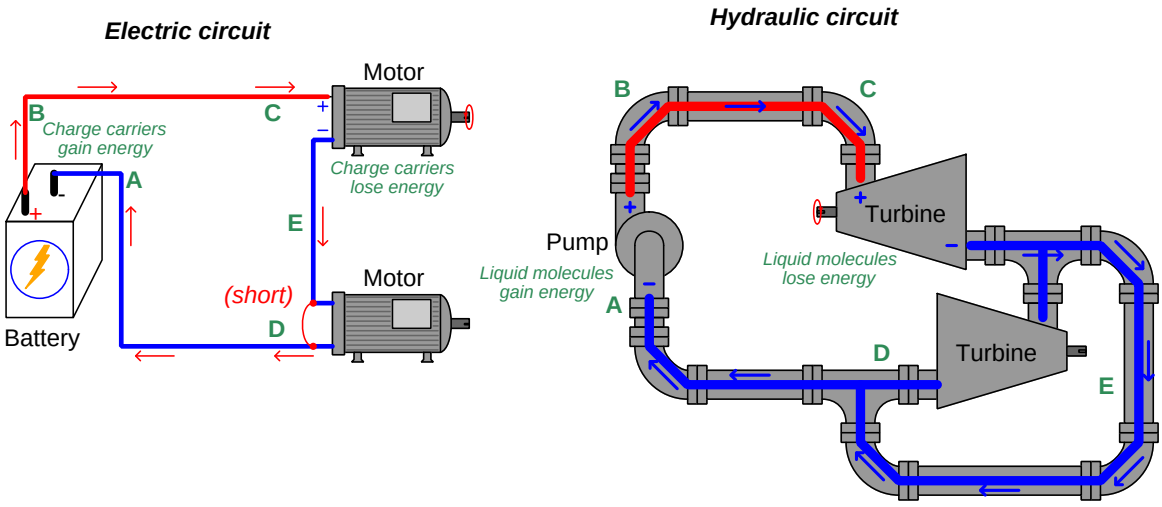
The "open" placed between the two loads creates a new distinct point which we label as **F**. Note how the lower load and its connection to the source maintains a low potential throughout, while the upper load and its connection to the source is at high potential throughout. Neither load has a difference of potential across it, but there is a difference of potential across the "open" in each circuit. The lack of flow, however, means no work is being done.

"Shorting" past loads in a circuit also affects the distribution of potential. Here we see the upper load shorted in each circuit:



Making both ends of the upper load "common" to each other ensures equipotentiality, robbing the upper loads of any potential difference. This means the flow will not lose any energy going past the shorted load, and instead will deliver all its energy to the lower load which still provides resistance to the flow and is therefore able to extract energy from the flow.

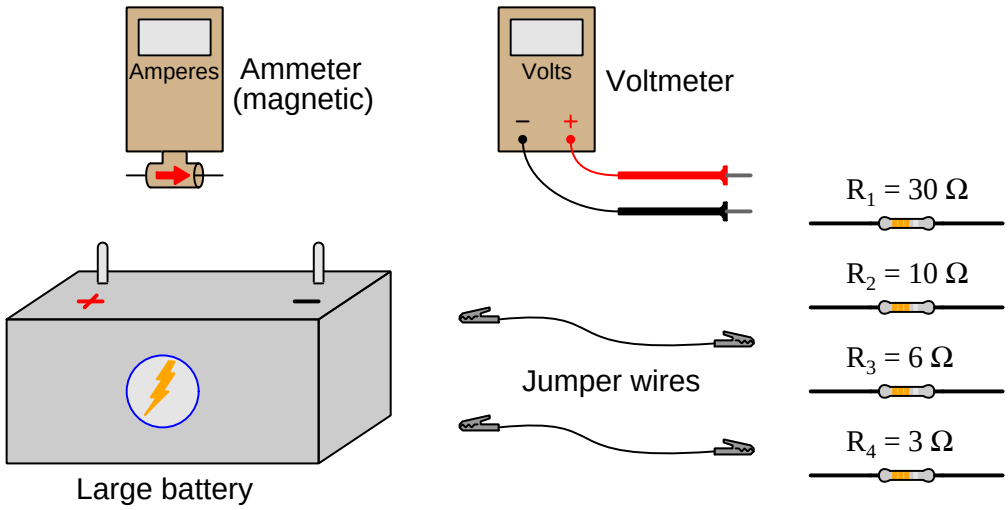
Now we will short past the lower load in each circuit to see the effects:



Making both ends of the lower load "common" to each other ensures equipotentiality, robbing the lower loads of any potential difference. This means the flow will not lose any energy going past the shorted load, and instead will deliver all its energy to the upper load which still provides resistance to the flow and is therefore able to extract energy from the flow.

2.2 Example: Battery and resistors

Here, a large 12 Volt battery and several resistors are provided for experimentation, along with "jumper" wires consisting of plastic-clad stranded copper conductors terminated with spring-loaded "alligator" clip jaws at either end. A simple voltmeter with red- and black-colored test leads stands ready to measure voltage, while a simple ammeter with a magnetic sensor stands ready to measure electrical current:

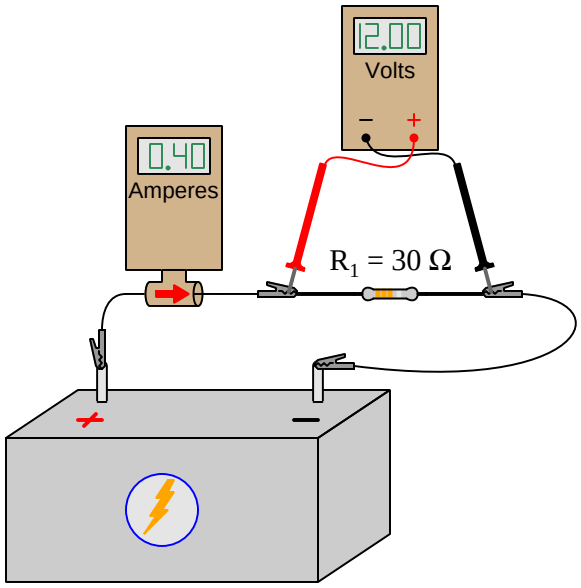


Current is the motion of subatomic "electric charge carriers" through the bulk of electrically conductive materials such as copper metal. The standard metric unit of measurement for electric current is the *Ampere*, with one Ampere (1 A) being equivalent to 6.2415×10^{18} individual charge carriers drifting past a given location per second of time. The ammeter we will use senses electric current by the magnetic field produced around a current-carrying conductor. A positive indication on the ammeter's display means charge carriers are moving (as interpreted by the "conventional flow" standard) in the direction of the meter's arrow; a negative indication means motion in the opposite direction.

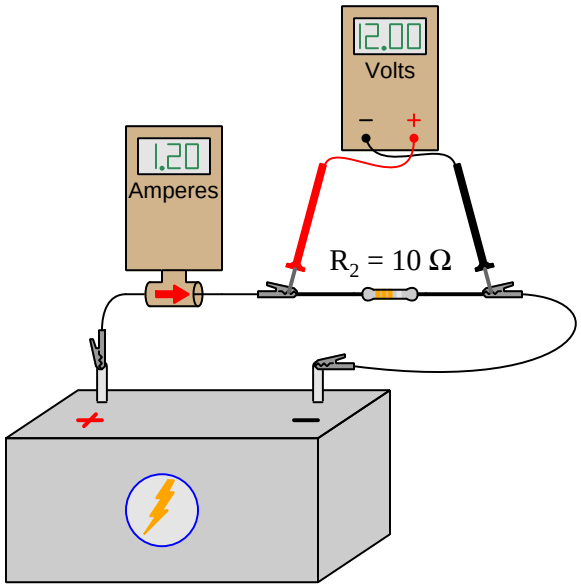
Voltage is the difference in energy between an electric charge carrier at one location and an electric charge carrier at another location. The standard metric unit of measurement for voltage is the *Volt*, with one Volt (1 V) being equivalent to one Joule of energy difference per 6.2415×10^{18} individual charge carriers. The voltmeter we will use has two copper-wire *test leads* that are touched to the two locations of interest. The red test lead is the "measurement" lead while the black test lead is the "reference" lead. A positive indication on the voltmeter's display means charge carriers along the red lead are at a higher state of energy than charge carriers along the black lead; a negative indication means the opposite.

Resistance transfers energy away from moving charge carriers, converting the transferred energy into heat. The standard metric unit of measurement for resistance is the *Ohm*, with one Ohm (1 Ω) being equivalent to one Volt of potential difference while passing 1 Ampere of current.

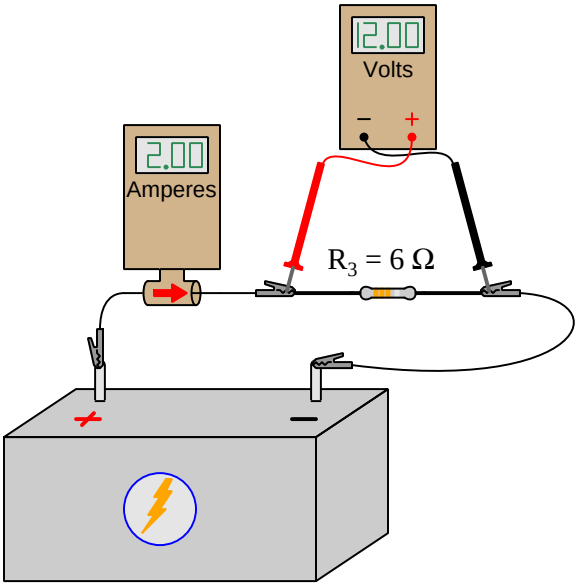
First we will connect the first resistor (having a value of 30 Ohms) to the 12 Volt battery, measuring both resistor voltage and resistor current:

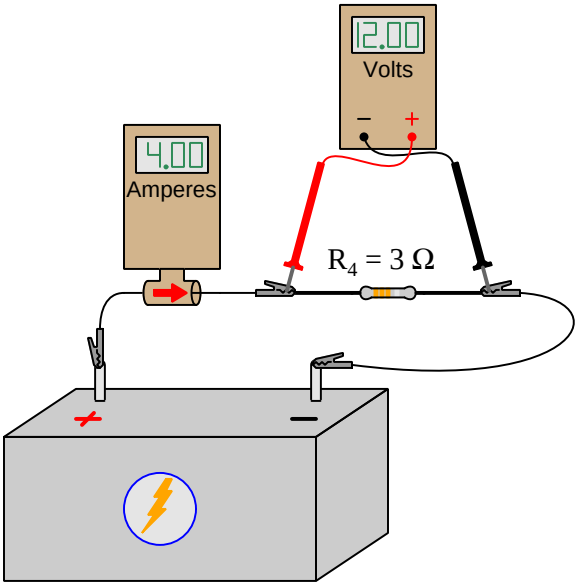


Next, resistor R_2 with a value of 10 Ohms:



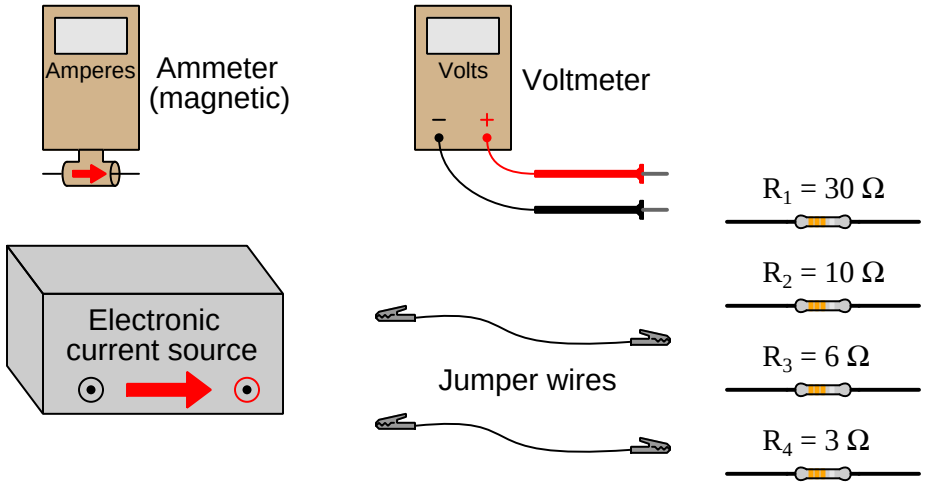
Lastly, the final two resistors:





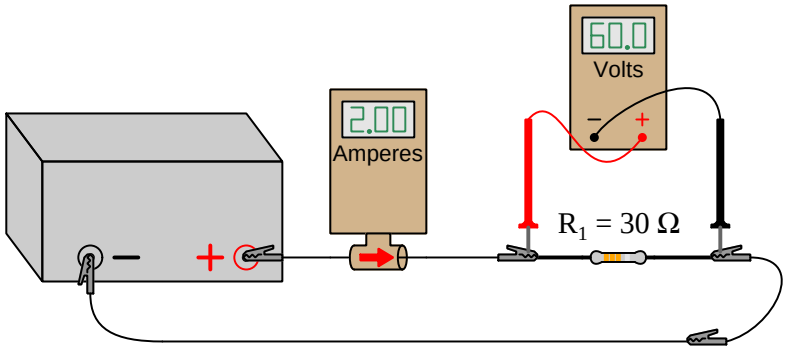
2.3 Example: Current source and resistors

Here, an electronic *current source*[2] and several resistors are provided for experimentation, along with "jumper" wires consisting of plastic-clad stranded copper conductors terminated with spring-loaded "alligator" clip jaws at either end. A simple voltmeter with red- and black-colored test leads stands ready to measure voltage, while a simple ammeter with a magnetic sensor stands ready to measure electrical current:



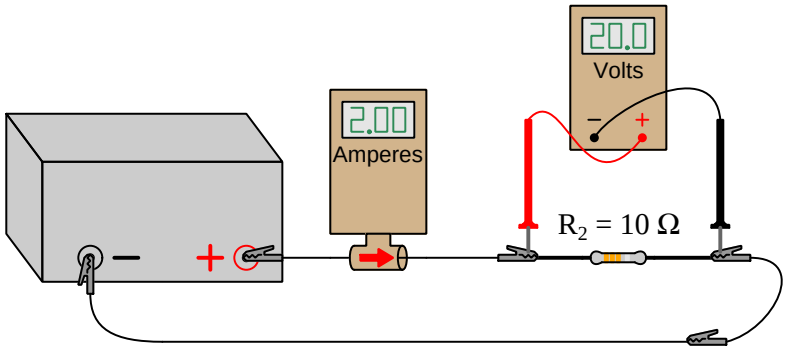
In this case, the current source is configured to output 2 Amperes of current.

First we will connect the first resistor (having a value of 30 Ohms) to the 2-Ampere current source, measuring both resistor voltage and resistor current:

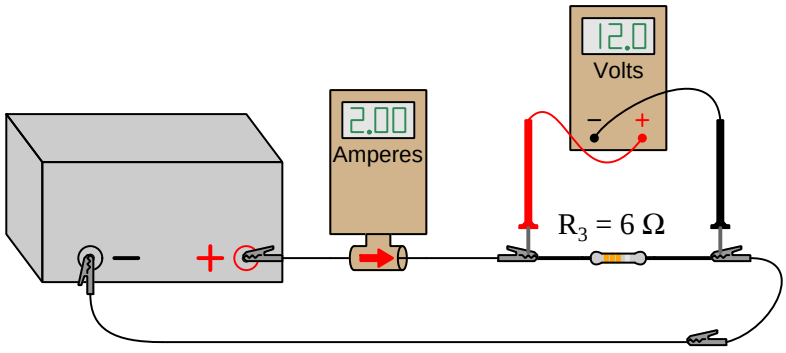


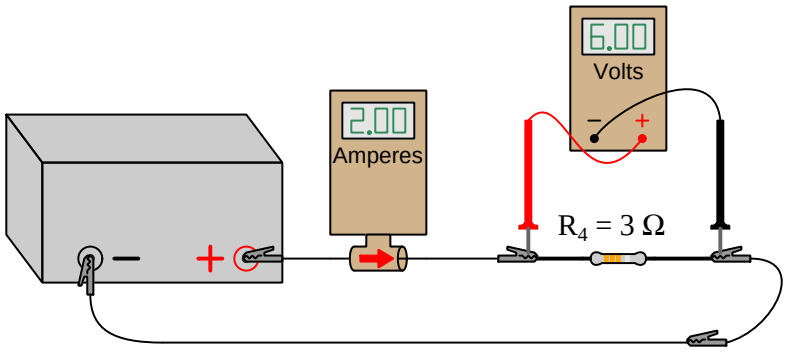
[2]Unlike electrochemical *batteries* which tend to maintain a nearly constant voltage between their terminals over a wide range of current values, a *current source* maintains a nearly constant current over a wide range of voltages.

Next, resistor R_2 with a value of 10 Ohms:



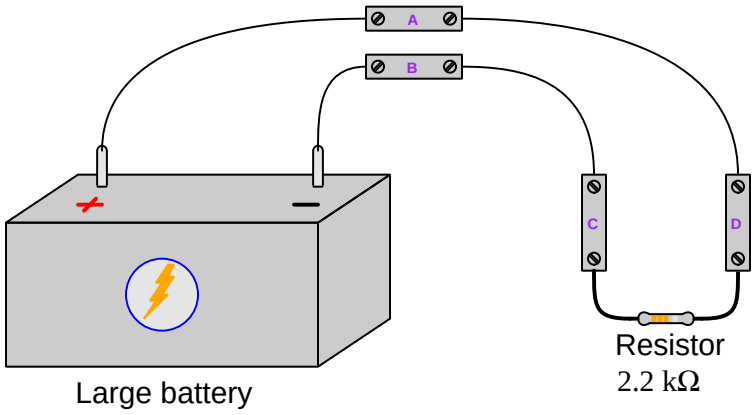
Lastly, the final two resistors:





2.4 Example: Terminal block circuit

In this scenario we will use *terminal blocks* to neatly organize all wire connections between a 12 Volt battery and a 2200 Ohm resistor:

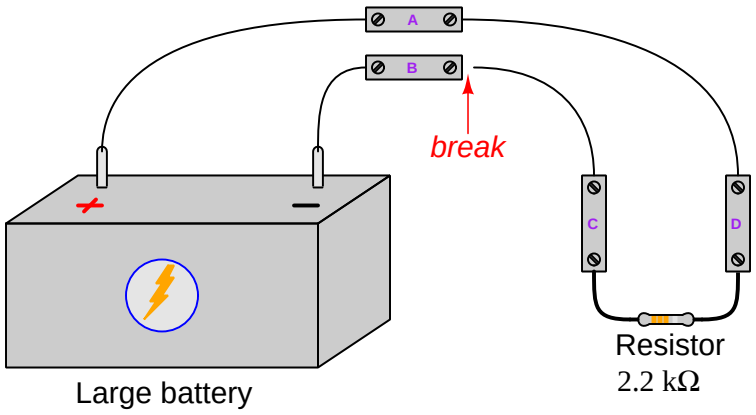


Rather than visually show where voltmeters and ammeters connect to circuit components, voltmeter and ammeter indications will be in written form as V and I values[3]. With the circuit constructed as shown in the above illustration, we obtain the following measurements:

- $V_{AB} = 12.00$ Volts
- $V_{BA} = -12.00$ Volts
- $V_{DC} = 12.00$ Volts
- $V_{CD} = -12.00$ Volts
- $V_{CA} = -12.00$ Volts
- $V_{DB} = 12.00$ Volts
- $V_{AD} = 0.00$ Volts
- $V_{CB} = 0.00$ Volts
- $I_C = 5.45$ milliAmperes (conventional flow up)
- $I_B = 5.45$ milliAmperes (conventional flow right to left)

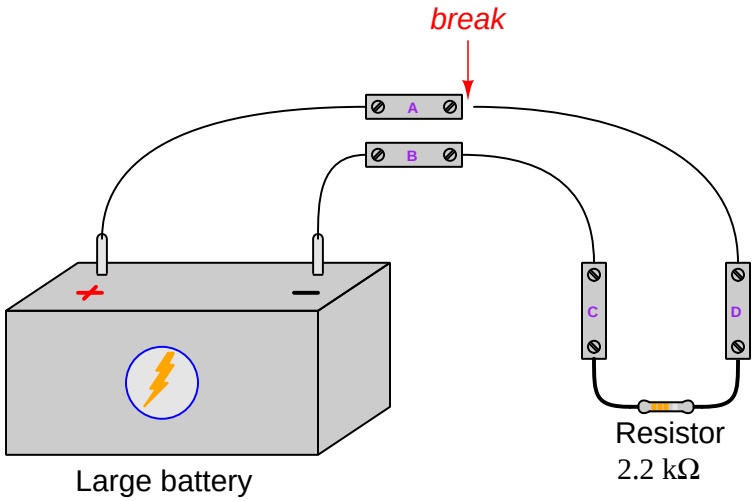
[3]Double-lettered subscripts for V denote the placement of voltmeter test leads, with the first and second letters always representing the red and black test leads respectively. For example, V_{BC} means the voltage measured between terminals B and C with the red test lead touching B and the black test lead touching C. Single-lettered subscripts for V represent the voltmeter's red test lead, with the black test lead touching a defined "ground" point in the circuit. Current measurements (I) imply measurements made at a single location, and so there will only ever be single-lettered subscripts for I. Conventional flow notation will be used to specify current direction.

Now we will intentionally *break* the circuit by removing the wire connecting terminals B and C, at the B terminal, and re-take all the former measurements:



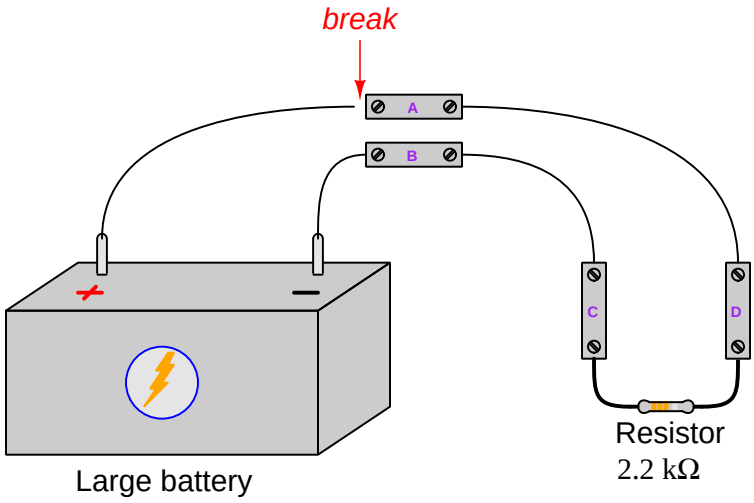
- $V_{AB} = 12.00$ Volts
- $V_{BA} = -12.00$ Volts
- $V_{DC} = 0.00$ Volts
- $V_{CD} = 0.00$ Volts
- $V_{CA} = 0.00$ Volts
- $V_{DB} = 12.00$ Volts
- $V_{AD} = 0.00$ Volts
- $V_{CB} = 12.00$ Volts
- $I_C = 0.00$ milliAmperes
- $I_B = 0.00$ milliAmperes

Next we will intentionally break a different portion of the circuit, this time removing the wire connecting terminals A and D, at the A terminal, and re-take all the former measurements:



- $V_{AB} = 12.00$ Volts
- $V_{BA} = -12.00$ Volts
- $V_{DC} = 0.00$ Volts
- $V_{CD} = 0.00$ Volts
- $V_{CA} = -12.00$ Volts
- $V_{DB} = 0.00$ Volts
- $V_{AD} = 12.00$ Volts
- $V_{CB} = 0.00$ Volts
- $I_C = 0.00$ milliAmperes
- $I_B = 0.00$ milliAmperes

Next we will intentionally break yet another portion of the circuit, this time removing the wire connecting terminal A to the positive terminal of the battery, at the A terminal, and re-take all the former measurements:



- $V_{AB} = 0.00$ Volts
- $V_{BA} = 0.00$ Volts
- $V_{DC} = 0.00$ Volts
- $V_{CD} = 0.00$ Volts
- $V_{CA} = 0.00$ Volts
- $V_{DB} = 0.00$ Volts
- $V_{AD} = 0.00$ Volts
- $V_{CB} = 0.00$ Volts
- $I_C = 0.00$ milliAmperes
- $I_B = 0.00$ milliAmperes

2.5 Example: Ohm's and Joule's Law examples with metric-prefixed quantities

If we connect a 230 Volt source to a 15 kiloOhm (15 kΩ) resistor, a current of 0.015333 Amperes will flow, and the resistor will dissipate 3.527 Watts of power. That 0.015333 Ampere current could also be expressed as 15.333 milliAmperes (15.333 mA), or even as 15333 microAmperes (15333 μA). The resistor's value of 15 kΩ could likewise be expressed as 15000 Ohms, or even 0.015 megaOhms (0.015 MΩ).

A current of 472 microAmperes (472 μA) passing though a resistance of 470 Ohms will develop a voltage drop of 0.2218 Volts, which may also be expressed as 221.8 milliVolts (221.8 mV). That same resistor will also dissipate 0.0001047 Watts of power, which may be written as 0.1047 milliWatts (0.1047 mW) or 105 microWatts (104.7 μW).

A resistor dropping 25 milliVolts while passing 2.9 microAmperes of current will have a resistance value of 8620.7 Ohms, which could also be written as 8.6207 kiloOhms (8.6207 kΩ).

A resistor with a four-band color code of Orange-Yellow-Blue-Gold has a possible range of resistance values spanning from 32.3 megaOhms to 35.7 megaOhms. If connected to a 24 Volt source, the possible range of currents will be from 0.6723 microAmperes to 0.7430 microAmperes. We could also express this same current range as 672.3 nanoAmperes (672.3 nA) to 743.0 nanoAmperes (743.0 nA).

If a 22 kΩ resistor dissipates 350 mW of power, it will pass a current of 3.989 mA and drop a voltage of 87.75 V.

A resistor dissipating 40 mW of power while dropping 170 mV of voltage will have a resistance value of 722.5 mΩ and pass a current of 235.3 mA.

If two overhead power line conductors accidently touch each other during a windstorm, with the resulting short-circuit creating a fault current of 35 kA given a source voltage of 13.8 kV, the fault resistance will be 394.3 mΩ.

A turbine-electric power plant aboard a large ship sources 15 MW of power to the DC drive motor at a voltage of 3.8 kV, resulting in a motor current of 3.947 kA. This is the same amount of current as would pass through a 0.9627 Ω resistor connected to the same 3.8 kV source, except of course the motor is turning that electrical energy into motive force for the ship whereas a resistor would simply dissipate a large amount of heat.

2.6 Example: money analogy for voltage, current, power, and resistance

Imagine a scenario where customers steadily enter and exit a large business, spending precisely the same amount of time within that business, and each spending precisely $50. Now imagine the rate of people entering and exiting this business to be 20 persons per second. We will use this scenario as an analogy for electrical parameters associated with a *load* within an electric circuit.

Here, the stream of 20 customers per second is analogous to *electric current* expressed as 20 Amperes. The fundamental units of measurement comprising the Ampere in an analogous electric circuit would be 20 Coulombs of charge carriers passing through the load per second of time.

The amount of money spent by each customer passing through the business ($50) is analogous to *voltage* expressed as 50 Volts. In an electric circuit this voltage "drop" of 50 Volts across the load's terminals represents 50 Joules of energy delivered to the load per Coulomb of electric charge carriers passing through.

The rate of customers per second multiplied by the amount of money spent by each customer passing through the business is analogous to *power* ($P = IV$) expressed as 1000 Watts. In an electric circuit this power of 1000 Watts represents 1000 Joules of energy delivered to the load per second of time, which makes intuitive sense if there are 20 Coulombs of charge carriers passing through per second and each Coulomb delivers 50 Joules of energy. In all systems, *power* is defined as the *rate of energy exchange*. In the customer-business analogy, since we are likening money to energy, the analogue to electrical power would be the business's gross sales rate in dollars per unit time – here it is $1000 per second: 20 customers per second with each of those customers spending $50.

The amount of money spent per customer divided by the rate of those customers' patronage is analogous to *resistance* ($R = \frac{V}{I}$) expressed as 2.5 Ohms. The fundamental units comprising the Ohm for an electric load are Joule-seconds per Coulomb squared. In the customer-business analogy the units would be dollar-seconds per customer squared. These units may not be as conceptually enlightening as the others, but they are equivalent nonetheless.

If we calculate a total accumulation of sales in this business over a one-minute period, we will arrive at $60,000: a steady rate of $1000 dollars' worth of sales per second multiplied by the 60 seconds of time contained within one minute. In an electric circuit this would be the total amount of work done or energy dissipated by the 1000 Watt load over the same one-minute period of time, or 60,000 Joules: 1000 Watts (i.e. 1000 Joules of energy per second) multiplied by 60 seconds of time.

2.7 Example: Resistor values and tolerances

For each of the resistors photographed here, we see the nominal value in Ohms, the tolerance in percent, and the range of resistance possible within that tolerance:

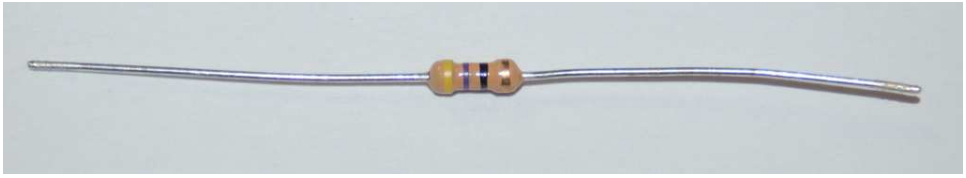
Resistor example #1

Nominal resistance = 100 Ω ±5% (colors = Brown-Black-Brown-Gold)
Resistance span = (100 Ω)(±5%) = ±5 Ω
Possible resistance range = 95 Ω to 105 Ω

Resistor example #2

Nominal resistance = 82 kΩ ±5% (colors = Grey-Red-Orange-Gold)
Resistance span = (82000 Ω)(±5%) = ±4100 Ω
Possible resistance range = 77.9 kΩ to 86.1 kΩ

Resistor example #3

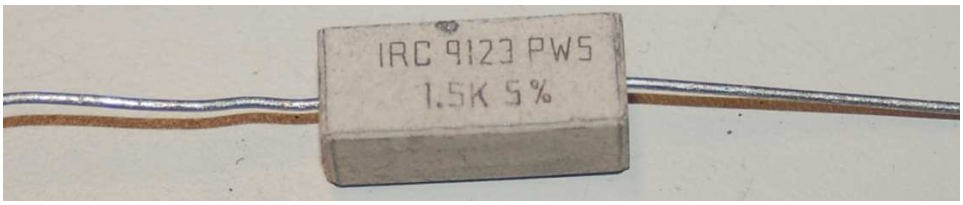


Nominal resistance = 47 Ω ±5% (colors = Yellow-Violet-Black-Gold)
Resistance span = (47 Ω)(±5%) = ±2.35 Ω
Possible resistance range = 44.65 Ω to 49.35 Ω

Resistor example #4

Nominal resistance = 15 kΩ ±1% (colors = Brown-Green-Black-Red-Brown)
Resistance span = (15000 Ω)(±1%) = ±150 Ω
Possible resistance range = 14.85 kΩ to 15.15 kΩ

Resistor example #5



Nominal resistance = 1.5 kΩ ±5%
Resistance span = (1500 Ω)(±5%) = ±75 Ω
Possible resistance range = 1.425 kΩ to 1.575 kΩ

Resistor example #6

Nominal resistance = 14 Ω ±3%
Resistance span = (14 Ω)(±3%) = ±0.42 Ω
Possible resistance range = 13.58 Ω to 14.42 Ω

Resistor example #7

Nominal resistance = 6.8 kΩ ±5% ("J" tolerance code = 5%)
Resistance span = (6800 Ω)(±5%) = ±340 Ω
Possible resistance range = 6.46 kΩ to 7.14 kΩ

Resistor example #8

Nominal resistance = 825 Ω (825×10^0)
Tolerance is unmarked on this surface-mount device (SMD) resistor, and so span and range calculations are impossible

Chapter 3

Simplified Tutorial

Voltage is the energy difference between identical charge carriers at different physical locations, symbolized by the variable V and measured in the unit of the *Volt* (V), one Volt being one Joule of energy gained or lost by one Coulomb[1] of electric charge.

Current is the rate of charge carrier motion, symbolized by the variable I and measured in the unit of the *Ampere* (A), one Ampere being one Coulomb of electric charges passing by per second of time.

Resistance is the "friction" encountered by charge carriers as they pass through a conductive substance, symbolized by the variable R and measured in the unit of the *Ohm* (Ω).

Electrical sources result in charge carriers entering at lower energy ($-$) and exiting at higher energy ($+$). *Electrical loads* result in charge carriers entering at higher energy ($+$) and exiting at lower energy ($-$).

When an electric current flows through any resistance, the charge carriers comprising that current randomly collide with the atoms of the conductive substance. These collisions result in energy transferred from the charge carriers to the atoms in the form of increased vibration (i.e. heat). Thus, resistance always acts as a *load* because it robs charge carriers of the energy they once had. These collisions limit how much current will flow for a given amount of voltage. A formula called *Ohm's Law* describes the mathematical relationship between applied voltage (V), resistance (R), and resulting current (I):

$$I = \frac{V}{R} \qquad [\text{Amperes}] = \frac{[\text{Volts}]}{[\text{Ohms}]} \qquad [\text{A}] = \frac{[\text{V}]}{[\Omega]}$$

If we know the values of any two variables in this formula, we may calculate the value of the third.

Components called *resistors* are designed to manifest very specific amounts of electric resistance, and are rated both in Ohms as well as Watts of power dissipation ability. *Power* is the rate of energy transfer, symbolized by the variable P and measured in the unit of the *Watt* (W), one Watt being one Joule of energy transferred per second of time.

[1] One Coulomb is defined as a quantity of 6.2415×10^{18} single electric charges (i.e. single protons or electrons).

The amount of power dissipated by any resistance as charge carrier energy is converted into heat is described by a formula called *Joule's Law*:

$$P = IV \qquad \text{[Watts]} = \text{[Amperes]} \times \text{[Volts]} \qquad \text{[W]} = \text{[A]} \times \text{[V]}$$

A resistor's power rating is the maximum amount of power it can safely dissipate, and is a function of surface area because the more surface area a resistor has, the more thermal energy it can shed to its surroundings without overheating. Some high-power resistors are built with mounting tabs in order to firmly fasten to a large metal *heat sink* for even better heat shedding capacity.

The human body may also become an electrical load if connected to an energized source. Threats of bodily injury from electricity come in two forms: (1) electric *shock*, where the body's nervous system is overruled by the external current; and (2) electric *burns*, where flesh itself is charred from heat produced by the current forced through the body's natural resistance. Very little electric current (well less than one Ampere) is sufficient to cause shock.

Electrical hazards may be reduced by placing as much resistance as is practical between your body and the electrical source(s). Avoiding direct contact with electrical conductors, opening up disconnect switches, and wearing insulating protective clothing are all effective means of avoiding electric shock while performing work on electric circuits.

Special *bonding* conductors may be installed in a circuit to force points in that circuit to become electrically common with each other and therefore prevent voltage from manifesting between them. This is done to guarantee negligible voltage between points that your body may span through either accidental or intentional contact.

If a electric current is forced through air by high voltage, the air *ionizes* and becomes very hot. This is a potential danger to anyone working near high-voltage electrical circuits, and the source of danger may be mitigated in the same way as for electric shock: disconnecting known energy sources and bonding conductors to ensure no substantial voltage may exist between them. Furthermore, special heat-resistant "arc flash" clothing may be worn to protect the wearer's skin against burns caused by high-temperature electric arcs.

With enough power, an electric arc may become explosive. The so-called *arc blast* is capable of severe bodily harm, and the only defense is to maintain sufficient distance from the blast.

Chapter 4

Full Tutorial

4.1 Basic concept review

The study of electricity is at root the study of energy transfer via electric charges. *Energy*, as we have seen in previous modules, is *that which sets matter into motion*. It can neither be created nor destroyed, but may be transformed from one form into another. Electric charge carriers, whether they be electrons, protons, or ionized atoms, experience a force under the influence of an electric field similar to how objects with mass experience a force when exposed to a gravitational field. Like masses in a gravitational field, energy is invested in electric charges when moved against the force of the electric field, and energy is returned from those charges when moved by the force of the electric field.

Conductors are materials possessing mobile charge carriers, which allow those charges to be easily transported from one location to another. Metals are characteristically good conductors of electric charges, while substances such as glass, air, pure water, most oils, and most plastics are not. Materials with few or no mobile charge carriers are called *insulators*.

Voltage is defined as the difference in energy possessed by electric charge carriers between two different locations. Voltage is measured in the unit of the *Volt*, which is defined as one Joule[1] of energy per Coulomb[2] of electric charge. In an algebraic formula, voltage is symbolized by the variable V or E, while its unit of measurement (Volt) is always symbolized by the letter V. Since voltage is fundamentally a *differential* measurement, there is no such thing as voltage at a single point anywhere in the universe. Any rational expression of voltage must reference *two* locations, much the same as *distance* is a relative quantity which must always be specified between two points.

Current is defined as the rate of net charge carrier flow past a specific point through an electrical conductor. At any temperature above absolute zero, electric charge carriers inside any conductor will be found moving in random directions and at random velocities, but such random motion does

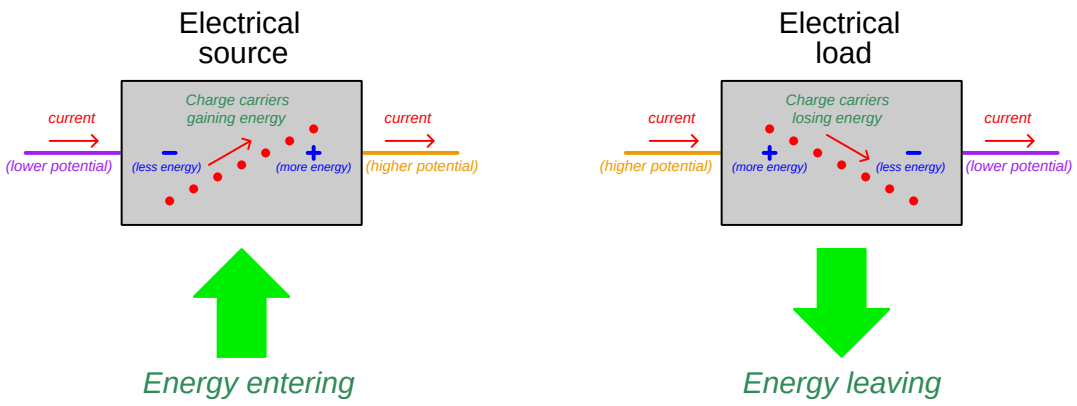
[1] One Joule is defined as the amount of work done moving an object one meter's distance using a force of one Newton.

[2] One Coulomb is defined as a quantity of 6.2415×10^{18} single electric charges (i.e. single protons or electrons).

not constitute a current, any more than the random motion of individual air molecules in a room constitute a wind. An electric current, analogous to wind, is a net movement of charge carriers in a particular direction. Current is measured in the unit of the *Ampere* (often abbreviated *Amp*), which is defined as one Coulomb of electric charge passing by per second of time. In an algebraic formula, current is symbolized by the variable I, while its unit of measurement (Ampere) is symbolized by the letter A.

Resistance is defined as an opposition to electric current resulting in energy being removed from the circuit, and it is measured in the unit of the *Ohm* which is defined as that amount of resistance resulting in one Volt potential difference per Ampere of electric current. In an algebraic formula, resistance is symbolized by the variable R, while its unit of measurement (Ohm) is symbolized by the capital Greek letter Omega (Ω).

An electrical *source* is any device imparting energy to charge carriers flowing through it. An electrical *load* is any device extracting energy from charge carriers flowing through it. A general comparison between sources and loads is shown in the following illustration:



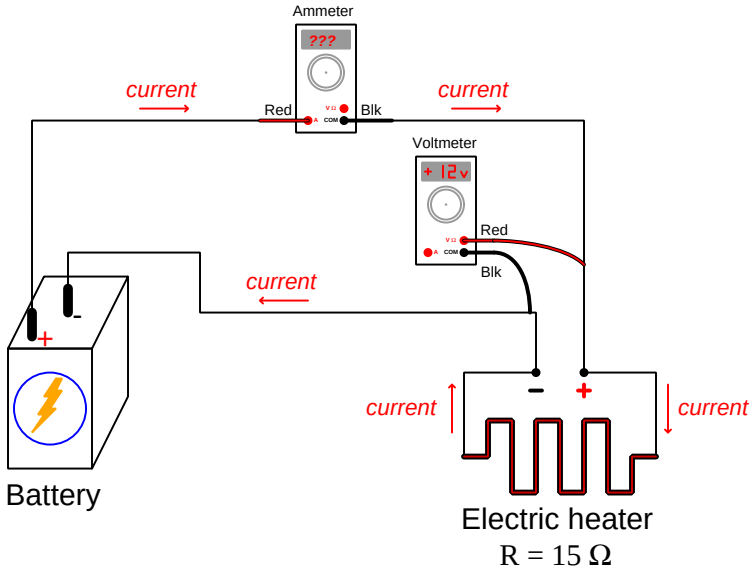
Following the "conventional" notation for electric charge motion in circuits, the + and − symbols used to denote voltage across the two terminals of any electrical component mark the relative energy levels of those charge carriers before and after they pass through. Through a source, where charge carriers gain energy passing through, current enters the lower-energy terminal (−) and exit the higher-energy terminal (+). Through a load, where charge carriers lose energy passing through, current enters the higher-energy terminal (+) and exit the lower-energy terminal (−). The total amount of energy transferred by any source or load is equal to amount of energy gained or lost by each Coulomb's worth of charge (i.e. the voltage across the device), multiplied by the number of Coulombs of charge that passed through.

4.2 Ohm's Law

One of the most fundamental equations describing electricity is *Ohm's Law*, published by Georg Simon Ohm in the year 1827. Ohm's discovery was that the amount of electric current passing through a resistance was directly proportional to the voltage across that resistance[3], and inversely proportional to the resistance for any fixed amount of voltage:

$$I = \frac{V}{R} \qquad [\text{Amperes}] = \frac{[\text{Volts}]}{[\text{Ohms}]} \qquad [\text{A}] = \frac{[\text{V}]}{[\Omega]}$$

We may use Ohm's Law to predict how much electric current will pass through a known resistance of 15 Ohms while powered by a 12 Volt source. Note the connections of the two meters – the ammeter connected in *series* (in-line) with the load to experience the same current, and the voltmeter connected in *parallel* (across) with the load to experience the same voltage:

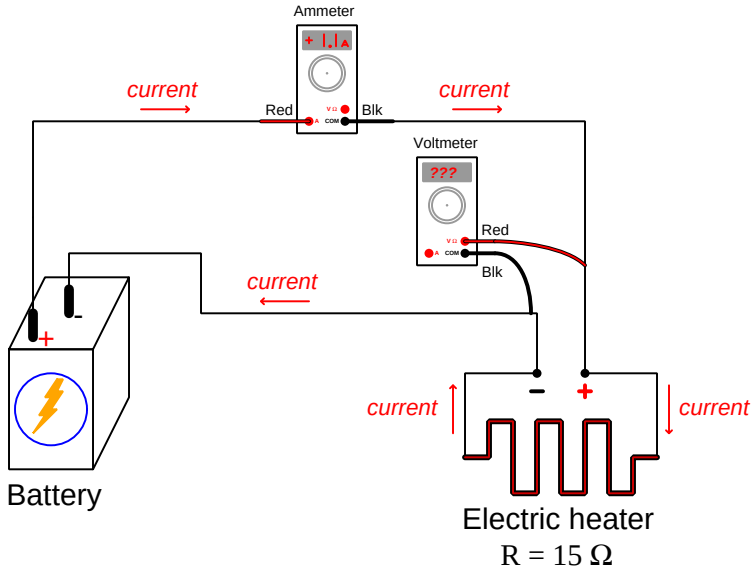


$$I = \frac{V}{R} = \frac{12\ \text{V}}{15\ \Omega} = 0.8\text{A}$$

Using Ohm's Law, we divide the known load voltage of 12 Volts by the known load resistance of 15 Ohms to compute 0.8 Amperes of current through the load. If twice this much voltage were applied to the load, current would double: 24 Volts divided by 15 Ohms equals 1.6 Amperes. If the original voltage were applied to a different heater having twice the resistance, current would decrease by half: 12 Volts divided by 30 Ohms equals 0.4 Amperes.

[3]The theoretical basis for Ohm's Law is the random collision of charge carriers passing through an electrical resistance. The amount of energy lost by each charge carrier from one end of the resistance to the other (i.e. voltage) is directly proportional to the number and intensity of collisions those charge carriers experience while passing through. This, in turn, increases with those charge carriers' drift velocity. The faster the charge carriers move, the more violent the collisions, and therefore the more energy lost by each charge carrier from beginning to end.

Suppose we encounter a different scenario where we know the resistance and current, but not the voltage. Consider a modified version of the same battery-heater circuit:



Ohm's Law is just as useful here, but we must manipulate the Ohm's Law formula to solve for V instead of I. First, we write the Ohm's Law formula in standard form:

$$I = \frac{V}{R}$$

The variable V which we wish to solve for in this formula happens to be in the numerator of a fraction (with R being the denominator). Multiplication of both sides of the formula[4] by R cancels R on the right-hand side and places it on the left where it is multiplied by I.

First, multiplying both sides by R:

$$IR = \left(\frac{V}{R}\right)(R)$$

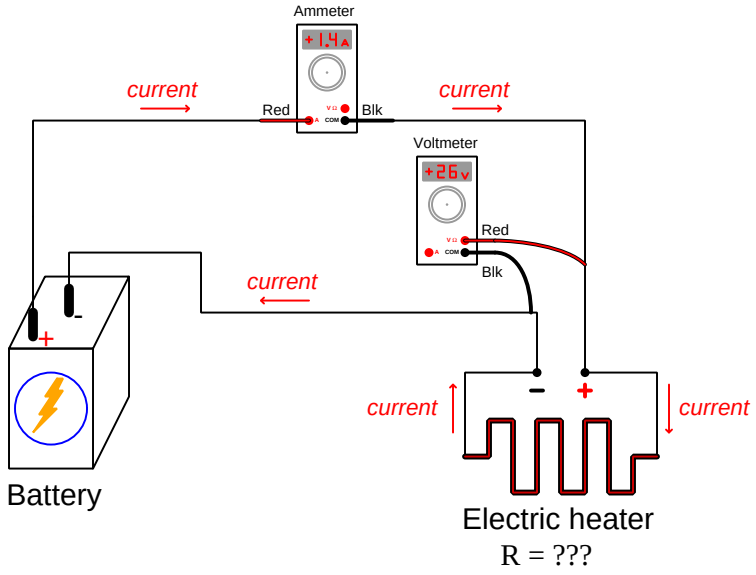
Then, after canceling R on the right-hand side of the equation we have our desired result:

$$IR = V \qquad \text{or} \qquad V = IR$$

$$V = (1.1\text{ A})(15\,\Omega) = 16.5\text{ V}$$

[4]The fundamental rule of algebraic manipulation is that you may apply any arithmetic operation desired to an equation, so long as that same operation is applied to both sides. Since an equation describes an *equality* between two values, those two quantities must still remain equal to each other if we apply the exact same arithmetic operation to both of them.

Likewise, we may also apply Ohm's Law to scenarios were voltage and current are known but resistance is not. Again, consider another battery-heater circuit with different component values:



Our algebraic task now is to manipulate Ohm's Law to solve for R. Beginning with the original form of Ohm's Law, we multiply both sides of that formula by R to cancel out R from the right-hand side. Next, we divide both sides by I to cancel out I on the left-hand side:

$$I = \frac{V}{R}$$

$$IR = \left(\frac{V}{R}\right)(R)$$

$$IR = V$$

$$\frac{IR}{I} = \frac{V}{I}$$

$$R = \frac{V}{I}$$

Plugging in our given values from the problem to solve for this heater's resistance:

$$R = \frac{26 \text{ V}}{1.4 \text{ A}} = 18.57\,\Omega$$

4.3 Resistors

An electric heater is just a special case of a more general form of electrical component called a *resistor*. The purpose of a resistor is to provide a set amount of *resistance* (i.e. opposition, or hindrance) to the passage of electric current, sometimes for the express purpose of dissipating heat (as in the case of the heater) but also for other purposes. Resistors enjoy a great variety of practical applications, including the intentional generation of heat, shedding of energy from a circuit, measurement of current values, division of voltage values, and others. Resistors are constructed of materials selected to have a certain amount of resistivity (e.g. carbon, various metal alloys) and like many other electrical and electronic components are often coated with an insulating material to avoid unintentional contact between the internal material and any other conductors of electricity.

Resistors are represented in schematic form as zig-zag lines (NEMA diagram standard) or as rectangles (IEC diagram standard), their connection points designated by short lines at either end:

An example of a resistor with printed values appears here next to my fingertip, in this case a 470 Ohm resistor with a ± 5% tolerance, which means the resistor's actual value may lie anywhere in the range of 446.5 Ohms to 493.5 Ohms:

Error is typically calculated as a ratio of the difference between the actual (measured or predicted) value and the ideal (theoretical) value divided by that same ideal value:

$$\text{Error (percent)} = \frac{\text{Actual} - \text{Theoretical}}{\text{Theoretical}} \times 100\%$$

The reason for specifying a tolerance for any component such as a resistor is the fact that they are mass-produced items, and variances in manufacturing inevitably result in slight deviations from ideal value. Mass-producing a highly precise component is possible, but also costly because of the time and care which must be taken to ensure close fidelity to the ideal value for each component. In the case of resistors, general-purpose tolerances of ± 5% or worse are usually the domain of *carbon composition* construction, where the resistive element is formed of carbon. *Precision* resistors typically exhibit tolerances of ± 1% or better, and are usually manufactured from metal film or wire. Resistors intended for heat dissipation (such as the heater previously referenced) are almost always made from metal wire.

Another popular style of resistor uses colored bands[5] to represent resistance values and tolerances. An example of this resistor style appears in the following photograph:

Four-band resistors are the most popular of the banded style, with the first and second bands representing significant digits, the third band representing a power-of-ten multiplier, and the fourth band representing tolerance.

Band color	**First digit value**	**Second digit value**	**Multiplier**	**Tolerance**
Black	0	0	10^0	
Brown	1	1	10^1	
Red	2	2	10^2	
Orange	3	3	10^3	
Yellow	4	4	10^4	
Green	5	5	10^5	
Blue	6	6	10^6	
Violet	7	7	10^7	
Grey	8	8	10^8	
White	9	9	10^9	
Gold			10^{-1}	$\pm$ 5%
Silver			10^{-2}	$\pm$ 10%
None				$\pm$ 20%

The "loose" tolerances of $\pm$ 5%, $\pm$ 10%, and $\pm$ 20% codified by these colors makes the color code well-suited for carbon composition resistors. Precision resistors made of metal wire or film typically have character markings rather than colors to specify nominal resistance and tolerance.

Applying this color code to the resistor shown above, we see that yellow = 4, violet = 7, red = 2, and silver = $\pm$ 10%. Therefore, this resistor's value is 47 $\times$ 10^2 Ohms (i.e. 4700 Ω) plus or minus 10%, which means it could be as low as 4230 Ω or as high as 5170 Ω.

[5] A useful mnemonic for associating these colors with decimal digits 0 through 9 and the percentages 5-10-20% is as follows: *"Better Be Right Or Your Great Big Venture Goes Wrong. Get Started Now."*.

4.4 Joule's Law

Resistors of all types, like any electrical or electronic component possessing resistance, exhibit power dissipation when electric current travels through. The voltage dropped by a load represents the amount of energy lost by each Coulomb of charge passing through that load, that energy lost by the moving charge carriers transferred to some other form, typically heat. *Power* is defined as the rate of energy transfer, in this case the transfer of energy from electric charge carriers to heat as those charge carriers pass through the device. Power is symbolized by the variable P, while its unit of measurement (Watt) is symbolized by the letter W, a Watt being defined as one Joule of energy transferred per second of time.

Recall that the definition of the Volt was one Joule of energy per Coulomb of electric charge, and that the definition of the Ampere was one Coulomb of electric charge motion per second of time. If we write each of these units as fractions and multiply them together[6], we see that the unit of Coulombs cancels, leaving Joules per second:

$$\left(\frac{[\text{Joules}]}{[\text{Coulomb}]}\right)\left(\frac{[\text{Coulombs}]}{[\text{second}]}\right) = \frac{[\text{Joules}]}{[\text{second}]}$$

What this "dimensional analysis" shows us is that Volts multiplied by Amperes equals Watts. Expressed using variables instead of units (V for voltage, I for current, and P for power), we have a formula relating power to voltage and current:

$$VI = P \qquad \text{or} \qquad P = IV$$

This is commonly referred to as *Joule's Law*, named after James Prescott Joule who published his discovery in the year 1841. Joule's research involved the amount of heat energy liberated by a current-carrying metal wire, the resistance of that wire resulting in electric charge carriers losing some of their energy as they passed from end to end. The formula describing this power loss in terms of current and resistance is as follows:

$$P = I^2R$$

At first this may seem quite unrelated to the formula $P = IV$, but if we recall Ohm's Law relating voltage to current and resistance ($V = IR$), we see that we may derive the formula $P = I^2R$ by algebraic substitution[7]:

$$P = IV \qquad \text{and} \qquad V = IR$$

$$P = I(IR)$$

$$P = I^2R$$

[6] This technique of writing units of measurement as though they were variables in mathematical expressions, and then seeing which units cancel out, is called *dimensional analysis*, and it is an extremely useful technique in the physical sciences.

[7] Substitution is a very powerful algebraic technique, used to combine equations in order to form new equations. In this application we interpret Ohm's Law ($V = IR$) such that IR becomes a definition or a *substitute* for V. This means we may replace V with IR anywhere we see V in the Joule's Law formula.

This same algebraic technique may be used to derive a formula predicting power dissipation given voltage and resistance, this time using a different form of Ohm's Law for the substitution[8]:

$$P = IV \qquad \text{and} \qquad I = \frac{V}{R}$$

$$P = \left(\frac{V}{R}\right) V$$

$$P = \frac{V^2}{R}$$

Armed with these three forms of Joule's Law, we may return to the previous electric heater circuits and calculate heater power for each scenario:

First scenario: a voltage of 12 Volts and a heater resistance of 15 Ohms

$$P = \frac{V^2}{R} = \frac{(12 \text{ V})^2}{15\,\Omega} = 9.6 \text{ W}$$

Second scenario: a current of 1.1 Amperes and a heater resistance of 15 Ohms

$$P = I^2 R = (1.1 \text{ A})^2 (15\,\Omega) = 18.15 \text{ W}$$

Third scenario: a voltage of 26 Volts and a current of 1.4 Amperes

$$P = IV = (1.4 \text{ A})(26 \text{ V}) = 36.4 \text{ W}$$

[8] In this case we substitute $\frac{V}{R}$ in place of I in the formula $P = IV$, since the Ohm's Law formula $I = \frac{V}{R}$ tells us I and $\frac{V}{R}$ are identical to one another.

4.5 Resistor power ratings

In addition to being rated according to their resistance, resistors are also rated for the maximum amount of power they may safely dissipate without overheating. Of course, power dissipations less than this maximum rating are perfectly acceptable, but continuous[9] power exceeding the resistor's maximum rating will cause it to overheat and possibly be destroyed. This rating (in Watts) is generally proportional to the resistor's physical size, the reason for this rooted in the physics of heat transfer: in order to avoid temperatures high enough to damage the resistor, the resistor must possess enough surface area to effectively radiate and convect thermal energy to the surrounding environment. Therefore, higher-power resistors must have larger surface areas to effectively shed their heat.

Carbon-composition resistors do not use color coding or printed markings to specify power dissipation. Instead, the end-user is expected to recognize the resistor's power rating by the length of the resistor's body[10]. Typical body lengths for carbon composition resistors are as follows: 0.145 inches long for $\frac{1}{8}$ watt, 0.25 inches long for $\frac{1}{4}$ watt, 0.375 inches long for $\frac{1}{2}$ watt, 0.562 inches long for 1 watt, and 0.688 inches long for 2 watts.

High-power resistors (greater than 2 Watts rated) typically bear printed labels showing their various ratings, such as this 0.3 Ohm power resistor with a tolerance of $\pm$ 1% and a power rating of 30 Watts:

Note the mounting tabs on this particular resistor, intended to secure it to a flat metal surface which will act as a *heat sink* to draw thermal energy away from the resistor and into the surrounding air. This holds an important lesson for anyone designing a high-power electric circuit – namely, that electrical devices dissipating substantial amounts of power may require special installations in order to deliver on their promised power ratings. This particular 30-Watt resistor will only be able to safely dissipate 30 continuous Watts of power when attached to a sufficient heat sink, and not in isolation. Another factor in achieving rated power dissipation levels are ambient conditions such as air temperature, and in some cases even the mounting position (to ensure natural convection of air as the device's temperature rises).

[9] It is possible to safely over-power a resistor, but only for limited amounts of time. The deciding factors are the thermal mass of the resistor and its material(s) of construction, which give it some transient heat capacity for absorbing bursts of energy without exceeding its maximum safe operating temperature.

[10] This would be the length of the insulated package containing the resistive carbon element. The length of the resistor's wire leads is irrelevant to power rating.

4.6 Electrical safety

A subject of extreme importance to all electrical practitioners is electrical *safety*, with Ohm's and Joule's Laws being excellent starting points for a discussion on that topic. Here we examine the human body as an electrical *load*: electrical charge carriers passing through the resistance of the body from an external source relinquish some of their energy in the same way charge carriers lose energy passing through any other resistance. The rate of energy dissipation (i.e. *power*) through the body's resistance is predicted by Joule's Law, $P = I^2R$. The total amount of energy delivered to a body by an electric current is a function of that power dissipation rate multiplied by the amount of time current flowed[11].

Electrical energy poses two distinctly different threats to any living body: the first threat is forced activation of the body's nervous system by electric current passing through nerve cells, and the second threat is burning from the thermal power dissipated in flesh and bone. Both threats are direct functions of the amount of energy delivered to the body, with the first effect (called *electric shock*) beginning at lower levels of current than the second effect.

Electric shock – not to be confused with the general condition of *circulatory shock* characterized by reduced blood circulation in the body – first manifests as a tingling sensation, then as pain with greater electric current intensity. At a certain threshold value, the current will be sufficient to override voluntary muscle control. At higher levels of current, breathing will become difficult or may cease due to paralysis of the diaphragm muscles within the chest. At even higher levels of current, the heart (itself a muscle of the body) will either fall into an arrhythmic beat pattern or cease beating altogether. *All of these effects will occur at current levels significantly less than one Ampere.*

Some of the most detailed data we possess on the effects of electric shock come from the research of University of California Berkeley Professor Charles Dalziel, who in the year 1961 published a report entitled "Deleterious Effects of Electric Shock". Dalziel performed electric shock experiments on human volunteers, subjecting both males and females to varying degrees of electric current, both direct (DC) and alternating (AC), for the purpose of determining thresholds of sensation, pain, and loss of muscular control.

Table II of Dalziel's' report (shown on page 24) is partially[12] reproduced in the following table. The headings "M" and "F" refer to male and female subjects, respectively. Tests conducted using direct current[13] are labeled "DC" while tests conducted using alternating current[14] are labeled with

[11] Putting units of measurement to this concept, the amount of energy in *Joules* is equal to average power in *Joules per second* multiplied by time in *seconds*, with the unit of "seconds" canceling out. For brief exposures to electricity, such as lightning strikes, the most important measurement with regard to safety is the total energy delivered to the body. The same is true for deliberate applications of electricity to the body, for example cardiac defibrillators, where the machine's setting is calibrated in Joules of energy delivered per impulse.

[12] The original Table II contained a column of data representing thresholds for women at 10 kHz alternating current, but these were estimations and not actual data. Extrapolating from the other data points where women tended to exhibit the same effects as men at approximately $\frac{2}{3}$ the current, Dalziel writes, *"Tests on women were not made on frequencies other than 60 cycles, but if it is assumed that the response for women would be similar, values for women can be estimated at two-thirds of the corresponding value for men."* Readers should note that I have taken editorial liberties with the description of bodily effects, for no reason other than formatting.

[13] Direct current, or DC, refers to a continuous flow of electric charge carriers in one direction only.

[14] Alternating current, or AC, refers to an electric current that periodically switches direction, the period of that

frequency values expressed in the unit of Hertz (Hz) or cycles per second. All data points are expressed in *milliAmperes* (mA), one milliAmpere being $\frac{1}{1000}$ of an Ampere:

Bodily effect	**DC, M**	**DC, F**	**60 Hz, M**	**60 Hz, F**	**10 kHz, M**
Slight sensation felt on hand	1 mA	0.6 mA	0.4 mA	0.3 mA	7 mA
Median perception threshold	5.2 mA	3.5 mA	1.1 mA	0.7 mA	12 mA
Shock, with no loss of muscular control	9 mA	6 mA	1.8 mA	1.2 mA	17 mA
Pain, with 50% of subjects losing muscular control	62 mA	41 mA	9 mA	6 mA	55 mA
Pain, labored breathing, 99.5% of subjects losing muscular control	90 mA	60 mA	23 mA	15 mA	94 mA

For rather obvious reasons no human tests were conducted to the point of cardiac fibrillation. Dalziel's report does, however, provide data collected on a variety of animals (pigs, sheep, calves, dogs, cats, guinea pigs, rabbits) which were anesthetized and then administered large amounts of electric current until their hearts malfunctioned. From this admittedly limited data, Dalziel extrapolated the values to obtain 500 mA ($\frac{1}{2}$ Ampere) of direct current and 100 mA ($\frac{1}{10}$ Ampere) of alternating current as thresholds for "possible" human heart fibrillation following a three-second electric shock.

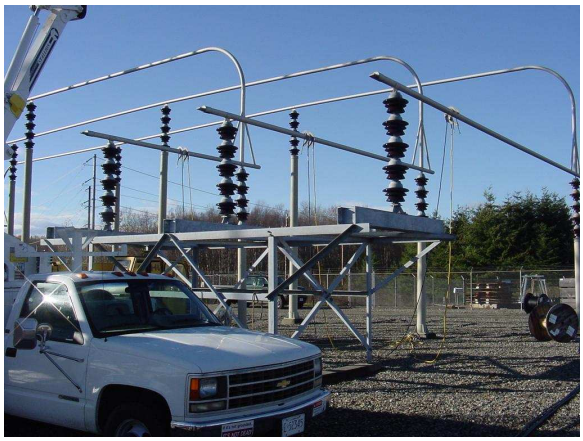
All gruesome details aside, the lesson to be learned here is very plain: *very little electric current is necessary to induce painful and even life-threatening effects on the human body!* These danger thresholds are all substantially less than the amount of current most power conductors are rated to handle, and less than the ratings of fuses and circuit breakers designed to protect conductors from overheating.

switching measured in cycles per second or Hertz. In North America, the standard AC grid power frequency is 60 cycles per second, or 60 Hz. The second AC frequency used in Dalziel's experiments is 10 kHz, which is 10 *kilo*-Hertz, or 10000 cycles per second.

The first line of defense against electrical shock is to place as much electrical resistance between your body and the circuit's conductors as is practical, as a means of impeding the flow of electric current to and through your body. Turning "off" any disconnecting switches between the circuit and its energy source is a simple means to do this, essentially inserting an air gap between the circuit and its normal source of power. This allows all points within the circuit to achieve an equipotential state, which may then be made equipotential to your body by connection to Earth ground (where you are standing). If there is no voltage present (i.e. no difference in the potential energy levels of electric charge carriers at different points), then there should be no possibility of dissipating electrical energy into your body.

Once all electrical energy sources have been disconnected from the circuit you intend to work on, an additional safety measure is to *bond* that circuit's power conductors to Earth ground. This step forces the power conductors to be *electrically common* with Earth, and therefore guarantees a condition of equipotentiality with the Earth. Line workers who install and maintain electric power line conductors do this as a standard part of their operating procedure: attaching temporary grounding cables between the power conductors and Earth after opening all disconnect switches normally connecting those lines to electrical sources. This extra step of bonding the power conductors ensures no stray sources[15] of electrical energy may pose a threat.

The following photograph shows a work site at a 230 kV (230,000 Volt!) electrical substation, where electricians are busy performing maintenance work on a high-voltage component. In addition to opening large switches (called *disconnects*) to isolate this new component from any source of voltage, they have *bonded* the high-voltage conductors to each other and to Earth ground by means of temporary wire cables. The cables on this work site happen to be yellow in color, and may be seen hanging down from C-shaped clamps attached to three horizontal metal tubes called *busbars* which serve as conductors for electricity in this substation:



[15] Examples include electrostatic or magnetic "coupling" with adjacent energized power lines, nearby lightning strikes, etc.

Obviously, such measures are quite necessary on high-voltage systems such as substation busbars – there simply is no safe way to work on energized conductors at this voltage level. However, in lower-voltage circuits it is often necessary to take electrical measurements and make certain adjustments while the circuit is in an energized state. If the circuit in question cannot be "killed" by disconnection of its power source and therefore must be worked on "live", the next best protective measure is to layer insulating material on your body where contact might otherwise be made to permit an electric current through it. This means wearing insulating gloves and shoes, at minimum. The principle behind this technique is Ohm's Law: for any given amount of voltage (V), current (I) will be inversely proportional to the total resistance (R) of the circuit pathway. Layering electrically insulating material over your body's possible points of contact (e.g. hands, feet) increases the total resistance of the circuit pathway, and therefore minimizes the amount of current that may flow in the event of physical contact between two points where a substantial voltage exists.

Lastly, in order to minimize the risk of electric current passing through one's chest (where the heart and diaphragm muscles are located), a wise habit when working on energized circuits is to place one hand in a pocket so that only one hand is in use. This will not only prevent arm-to-arm passage of electric current, but it also minimizes the number of potential points of contact with bare skin. Electrical practitioners commonly refer to this as the *One-Hand Rule*. Ideally, the best hand to place in a pocket is the left hand, because this is the side of the body where the heart is most vulnerable.

It is worth noting that the danger from electric shock is best quantified in terms of current, not voltage, since it is electric current that activates nerve cells. The amount of current passing through a victim's body from an applied voltage is a function of Ohm's Law ($I = \frac{V}{R}$), and since resistance (R) varies greatly with skin dryness and layering provided by shoes and clothing, it is difficult to predict how much voltage poses a shock hazard. A generally accepted threshold of danger is 30 Volts, but this assumes direct contact with dry skin. Moist skin, perspiration, cuts or punctures, and other factors reducing body resistance may greatly reduce the voltage threshold for shock hazard! Another factor is the general health of the victim prior to receiving the electric shock. A preexisting cardiac condition will likely predispose that individual to harm resulting from an electric shock.

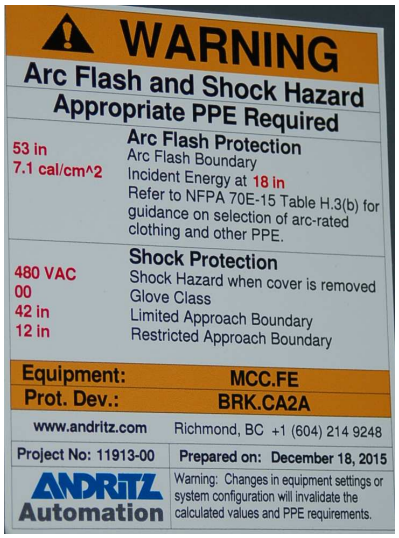
Burns produced by electricity passing through the body may manifest on the skin, at the point of contact with an electrical conductor (such as a wire), or in severe cases may extend to internal organs. Comparing internal flesh with skin, dry human skin tends to exhibit much greater levels of electrical resistance than the internal organs which are wet. This is why electricity causes skin-surface burns before causing internal organ burns: for any given amount of electric current passing through different resistances, power dissipated by that current will be greatest wherever the electrical resistance is greatest. Mathematically stated, P is maximized where R is greatest, given any value of (I), in accordance with Joule's Law (I^2R).

Another mechanism of electrically-caused burns is *arc flash*: the heating of air by the passage of electric current through it (rather than through the body). Under normal conditions air is an extremely good insulator of electricity, with no free charge carriers available to sustain an electric current. However, when sufficient voltage causes the electrons in air molecules to separate from their respective atoms, the negatively-charged electrons and positively-charged ions constitute charge carriers, and will form an electric current called either a *spark* or an *arc*. This current heats the air molecules by dissipating power as described by Joule's Law ($P = I^2R$), with I being the magnitude of current traveling through the ionized air and R being the resistance of the arc path.

The amount of resistance exhibited by a high-temperature arc is surprisingly low, typically less than one Ohm across the entire length of the arc. With such low resistance, Ohm's Law predicts relatively high current values for even modest voltages ($I = \frac{V}{R}$), resulting in high power levels. Even if the amount of energy released by each charge carrier moving through the arc is small, the fact that a great many charge carriers are moving through the arc each second means that the total amount of energy dissipated may be phenomenally large. This is why arcs forming in high-voltage electric power systems may reach temperatures of tens of thousands of degrees[16]!

In the United States of America, a widely respected standard document for electrical hazards and protection is the National Fire Protection Association (NFPA) standard 70E. This document rates both electric shock and arc flash hazards for electric power circuits based on voltage and current capabilities, as well as specifies best practices for protection against those hazards.

An example of NFPA 70E standards applied to an industrial installation is the following pair of photographs showing warning labels affixed to metal-clad electrical switchgear (i.e. metal cabinets housing large circuit breakers). Each label cites both arc flash and electric shock hazards, including *boundary* distances within which greater hazards exist:



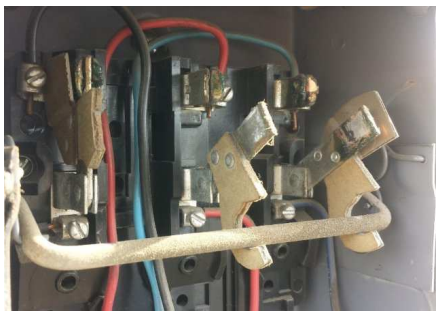
The first line of defense against arc flash is the same as for electric shock: *de-energize the circuit* so there will be no electrical energy present to harm you. The procedure for de-energizing includes placing a warning *tag* as well as a secure *lock* on any main disconnecting switches or circuit breakers to ensure power does not get accidently applied to the circuit while people are in harm's way. This is referred to in industry as *lock-out, tag-out*, or *LOTO*.

[16]The NFPA 70E electrical safety standard (Informative Annex K) cites temperatures as high as 35,000 degrees Fahrenheit in arc flash events, and states that such events are lethal at distances up to 10 feet (3.05 meters). It is worth noting that electric arc temperatures are limited only by the rate of power dissipated in the arc. Unlike chemically-driven combustion events, where temperature is limited by the rate at which the various chemical reactants are able to combine, no such limiting factor exists with electric arcs: the more power dissipated in the arc, the hotter it will become. These temperatures involved with electric power faults can be so high that they *vaporize* the metal wires!

Generally accepted lock-out, tag-out procedures for electrical equipment include (but are not limited to) the following steps:

1. Turn equipment off using regular on/off switch to interrupt load current
2. Open all disconnect switches and/or circuit breakers feeding electrical power to the equipment
3. Visually confirm (if possible) that *all* poles of the disconnecting switch(es) are open
4. Attempt to re-start equipment as your first confirmation that power is indeed shut off
5. Attach locks and tags to prevent disconnecting switches from being re-closed; if no lockable disconnect means exists, you must open and tag *two* or more redundant disconnects!
6. Confirm proper operation of voltage meter against a known source
7. Test for dangerous voltage between all relevant conductors, especially those you could bodily contact, including between pairs of phase conductors in a polyphase system as well as between each phase conductor and earth ground
8. Confirm (again) proper operation of voltage meter against a known source

Such a lengthy procedure may seem paranoid, but there is good reason for all these steps. Remember that *all safety standards and procedures are written in blood:* in other words, every one of them exists because either someone got hurt or came close to getting hurt by not taking appropriate precautions. One example of the latter is the following photograph generously shared by Jim Lyon[17] who discovered a failed three-phase disconnect switch during a routine LOTO procedure:



As you can see in this photograph, one of the linkages between the disconnecting switch pole and the actuating lever has broken, allowing one phase to remain closed while the other two opened as they should. Such a failure would neither be apparent to the operator of that switch nor by anyone's external inspection of it, but would be revealed by proper voltage testing (phase-to-ground) on that faulted phase conductor. Had Mr. Lyon simply trusted the switch handle's "off" position as proof of a zero-energy state, he could have been electrocuted touching the un-opened conductor "downstream" of the switch.

[17] Mr. Lyon granted me permission to include his safety-related photographs in my open-source writings during an exchange on the professional social-media website `LinkedIn`.

Another important note with regard to electrical safety and LOTO is the proper function of your test equipment. Multimeters and test leads are not just tools for precision measurement, but are life-saving indicators of dangerous voltage. I have personally witnessed multiple instances of failed multimeter test leads, where one or more leads failed open such that the meter could not reliably register the presence of voltage. This is why good LOTO procedure always includes verification of the meter both *before and after* checking for dangerous voltages at the system conductors.

In cases where de-energization is not possible or not practical, special "arc-flash rated" clothing may be worn to protect your skin against the high temperatures of arc flash should an arc flash occur. Arc flash suits cover all skin surfaces, and are rated according to the number of calories[18] of heat the fabric may sustain without disintegrating. The following photograph shows a pair of arc flash suits hanging on a wall ready for electricians to use while working on circuit breakers at an electric power generating station:

The blue-colored hood covers the worker's head and neck, while the grey-colored jumpsuit covers the rest of the worker's body.

[18] A *calorie* is simply another unit of energy measurement. The unit-conversion equivalence is 4.187 Joules per calorie.

The hazards of electrical arcs are not limited to bodily burns. Given sufficient arc power, the explosive expansion of hot air and the shrapnel created by disintegrating hardware represents its own unique hazard, known as *arc blast*. As an *electrically-driven* explosion[19], arc blast is limited only by the available power of the fault, and can in fact be more violent than a chemical explosion. No suit can ensure safety against arc blast, and so the only reasonable precaution is maintaining a safe distance beyond the blast radius.

[19]The concussive effects of an arc blast originate from the rapid expansion of air and vaporized metal, producing intense sound waves and blast pressures. Extremely bright light, as well as high temperatures caused by convection of super-heated air and by radiation of infrared light from the arc are capable of creating third-degree burns on unprotected skin.

Chapter 5

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

5.1 Georg Simon Ohm in his own words

Georg Simon Ohm wrote a treatise entitled *The Galvanic Circuit Investigated Mathematically* in 1827, in which we find the first formulation of Ohm's Law, as shown here[1]:

> *. . . The magnitude of the current in any homogeneous portion of the circuit is equal to the quotient of the difference between the electrical forces present at the extremities of such portion divided by its reduced length.*
>
> This expression for the forces of the [page 49]
>
> current will continue to be subsequently employed.
>
> The second of the former equations passes, by adopted change, into $S = \frac{A}{L}$, which is generally true, and already reveals the equality of the force of the current at all parts of the circuit; in words it may be expressed thus: –
>
> *The force of the current in a galvanic circuit is directly as the sum of all the tensions, and inversely as the entire reduced length of the circuit*, bearing in mind that at present by reduced length is understood the sum of all the quotients obtained by dividing the actual lengths corresponding to the homogeneous parts by the product of the corresponding conductivities and sections. [page 50]

Throughout Ohm's treatise, he uses S to represent current, A to represent voltage, and L to represent length of metal wire (which was the only significant resistance in his crude experimental circuits). Toward the end of this text he re-states his Law as it applies to total circuit voltage and resistance:

> . . . we then obtain the extremely simple equation $S = \frac{A}{L}$, where L denotes the entire resistance of the circuit, and A the sum of all its electromotive forces. [page 198]

[1] Ohm's treatise was written in German, of course, and the text cited here is William Francis' translation, written in 1891. This particular translation is augmented by numerous editorial comments from Thomas D. Lockwood, M.I.E.E. which are instructive as to later citation and application of Ohm's work by other researchers.

5.2 Early descriptions of fundamental electrical quantities

What follows is a several pages' worth of John Ambrose Fleming's text *Electric Lamps and Electric Lighting* published in 1894. This text is noteworthy in the clear way it introduces the reader to the fundamental concepts of voltage, current, resistance, magnetic fields, Ohm's Law, Joule's Law, mechanical work, and power. You will also note some archaic terms used in Fleming's presentation, which were no doubt in common use at that time in London, England.

Fleming's book on electric lighting consisted of transcriptions of four lectures he delivered at the Royal Institution in England, which explains the inclusion of statements in the text describing certain actions before performed for the reader, as though the reader were a member of the audience within Fleming's lecture hall observing an experiment in progress.

> It will be necessary to open the whole of our discussion by some simple illustrations of the meaning of fundamental terms. Every science as well as every art has its necessary technical terms, and even if these words at first sound strangely, they are not therefore necessarily difficult to understand. We are all familiar with the fact that electric illumination depends upon the utilisation of something which we call the electric current. Little by little scientific research may open up a pathway towards a fuller understanding of the true nature of an electric current, but at the present moment all that we are able to say of it is, that we know what it can do, how it is produced, and the manner in which it can properly be measured. Two principal facts connected with it are, that when a conductor, such as a metallic wire or a carbon filament, or any other material which is capable of being employed as a conductor, is traversed by an electric current, heat is generated in the conductor, and the space round the conductor becomes capable of influencing a magnetic needle. These facts can be simply [page 6]

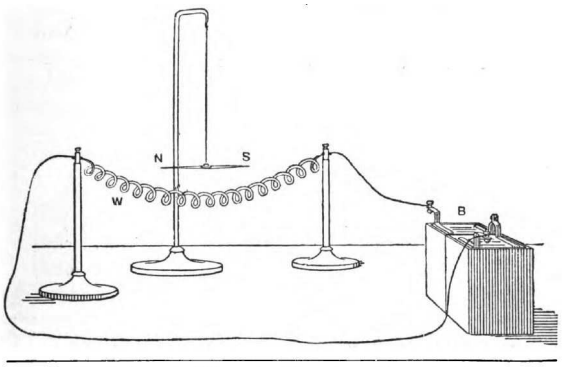


FIG. 2.—An iron wire **W** is rendered incandescent by an electric current sent through it from a battery **B**. The magnetic needle **N S** held near it sets itself across the wire.

> illustrated by passing an electric current through an iron wire (see Fig. 2). You will notice that as the current is gradually increased the iron wire is brought up from a condition in which it is only slightly warm to one in which it becomes visibly red hot in the dark, and finally brilliantly incandescent. At the same time if we explore the region round about the wire with a suspended compass needle, we find that at every point in

the neighbourhood of the wire the magnetic needle places itself, or tries to place itself, in a position perpendicular to the wire. This fact, of capital importance, was discovered by H. C. Oersted in 1820, and in the Latin memoir in which he describes his epoch-making discovery he employs the following striking phrase to express the behaviour of a magnetic needle to the wire conveying the current. He says, "The electric conflict performs circles round the wire." That state which he called the electric conflict round the wire, we now in more modern language call the *magnetic field* embracing the conductor. We shall return in a later lecture to this last fact. [page 7]

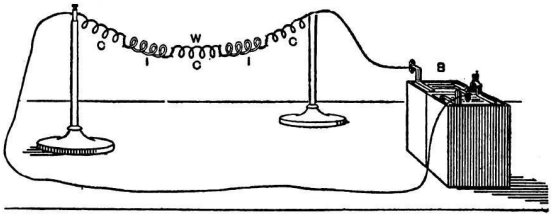


FIG. 3.—A chain W composed of alternate spirals of copper C and iron I is traversed by an electric current sent through it by a battery B. The iron links become red hot, the copper links only slightly warm.

Meanwhile I wish at present to fasten your attention on the heating qualities of an electric current, and the laws of that heat production and radiation. The same electric current produces heat at very different rates in different conductors, and the quality of a body in virtue of which the electric current produces heat in passing through it is called its electric resistance. If the same electric current is passed through conducting wires of similar dimensions, but of different materials, it produces in them different quantities of heat in the same time. Before you (Fig. 3) is a chain composed of spirals of iron and copper wire. These wires are each of the same length and of the same diameter. Sending through this compound chain an electric current, we notice that the iron wire links are very soon brought up to a bright red heat, whilst the copper links, though slightly warm, are not visibly hot. We have, therefore, before us an illustration of the fact that a current heats the conductor, but that each conductor has a specific quality called its electrical resistance, in virtue of which the same strength of current produces heat in it at a rate depending on the nature of the material. Other things being equal, the bodies which are most heated are said to have the highest resistance. [page 8]

It is now necessary to notice the units in which these two quantities, namely, electric current and electric resistance, are measured. For the sake of distinction, units of electric quantities are named after distinguished men. We follow a similar custom in some respects in common life, as when we speak of a "Gladstone" bag or a "Hansom" cab, and abbreviate these terms into a gladstone and a hansom. Primarily the distinctive words here used are the names of persons, but by application and abbreviation they become the names of things. An electric current is measured in terms of a unit current which is called an *ampere*, and electrical resistance is measured in terms of a unit which is called an *ohm*, these being respectively named after two great investigators, Andre Marie Ampere and Georg Simon Ohm. In order to understand the mode in which an electric current can thus be defined, we must direct attention to another property of

electric currents, namely, their power of decomposing solutions of metallic salts. You are all familiar with the substance which is called sugar of lead, or, in chemical language, acetate of lead. Placing in a small glass trough a solution of acetate of lead and two lead plates (see Fig. 4), I place the cell in the electric lantern and project the image upon the screen. If an electric current is passed through the solution from one lead plate to the other it decomposes [page 9]

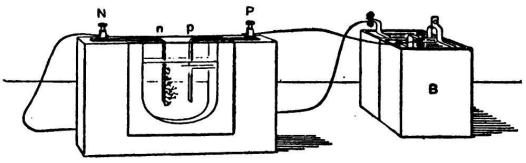


FIG. 4.—Glass lantern trough containing two lead plates n p, and a solution of sugar of lead. When a current from a battery B is sent through the cell it deposits the lead in tufts on the negative plate n.

the solution of acetate of lead, extricating from the solution molecules of lead and depositing them on one of the lead plates, and you see the tufted crystals of lead being built up in frond-like form on the negative pole in the cell. We might employ, in preference to a solution of acetate of lead, a solution of nitrate of silver, which is the basis of most marking inks, and the same effect would be seen. It was definitely proved by Faraday that we might define the strength of an electric current by the amount of metal which it extricates from the solution of a metallic salt in one second, minute, or hour. The Board of Trade Committee on Electrical Standards have now given a definition of what is to be understood by an electric current of *one ampere in the following terms*: An electric current of one ampere is a current which will in one hour extricate from a solution of nitrate of silver 4.025 grammes of silver.[2] Otherwise we might put it in this manner: A current of electricity is said to have a strength of one ampere if, when passed through a solution of nitrate of silver, it decomposes it and deposits on the negative plate one ounce of silver in very nearly seven hours. We are acquainted in the laboratory with currents of electricity so small that they would take 100,000 years of continuous action to deposit one ounce of silver, and we are familiar in electric lighting practice with currents great enough to deposit one hundred weight of silver in thirty minutes. The simple experiment just shown is the basis of the whole art of electro-plating. Hence, when we speak later of a current of one ampere, or ten amperes you will be able to realise in thought precisely what such a current is able to achieve in chemical decomposition. It may be convenient at this stage to bring to your notice the fact that an 8 candle-power incandescent lamp working at 100 volts usually takes a current of about one-third of an ampere, a current which would deposit by electro-plating action one ounce of silver in about twenty-one hours. [page 10]

We pass next to consider another important matter, viz., that of electric pressure or potential; and we shall be helped in grasping this idea by considering the corresponding conception in the case of the flow of fluids. When a fluid such as water flows along a

[2] Footnote from Fleming's text: 28.3495 grammes = 1 ounce avoirdupois.

pipe it does so in virtue of the fact that there is a difference of pressure between different points in the pipes, and the water flows in the pipe from the place where the pressure is greatest to the place where the pressure is least. On the table before you is a horizontal pipe (Fig. 5) which is connected with a cistern of water, and which delivers water to another receptacle at a lower level. In that pipe are placed a number of vertical glass tubes to enable us to measure the pressure in the pipe at any instant. The pressure at the foot of each gauge glass is exactly measured by the *head* or elevation of the water in the vertical gauge glass, and at the present moment, when the outlet from the horizontal pipe is closed, you will notice that the water in all the gauge glasses stands up to the same height as the water in the cistern. In other words, the pressure in the pipe is everywhere the same. [page 11]

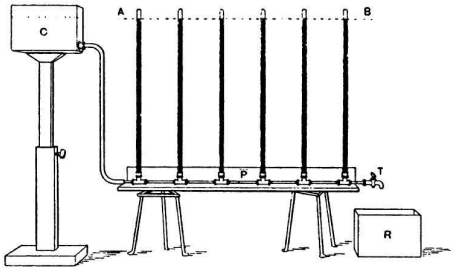


FIG. 5.—Horizontal pipe **P**, having six vertical gauge tubes attached to it. The pipe **P** is in connection with a water cistern **C**, and when the tap **T** is shut the water stands up at the same level, **A B**, in all the tubes.

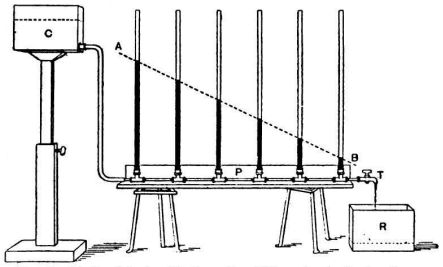


FIG. 6.—Horizontal pipe **P**, through which water is flowing from a cistern **C** to a reservoir **R**. When the tap **T** is open the water stands at gradually decreasing heights in the pressure tubes. The dotted line **A B** shows the hydraulic gradient.

Opening the outlet tap we allow the water to flow out from the pipe, and you will then observe that the water sinks (see Fig. 6) in each gauge glass, and, so far from being now uniform in height, there is seen to be a regular fall in pressure along the pipe, the gauge glass nearest the cistern showing the greatest pressure, the next one less, the next one less still, and so on, the pressure in the horizontal pipe gradually diminishing as we proceed along towards the tap by which the water is flowing out. This fall in pressure along the pipe takes place in every gas and water pipe, and is called the hydraulic gradient in the pipe. The flow of water takes place in virtue of this gradient of pressure. It will be next necessary to explain to you that there is an exactly similar phenomenon in the case of an electric current in a wire, and that there is a quantity which we may call the *electric pressure*, which diminishes in amount as we proceed along the wire when the current is flowing in it. In order to understand the manner in which this electric pressure can be [page 12]

measured, a few preliminary experiments will be essential. Every body which is charged with electricity has, in virtue of that charge, a certain electrical potential, or pressure, as it is called, and electricity always tends to flow from places of higher to lower potential, just as water or other fluids tend to flow from places of greater to less pressure. When two bodies are at different electric pressures, or potentials, it is found that there is an attraction or stress existing between [page 13]

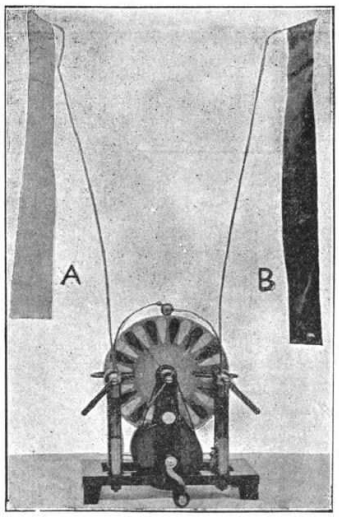


FIG. 7.—A small Wimshurst electrical machine, having two strips of paper **A** and **B** attached to its terminals. When the machine is worked the paper strips are drawn together.

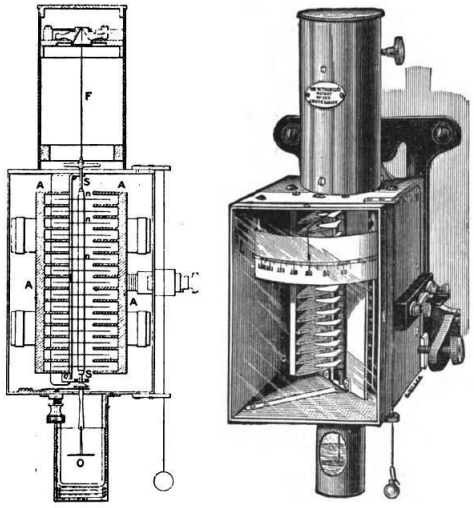


FIG. 8.—Lord Kelvin's Multicellular Electrostatic Voltmeter. The fixed plates or cells are marked **A** in the sectional drawing. The movable plates **n** are attached to an axis **S** suspended by a fine wire **F**.

them, and a tendency for them to move, if possible, nearer together. If I attach to the terminals of a small electrical machine two paper strips, and then charge those paper strips to different electric pressures, we find the strips are drawn together (see Fig. 7). The difference of pressure between these two bodies can be exactly measured by the mechanical force with which they attract one another, or by the force required to keep them apart by a certain distance. This fact is taken advantage of to construct many instruments, [page 14]

which are called electric pressure-measuring instruments, or voltmeters. One of the most valuable of these is the electrostatic voltmeter, invented by Lord Kelvin. It consists (see Fig. 8) of a series of fixed plates, which are called cells, and suspended between these are a number of movable plates, all attached to a common axis, this axis being suspended by a very fine wire. The suspended plates are so arranged that, when at a different electric pressure or potential from the fixed plates, they are attracted in between them, and the movement of the suspended plates is resisted by the torsional elasticity. The extent to which they thus move can be measured by an indicating needle fastened to the movable plates. If the fixed and movable plates in this instrument are brought to different electric pressures, or different electric potentials, they will be attracted towards one another, and we then have an instrument which can be converted by proper graduation into an electric pressure-measuring instrument. Furnished with such an appliance we can now explore the change in pressure down a wire through which the electric current is flowing. Through this manganese-steel wire we are now passing a current of electricity. One terminal of the voltmeter, namely, that connected to the fixed [page 15]

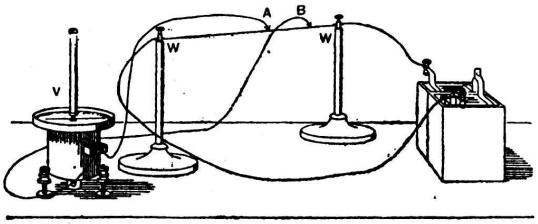


Fig. 9.—A battery C, which in the actual experiment consists of 50 cells, sends a current through a wire W W. By means of a pair of contact pieces A B, the terminals of an electrostatic voltmeter V are connected to various points on the wire W W, and the fall in electric pressure along it is thus measured.

plates, is kept connected to one end of that manganese-steel wire, whilst the wire connected to the movable plates of the voltmeter can be slid along the manganese-steel wire to different points (see Fig. 9). You will see from the indications of the voltmeter that as I slide the movable contact along the conductor conveying the current the indications of the voltmeter increase, and it is possible thus to show that there is a difference of electric pressure between two points on the wire conveying the current, precisely as there is a difference of fluid pressure between two points in a pipe along which water or gas is flowing. The water flows in the pipe from places where water pressure is greatest to places where water pressure is least. The electric current, whatever it may really be, likewise flows from places where the electric pressure is greatest to places where it is least. A unit of electric pressure has been selected which has been called a volt, after Volta, who, in 1800, gave us the first galvanic battery. It may be remarked in passing that the pressures at which it is most usual to work incandescent lamps are either 100 or 200 volts between the terminals of the lamp, and that the pressure between the terminals of a single galvanic cell, such as is used for working electric bells, is from 1 to $1\frac{1}{2}$ volts. We are then able to connect these two ideas of electric current and electric pressure when measured in the units above defined, and to give a definition of the unit in which electric resistance is measured. If we assume that a wire is taken through which an unvarying current of one ampere is passed always in one direction, and two points on this wire are found such that the difference of electric pressure between those points is one volt, then such wire is said to have a resistance of one ohm between those chosen points. The resistance of any conductor can be measured by comparing it by certain methods with that of a conductor whose resistance is one ohm, and the electrical resistance of [page 16]

any wire or conductor can thereby be expressed in units, each of which is called one ohm. The great service which Dr. G. S. Ohm rendered in 1827 to electrical science was that he gave the first clear definition of the manner in which electric current, electric pressure, and electric resistance are related to one another. This is now embodied in a statement which is a definition of the mode of measuring electrical resistance. If the strength of the electric current which flows in any conductor when that current has a uniform flow in one direction is measured in amperes, and the difference of the electric pressures between the ends of that conductor is given in volts, the electrical resistance of that conductor in Ohms is obtained by dividing the last number by the first. The

above statement as it stands is merely a verbal definition of what is meant by electrical resistance. It has, however, also been experimentally proved that the resistance of a conductor, as measured above, does not depend upon the value of the current, and is the same for large currents as for small ones if a correction is applied for the change of temperature of the conductor which is produced by the current. The resistance of a conductor is generally affected considerably by change of temperature; for some bodies, such as pure metals, it is increased, and for other bodies, such as carbon and certain metallic alloys, it is decreased.

Apart, however, from changes of temperature, it is an experimental fact that the strength of the current produced in any given conductor is exactly proportional to the fall in electric pressure down the conductor, and the numerical ratio of the numbers representing the fall of pressure in volts and the strength of the current in amperes is the value of the electrical resistance of that conductor in Ohms. In order that you may see the application of this in electric lighting, let us consider the above in connection with an incandescent electric lamp. Such a glow lamp, as at present constructed, consists, as [page 17]

we shall see in the next lecture, of a fine carbon thread, or filament, which, as usually made, is traversed by a current of about two-thirds of an ampere, when that conductor is one which is suitable for a l6-candle-power lamp worked at the usual pressure of 100 volts. The electric supply companies bring into our houses two wires, between which they are constantly engaged in keeping an electric pressure difference of 100 volts or 200 volts, or thereabouts. If, therefore, the terminals of a lamp are connected to these two supply wires, the ends of the carbon filament are exposed to an electric pressure of 100 volts. The electric resistance of that carbon, when incandescent, is therefore expressed in Ohms by dividing the number expressing the pressure difference in volts by the number defining the current in amperes; hence it is the quotient of 100 by two-thirds, or 150 Ohms. Another fundamental law in connection with the flow of an electric current in conductors was enunciated by Mr. Joule in 1841, and is called Joule's law. It is thus stated: If a current flows through an electric conductor, the heat produced in that conductor per second is proportional to the product of the square of the current strength as measured in amperes and the resistance of the conductor measured in Ohms. Joule deduced this law from elaborately careful experiments made on the quantity of heat produced in a certain wire when traversed by an electric current, that wire being immersed in water. His experimental procedure was as follows: He immersed a wire, formed into a spiral, in a vessel of water so protected as not to be able to lose heat from the outside. He then passed measured currents of electricity through the spiral, and observed with delicate thermometers the rise of temperature of the water in a stated time. The whole of the energy which is thus being spent in the wire is converted into heat, and that heat is employed in raising the temperature of the water. If by suitable means we prevent the loss of heat [page 18]

from the containing vessel, or otherwise take it into account, and if we try this experiment with currents of two different strengths, say of one ampere and two amperes, it will be found that, if the resistance of the conductor remains the same, the heat generated in a given time by the current of two amperes will be four times as great as the heat generated in the same time by a current of one ampere, and in like manner a current of three amperes

would generate nine times as much heat as a current of one ampere, always provided that the resistance of the wire is not sensibly changed when the current is altered. A little consideration of the law of Joule and the law of Ohm, when taken together, will show you that, since the total amount of heat produced per second by a current of a given magnitude is proportional to the products of the numbers representing the resistance of the circuit in Ohms, and the square of the strength of the current measured in amperes flowing through it; and, since the product of the value of the resistance of the circuit in Ohms and the current strength in amperes is numerically equal to the difference of pressure between the two ends of the conductor, it follows that the total rate at which energy is being expended in any conductor to produce heat when a current of electricity is flowing through it is measured by the numerical product of the strength of that current in amperes, and the pressure difference between the terminals of that conductor measured in volts. If we apply this rule to the case of an electric lamp we find that, in order to measure the total rate at which energy is being transformed into heat and light in an incandescent electric lamp, we have to measure, in the first place, the current passing through, it in amperes, and the pressure difference between the terminals of the lamp in volts, and the product then gives us, in certain units, which are called *watts*, the rate at which energy is being dissipated or converted into heat in the carbon filament. Thus, for example, if a lamp which takes two [page 19]

thirds of an ampere is placed upon a circuit having a pressure difference of 100 volts, the product of 100 and two thirds being 66, the lamp would be taking 66 *watts*, and this is the measure of the rate at which energy is being supplied to the lamp, and converted by it into light and heat. It is important that you should possess a very clear conception of the exact meaning attached to the *watt* as a unit of power. If a weight of one pound is lifted one foot high, the amount of exertion or work required to raise this weight is, in engineering language, called *one foot-pound* of work. If 550 pounds, or nearly one-quarter of a ton, are so lifted one foot high, the work done is called 550 foot-pounds. Imagine this last exertion made in one second, and repealed every second; the *rate at which work is being done*, or exertion made, will be equal to that which is called *one horse-power*. An ordinary man might for some time keep on lifting 55 pounds, say the weight of a good-sized full portmanteau, one foot high per second, and he would then be doing one-tenth of a horse-power. The work done in lifting one pound about nine inches high, or more nearly 0.7373 of a foot, has been selected as a unit of work, and is called one *joule*, and, if this work is repeated every second, this *rate of doing work*, or making exertion, is called *one watt*. It is necessary to notice carefully that *a watt* is a unit rate of doing work and not a unit of work. If the pound weight is lifted against gravity nine inches high slowly or quickly the work done is the same, viz., one *joule*. If it is lifted nine inches high in one second this rate of doing work is called *one watt*. If it is lifted nine inches high in half a second, the rate of doing work is doubled, and is then *two watts*. Hence it will be seen that one watt is a unit of power, which is the $\frac{1}{746}$th part of a horse-power. The reason for choosing such a small unit is that it gives convenient numbers in which to measure the rate at which work is done in such energy [page 20]

transforming agents as incandescent lamps. When a larger unit is necessary, it is usual to employ the *kilowatt*, which is equal to 1,000 watts, as a unit of power, and it is obvious

that a kilowatt is equal to about one and one-third of a horse power. Accordingly, such a lamp as we have above assumed dissipates energy at a rate which would require one horse-power to maintain eleven or twelve lamps, and the rate at which physical energy has to be supplied to a 16-candle-power glow lamp to keep it at full candle-power is almost as great as the maximum rate at which a strong man can do work. [page 21]

5.3 Early electrical safety

Early experimenters of electricity had to be rather intrepid individuals, as the hazards of electricity were relatively unknown at the time, and the human body was often the most readily available test instrument for detecting the presence of electricity and gauging its strength.

What follows is a series of illustrative and sobering quotations from John Ambrose Fleming's text *The Alternating Current Transformer In Theory And Practice* published in 1892:

> A few months later, in the July number of *Silliman's American Journal of Science*, 1835 (Vol. XXVIII., pp. 329-331), he[3] followed this up with a more explicit account of his investigations on the action of a spiral conductor, especially a flat tape spiral, in increasing the spark and the shock from a single cell of a galvanic battery . . . [page 2]
>
> . . . Moreover, he noted that if copper cylinders two inches in diameter and about five inches long were attached as handles to the ends of the spiral by supplementary wires, and if these cylinders were grasped by moistened hands, a series of sharp shocks were experienced . . . [page 3]

> We then come to an important contribution by the Rev. N.J. Callan, of Maynooth College . . .
>
> . . . He sent a current from a battery of one or two pairs of plates through the thick copper wire, and attached metallic handles to the ends of the iron wire for the purpose of taking a shock, and then on making and breaking the circuit of the battery rapidly he got severe shocks from the iron wire circuit. [page 7]
>
> . . . Callan followed up this Paper by another dated June 14, 1836, published in Sturgeon's *Annals*, Vol. I., p. 376, being "A description of the most powerful electro-magnet yet constructed." [page 7]
>
> . . . Provided with this formidable apparatus, the inventor proceeded to perform striking experiments with the induced currents. "When by means of an *electro-magnetic repeater* a rapid succession of secondary currents was induced in the fine wire, and passed between charcoal points attached to the ends of the secondary circuit, they were slightly ignited." The shock, as can be imagined, was exceedingly severe, and the ardent experimentalist proceeded to pass from this general experiment in the production of an arc light by means of a transformer to an experiment in *electrocution*. For he adds: "Although the igniting power of the electric current produced in the long coil of thin wire was very feeble, its intensity was exceedingly great. When it (the secondary current) was passed through the body of a large fowl instant death was produced." This [page 8]
>
> magnet, or one like it, was sent by Callan to Mr. Sturgeon, and by him exhibited to the London Electrical Society at a meeting held on August 5, 1837, and members and visitors enjoyed powerful shocks from the secondary wire of this electro-magnetic apparatus. [page 9]

[3] The "he" referred to in this passage was Joseph Henry.

> . . . He put a solid iron core in the bobbin, and he was delighted to find that he got powerful shocks from the secondary circuit when the current from one or two cells was interrupted in the primary. [page 10]

> Bachhoffner observed that a bundle of fine iron wires used as a core in Sturgeon's coil gave far better shocks than when a solid iron bar was employed. We must therefore credit Bachhoffner with being the first to recognize the value of a divided iron core. [page 11]

> . . . The result was a very considerably greater production of electromotive force in the secondary circuit. Page got brilliant sparks from the ends of the secondary circuit of this coil, and unbearably severe shocks. [page 25]

> In the years since 1867, Mr. A. Apps has devoted great attention to the production of large induction coils, and has been the designer and constructor of some of the most powerful coils in existence . . .
>
> . . . Excited by the current from 40 large Bunsen cells, this coil would give secondary sparks 29 in. in length, and could in a few seconds charge 66 Leyden jars, each having 11 square feet of internal coated surface. The secondary discharge could pierce blocks of glass 5 in. in thickness. The secondary sparks were of considerable thickness and apparent volume, and accompanied by a kind of flame. [page 54]

On page 13 of Fleming's book we find this alarming illustration, showing the intentional connection of an electrical apparatus to a subject's bare leg. Apparently this was considered acceptable laboratory practice in the 19th century:

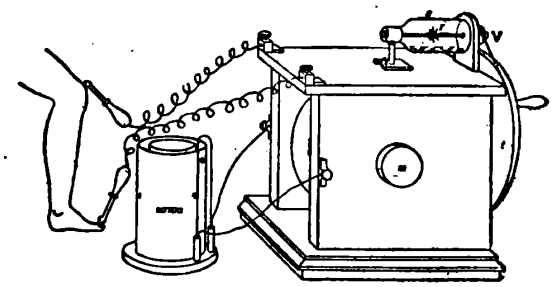


FIG. 7.—Clarke's Induction Coil.

m, core of coil. t, driving wheel of contact breaker. V, driven pulley. r, star wheel breaking contact with mercury in vessel s.

Even decades after these early experiments with "electro-magnet" coils were performed, it was still unclear just how much electric current the human body could sustain without suffering ill consequences, as Fleming noted in 1892:

> Information is wanting to show what current is in any particular case dangerous, but it is improbable that any person could receive even one third or one-half of an ampere through vital organs without its causing fatal consequences. [page 112]

Thirty years later, as recorded in an issue of *Power Plant Engineering* magazine (Volume XXV, Number 1, printed 1 January 1921), the danger threshold for electric shock was still quite uncertain:

> The exact quantity of electric current that may pass through the human body without danger to life has not been determined. It is well known that one-tenth of an ampere may be dangerous and that one-fourth of an ampere may prove fatal, although from 7 to 10 amp. are used during the electrocution of criminals. From the accident prevention standpoint at least, the only safe procedure is to "let it alone." [page 814]

This same article, entitled "Safety for Electrical Equipment" describes three specific hazards of electricity: electric shock, burns, and "flashed eyes" (referring to eye damage from the strong light emitted by an electric arc). As for the latter hazard, often encountered when opening or closing exposed-contact power switches and circuit breakers commonly used in those days, the article gives this advice:

> When welding electrically or doing other work near an electric arc, operators should be required to wear protective goggles with properly colored lenses, and it is well to take the same precaution when opening a switch where a strong arc may be formed. [page 814]

An early recorded observation of the dangers of electricity is found in Benjamin Franklin's book *Experiments and Observations on Electricity, made at Philadelphia in America* published in 1769 contains an Appendix entry written by someone other than Franklin (simply signed "N.B.") describing the effects of electric shock to birds and humans, delivered from glass jars coated in metal foil serving as *capacitors* to store static electric charges:

> As Mr Franklin, in a former letter to Mr Collinson, mentioned his intending to try the power of a very strong electrical shock upon a turkey, that gentleman accordingly has been so very obliging as to send an account of it, which is to the following purpose.
>
> He made first several experiments on fowls, and found, that two large thin glass jars gilt, holding each about six gallons, were sufficient, when fully charged, to kill common hens outright ; but the turkeys, though thrown into violent convulsions, and then lying as dead for some minutes, would recover in less than a quarter of an hour. However, having added three other such to the former two, though not fully charged, he killed a turkey of about ten pounds weight, and believes that they would have killed a much larger. He conceited, as himself says, that the birds kill'd in this manner eat uncommonly tender.
>
> In making these experiments, he found, that a man could, without great detriment, bear a much greater shock than he had imagined : for he inadvertently received the stroke of

> two of these jars through his arms and body, when they were very nearly fully charged. It seemed to him an universal blow throughout the body from head to foot, [page 153]
>
> and was followed by a violent quick trembling in the trunk, which went off gradually in a few seconds. It was some minutes before he could recollect his thoughts, so as to know what was the matter ; for he did not see the flash, tho' his eye was on the spot of the prime-conductor, from whence it struck the back of his hand ; nor did he hear the crack, though the by-standers said it was a loud one ; not did he particularly feel the stroke on his hand, tho' he afterwards found it had raised a swelling there, of the bigness of half a pistol-bullet. His arms and the back of the neck felt somewhat numbed the remainder of the evening, and his breast was sore for a week after, as if it had been bruised. From this experiment may be seen the danger, even under the greatest caution, to the operator, when making these experiments with large jars ; for it is not to be doubted, but several of these fully charged would as certainly, by increasing them, in proportion to the size, kill a man, as they before did a turkey. [page 154]

Note the description of the victim's breast being sore for a week after, "as if it had been bruised." This was due to the violent and involuntary muscular contraction caused by the electric shock, because muscle tissue is activated by electrical impulses (usually very small signals conducted by nerve cells in the body, but in this case the man's nervous system impulses were overridden by the discharge of the electrical energy stored in the capacitor-jars). It is not uncommon for survivors of electric shock to suffer torn muscles, bruises, burns both internal and external, and in some cases memory loss resulting from the electric shock's effect on brain cells.

Interesting examples of personal protective gear may be found in historical documents as well. T. O'Conor Sloan's *The Standard Electrical Dictionary* published in 1892 happens to mention an electrical safety apparatus called a *body protector*. It is defined by Sloan as follows:

> **Body Protector** A metallic short circuit connected with the wrists and lower legs of the human body, so that if by accident an active circuit is grounded by the hands and body of the workman wearing it, most of the current will pass through the wire conductors, thus avoiding the vital organs of the body.

In essence, the body protector was a *shunt* used to make the wrists and ankles electrically common, and in so doing avoid impressing substantial voltage across the torso. Later in Sloan's *Dictionary* we find the following entry:

> **Protector, Electric** A protective device for guarding the human body against destructive or injurious electric shocks. In one system, Delany's, the wrists and ankles are encircled by conducting bands which by wires running along the arms, back and legs are connected. A discharge it is assumed received by the hands will thus be short circuited around the body and its vital organs. India rubber gloves and shoe soles have also been suggested; the gloves are still used to some extent.

Chapter 6

Derivations and Technical References

This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

6.1 Metric prefixes

The *metric system* of measurement specifies certain units of measurement for various physical parameters, some of them listed here:

Parameter	**Unit**	**Symbol**
Length	Meter	m
Temperature	Celsius or Kelvin	C or K
Mass	Gram	g
Force	Newton	N

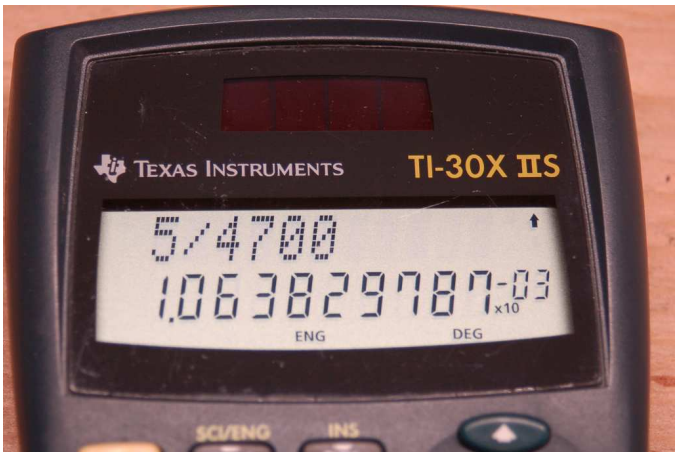
In order to make the expressions of large and small measurements more convenient, the metric system also includes *prefixes* representing power-of-ten multipliers, some of which are listed here:

Prefix	**Symbol**	**Power-of-ten**
Peta	P	$10^{15} = 1,000,000,000,000,000$
Tera	T	$10^{12} = 1,000,000,000,000$
Giga	G	$10^{9} = 1,000,000,000$
Mega	M	$10^{6} = 1,000,000$
Kilo	k	$10^{3} = 1,000$
Milli	m	$10^{-3} = \frac{1}{1,000}$
Micro	μ	$10^{-6} = \frac{1}{1,000,000}$
Nano	n	$10^{-9} = \frac{1}{1,000,000,000}$
Pico	p	$10^{-12} = \frac{1}{1,000,000,000,000}$
Femto	f	$10^{-15} = \frac{1}{1,000,000,000,000,000}$

In order to represent very large or very small quantities all we need to do is combine the right prefix with the unit. For example, a distance of 12,509 meters could be written as 12.509 *kilo*meters (12.509 km) because "kilo" simply means *thousand*. Similarly, a mass of 0.000000421 grams could be written as 0.421 *micro*grams (0.421 μg) or 421 *nano*grams (421 ng) because "micro" means *one-millionth* and "nano" means *one-billionth*.

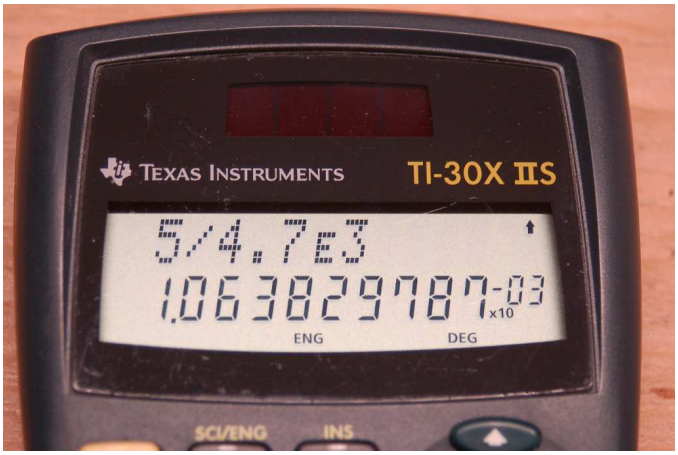
A useful way to think about metric prefixes is to consider the word *dozen*. Saying that we've collected three dozen eggs from a flock of chickens means the same thing as saying we've collected thirty-six eggs, because one "dozen" equals a quantity of twelve, and three times twelve is thirty-six. Here the word "dozen" is nothing more than a convenient multiplier for expressing some whole-numbered quantity of things. Metric prefixes constitute the same basic concept: they are simply multipliers used to help express a wide range of quantities while using numbers that are easier for us humans to handle.

Scientific hand calculators offer display modes and entry functions tailored for the purpose of expressing results and accepting input using standard metric prefix power-of-ten notation. Consider the following photograph of a Texas Instruments model TI-30X IIS calculator computing the current through a 4700 Ohm resistor energized by a 5 Volt source (using Ohm's Law, $I = \frac{V}{R}$):

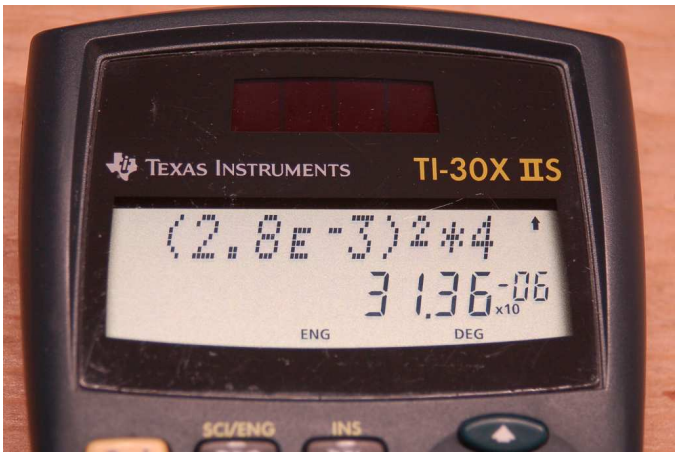


When the calculator has been set to the *Engineering* display mode, all results appear with a $\times 10^x$ label where x is an integer multiple of three to match with the metric prefixes listed previously. Here, the quotient $\frac{5}{4700}$ results in 1.0638×10^{-3}, or 1.0638 milliAmperes (1.0638 mA). It would be equally correct for the calculator to display the result as `0.001638` Amperes, but the 10^{-3} multiplier forced by Engineering mode results in a displayed number of 1.0638 that is easier for us to accurately read, write, and remember than 0.001638 with all the leading zeroes.

A button marked `EE` (sometimes $\times 10^x$ or simply `E`) allows entry of numerical values in either scientific notation or "engineering" form. Here, the same current calculation is performed entering the 4700 Ohm resistor's value as 4.7 kiloOhms (4.7 kΩ), entered as `4.7E3` in the calculator:



Another example shows the calculation of power dissipated by a 4 Ω resistor passing a current of 2.8 mA, using Joule's Law ($P = I^2R$) and once again making use of the `EE` button when entering the current value as `2.8E-3`:



Here, the resulting power dissipation is 31.36 microWatts (31.36 μW).

Some hand calculators provide the Normal/Scientific/Engineering display setting as a menu option, while others such as the TI-30X IIS shown here designate key functions to do the same. Note the `SCI/ENG` function visible in yellow-colored text above one of the buttons in these photographs.

Engineering mode and the `EE` button both require a knowledge of the powers-of-ten associated with common metric prefixes, but once those prefix multipliers are memorized they become very valuable in saving you the trouble of reading and entering numerical values filled with leading or trailing zeroes. As previously mentioned, without Engineering mode set our calculated current of 1.0638 mA would have been displayed by the calculator as 0.001638. Those leading zeroes, while mathematically accurate, are easy for humans to mis-count. The same is true for very large numbers with many trailing zeroes. *This is the chief purpose of metric prefixes: to reduce human error when reading, writing, and remembering very large and very small quantities alike.*

Mathematical formulae in science and engineering generally assume the use of *base units* in their variables. For example, *Ohm's Law* assumes voltage expressed in plain Volts (V), current expressed in plain Amperes (A), and resistance expressed in plain Ohms (Ω). However, for very large and very small quantities, it is more convenient for humans to read and write values using either metric prefixes or scientific notation rather than base units. For example, a voltage of 72 Volts applied across a resistance of 3,500,000 Ohms will result in a current of 0.00002057143 Amperes; but these quantities are much more easily written as 72 Volts, 3.5 megaOhms, and 20.57143 microAmperes, respectively.

Again, metric prefixes exist to make very large and very small numbers easier for human beings to manage. At root a metric prefix is nothing more than a particular power-of-ten multiplier. Thus, 3.5 MΩ is equal to 3.5×10^6 Ohms, or 3.5 *million* Ohms; likewise, 20.57143 μA is equivalent to 20.57143×10^{-6} Amperes, or 20.57143 *millionths* of an Ampere.

A very common error made by students new to the use of metric prefixes is to ignore them when inserting values into scientific and engineering formulae. For example, if someone tries to apply Ohm's Law to the example quantities of 72 V and 3.5 MΩ to find current ($I = \frac{V}{I}$) by simply dividing 72 by 3.5, their result will be grossly erroneous, as $72 \div 3.5 = 20.57143$. What this incorrect calculation *actually* finds is that 72 Volts applied across 3.5 Ohms yields a current of 20.57143 Amperes. When you enter "3.5" into a calculator, that calculator has no idea you really mean 3.5 *million* (3.5 *mega*) unless you specifically tell it so. This either requires you manually convert 3.5 MΩ into base units of Ohms (3,500,000 Ohms) by entering `3500000` into the calculator, or by using the calculator's power-of-ten entry key by entering `3.5E6` which means 3.5×10^6. In all cases, it is your responsibility to convert all metric-prefixed values into base-unit forms suitable for the formula(e) being calculated.

An interesting twist on the theme of base units is any formula involving *mass*, in which case the value for m must be computed in *kilograms* rather than grams. This is in accordance with the meter-kilogram-second (MKS) convention of modern[1] metric notation where the kilogram rather than the gram is considered to be the "base" scientific unit for mass.

For example, suppose we wished to calculate the kinetic energy of an 80 gram mass traveling at a velocity of 0.79 kilometers per second using the formula $E = \frac{1}{2}mv^2$. To properly calculate energy (E) in Joules, we would need to enter 0.080 for mass (m) in kilograms because 0.080 kg = 80 g and kilograms are the base unit for mass; we would also need to enter 790 or 0.79×10^3 or `0.79E3` for velocity (v) in meters per second because 790 m/s = 0.79 km/s with meters and seconds being base units. The proper result would be 24,964 Joules, or 24.964 kJ. If we were to ignore these metric prefixes by entering 80 for m and 0.79 for v, we would erroneously obtain a result of 24.964: an answer to a very different scenario where the mass is 80 kilograms rather than 80 grams and has a velocity of 0.79 meters per second rather than 0.79 kilometers per second.

So, just like the Ohm's Law example shown previously, we must first properly identify the base units required by the formula we're using, and then ensure our calculator sees all values expressed either directly in those base units or using powers-of-ten meaning the same thing. With the exception of mass where the *kilo*gram is considered the standard scientific base unit for all formulae, metric prefixes are nothing more than convenient ways to express large and small numerical values in order to avoid reading, writing, and remembering numbers containing a multitude of place-holding zeroes.

[1] The older metric convention was centimeter-gram-second (CGS) whereby all formulae using distance or displacement required casting that variable in *centi*meters rather than meters.

6.2 Resistor labeling

Resistors dissipate electrical energy in the form of heat, dropping voltage proportional to the amount of current passing through. This ratio of voltage to current is called *resistance* (R), measured in the unit of the *Ohm* (Ω), and it is the primary characterstic of any resistor. A popular method of labeling resistance values utilizes colored bands[2] to represent resistance values and tolerances. An example of this resistor style appears in the following photograph:

Four-band resistors are the most popular of the banded style, with the first and second bands representing significant digits, the third band representing a power-of-ten multiplier, and the fourth band representing tolerance.

Band color	**First digit value**	**Second digit value**	**Multiplier**	**Tolerance**
Black	0	0	10^0	
Brown	1	1	10^1	$\pm$ 1%
Red	2	2	10^2	$\pm$ 2%
Orange	3	3	10^3	$\pm$ 0.05%
Yellow	4	4	10^4	$\pm$ 0.02%
Green	5	5	10^5	$\pm$ 0.5%
Blue	6	6	10^6	$\pm$ 0.25%
Violet	7	7	10^7	$\pm$ 0.1%
Grey	8	8	10^8	$\pm$ 0.01%
White	9	9	10^9	
Gold			10^{-1}	$\pm$ 5%
Silver			10^{-2}	$\pm$ 10%
None				$\pm$ 20%

Applying this color code to the resistor shown above, we see that yellow = 4, violet = 7, red = 2, and silver = $\pm$ 10%. Therefore, this resistor's value is 47 $\times$ 10^2 Ohms (i.e. 4700 Ω) plus or minus 10%, which means it could be as low as 4230 Ω or as high as 5170 Ω.

[2] A useful mnemonic for associating these colors with decimal digits 0 through 9 and the percentages 5-10-20% is as follows: *"Better Be Right Or Your Great Big Venture Goes Wrong. Get Started Now."*.

Precision resistors require more significant digits to precisely quantify their values, and so use a *five-band* code where the first three bands represent digits, the fourth band represents the power-of-ten multiplier, and the fifth band represents tolerance. Both the four-band and five-band color codes are standardized as part of the international standard IEC 60062.

Many modern resistors are labeled with text rather than color-coded bands. For these resistors, a letter is used in place of a decimal point, the letter either being `R` (unit), `K` (kilo), `M` (mega), `G` (giga), `T` (tera), or `L` (milli). This is commonly referred to as the *RKM* code. Some labeling examples are shown in the following list:

- R82 = 0.82 Ω
- 3R9 = 3.9 Ω
- 47R = 47 Ω
- 560R = 560 Ω
- 3K3 = 3.3 kΩ
- 27K = 27 kΩ
- 100K = 100 kΩ
- 2M2 = 2.2 MΩ
- 15M = 15 MΩ
- 2L7 = 2.7 mΩ

Tolerances for text-labeled resistors use the following letter codes, the tolerance letter always being the last character of the resistor's text label:

Letter code	**Tolerance**
B	± 0.1%
C	± 0.25%
D	± 0.5%
F	± 1%
G	± 2%
H	± 3%
J	± 5%
K	± 10%
M	± 20%
N	± 30%

For example, a resistor labeled `6K8J` would be 6.8 kΩ ± 5%.

Surface-mount device (SMD) resistors are often labeled with numbers only, either a three-digit numerical code or a four-digit numerical code. These codes follow the same pattern as four- and five-band color codes (except with no specified tolerance, just **digit-digit-multiplier** or **digit-digit-digit-multiplier**). For example, `473` would be 47 kΩ and `2711` would be 2.71 kΩ.

An exception to this general rule appears in the following photograph of a 5 milli-Ohm surface-mount resistor with a tolerance of ± 1%. The `5L0` portion of the code indicates 5.0 mΩ, while the `F` portion indicates the ±1% tolerance:

This particular SMD resistor happens to be useful as a high-current *shunt resistor* developing a precise voltage drop proportional to current. Its low resistance value does little to impede the flow of charge carriers to the load, while its tight tolerance ensures its voltage drop will be a fairly good representation of current through it.

6.3 Resistor parameters and types

Resistors are manufactured in several different types, the primary distinction being the type of substance used for the resistive material inside the device. In the following list we will explore some of these resistive material types and their construction into practical resistors:

- **Carbon composition** – these resistors are manufactured from a mixture of carbon (in the form of graphite) and clay, compressed into a compacted form, the ratio and physical dimensions of this compacted sample determining its end-to-end electrical resistance. A coating of electrically-insulating material (e.g. plastic) protects the resistor against undesired contact with other conductors.

- **Carbon film** – these resistors are also manufactured from carbon (in the form of graphite), but instead of compressing a mixture of carbon and clay into a solid lump, carbon is carefully deposited onto the surface of an electrically-insulating core made of ceramic material. Following this deposition process, a spiral groove may be cut into the deposited carbon film to intentionally lengthen the current's travel path and thereby increase resistance.

- **Metal wire** – historically this was the first type of resistor widely used, being made of long lengths of thin metal wire with known resistance-per-unit-length rating. This long wire is usually wrapped into the shape of a coil in order to form a compact physical assembly. One advantage of this construction method is that it lends itself well to the making of custom resistance values: just take a metal wire having a known resistance-per-length rating and then cut the desired length of it to get the resistance you need.

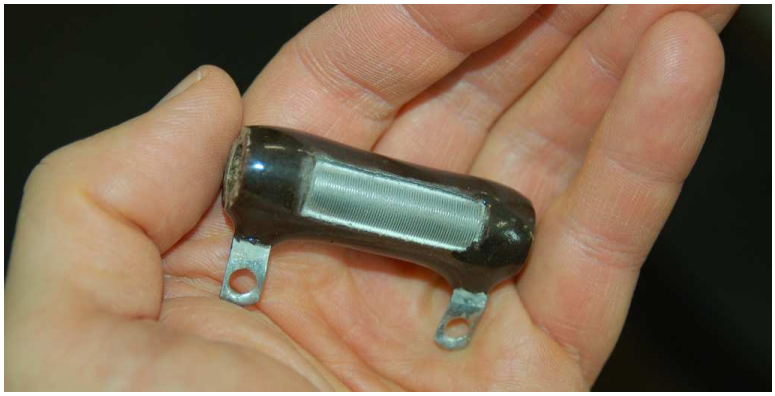
- **Metal film** – this type of construction is widely used for making resistors with precise resistance values, as the manufacturing process used to deposit and trim the metal film on a non-conducting substrate material are quite precise. Metal film resistors are subdivided into "thick" and "thin" film types depending on the specific method used to manufacture the metal film.

- **Metal oxide film** – rather than using pure metal or metal alloys as the resistive element, this type of resistor uses metal oxide substances.

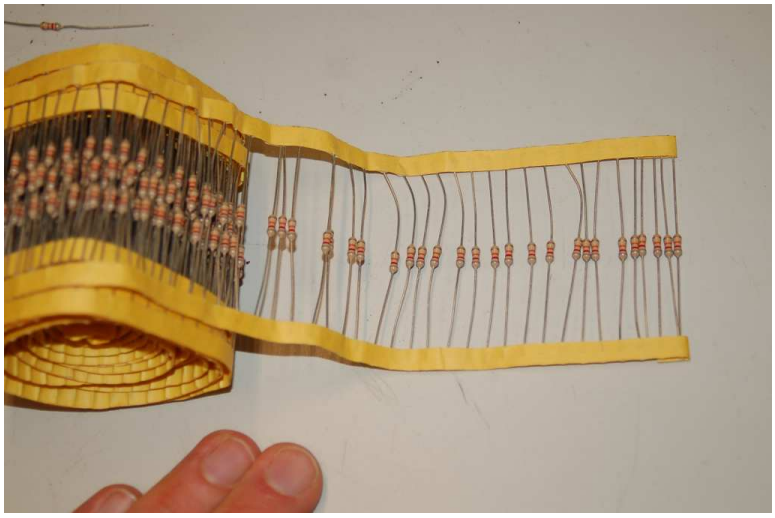
- **Metal foil** – another way to form the resistive element of a resistor is by shaping a piece of thin metal foil, the metal in question usually being an alloy of nickel and chrome having much greater electrical resistivity than copper. This technology currently represents the state-of-the-art for creating resistance values that remain stable despite changes in temperature and also remain stable over long periods of time.

- **Cermet** – this type of construction uses a mixture of ceramic and metal substances (hence the name, cermet) as the resistive element. Quite frequently used as the base material for small potentiometers and rheostats (variable resistors). Due to its ability to withstand high temperatures, cermet resistors are often used as electrical *heating elements*.

Here is a photograph of a metal wire resistor with some of the ceramic covering material removed to expose the wire coil underneath:



Next is a photograph of a many carbon composition resistors fastened between two adhesive-backed strips of paper, typically dispensed from a circular reel for use in an automated pick-and-place machine to populate printed circuit boards (PCBs) in an assembly-line manufacturing process. These resistors all bear the color code Grey-Red-Orange-Gold which is 82 kΩ nominal resistance with $\pm 5\%$ tolerance:



Aside from offering a specific amount of electrical resistance (measured in Ohms), resistors bear other ratings as well. The first and foremost of these after electrical resistance is its *power rating* measured in Watts. A resistor must be able to shed the heat it dissipates as electrical charge carriers pass through and release energy as a result of their collisions inside the resistor, and its outer surface area primarily determines this heat-shedding capability. Thus, resistors with a high power rating tend to be physically large.

Another technique for shedding heat and thereby increasing the power rating of a resistor is to affix some thermally-conductive surface to the resistor, that surface acting as a *heat sink* to "draw" heat away from the hot resistor and disperse it to the surrounding environment. The following wire-wound resistor has a power rating of 250 Watts not just because it's physically large, but also because it has mounting tabs to bolt to a suitable metal plate to function as a heat sink and pull even more heat away from the resistor than the resistor could shed on its own:

For very high-power applications, *forced convection cooling* is another option to keep resistors from overheating. Here, either a fan is used to blow ambient air past the resistor, or in very high-power applications a pump is used to move a liquid past the resistor's outer surface and thereby convect even more thermal energy away from the resistor. Forced convection cooling is often used for *dummy load* resistors, where the resistor in question acts as a substitute load for some electrical source that must be tested. One example of a dummy load in action is for testing the output of a radio transmitter system, where a dummy load resistor electrically mimics a transmitting antenna but without actually broadcasting any radio energy. If we needed to test the output of a 50 kW commercial broadcast transmitter without actually broadcasting radio signals, we would need to disconnect the antenna from the transmitter and connect a suitable resistor with a power rating of 50 kW (i.e. 50,000 Watts). Such a resistor will certainly need to be cooled by forced convection. A similar application of a dummy load resistor is for testing the output of audio power amplifiers without actually creating sound, the dummy load (usually an 8 Ohm resistor)[3] taking the place of

[3] A rather ingenious solution I've seen used for such a load is to find a heating element for an electric residential hot water heater rated for 7.2 kW at 240 Volts, which by Joule's Law is equivalent to 8 Ohms. By immersing the heating element in a bucket of cold water, it forms an 8 Ohm resistor with a power rating high enough to test all but

the loudspeaker at the amplifier's output terminals.

Other important resistor parameters and ratings include the following:

- **Precision** – otherwise known as *tolerance*, this is the percentage (or parts-per-million (ppm) for highly precise applications!) of allowable resistance deviation from the advertised (nominal) value. Legacy carbon composition resistors typically had tolerances of $\pm 10\%$ or even $\pm 20\%$, but modern material selection and manufacturing techniques have tightened carbon composition resistor tolerances to $\pm 5\%$. For greater precision, materials other than carbon composition should be used.

- **Maximum voltage** – excessive voltage for any given distance between two points is a function of the *breakdown* threshold for that insulating medium. Resistors rated for high voltage, therefore, are *long* in order to keep a large separation distance between its terminals.

- **Temperature coefficient of resistance** – the electrical resistance of most substances varies with changes in temperature, usually expressed as a percentage or ppm per degree Celsius. For graphite this correlation is *negative* (i.e. the resistance of graphite decreases with increasing temperature), and for most metals this correlation is *positive* (i.e. hotter temperatures make more resistance). Some metal alloys such as *constantan* and *manganin* have temperature coefficient values of nearly zero, which means we can manufacture wirewound and metal film/foil resistors with such alloys to achieve resistance values that are extremely stable over wide ranges of temperature.

- **Long-term stability** – this is a measure of how much a resistor's resistance is liable to change (or "drift") as it ages. Metal foil resistors are the current best-practice technology to achieve long-term resistance stability.

- **Reliability** – the most common failure mode for any type of resistor is *open* – i.e. a failed-shorted resistor is a very rare thing – and this occurs when the resistive material cracks or breaks into multiple pieces. Carbon composition resistor material is brittle and therefore susceptible to cracking with vibration. Wirewound and metal film/foil resistors are both more reliable than carbon composition resistors, with film or foil resistors slightly more reliable than wirewound.

- **Noise** – although resistors are generally considered to be electrical loads, they are in fact capable of producing very small voltage variations due to the action of temperature on the electrical charge carriers within. This *thermal noise* is actually common to all electrically conductive materials, and that includes all types of components (not just resistors). However, other types of electrical noise vary with the type of conductive material involved. One of these types of noise is called *flicker noise* or *excess noise*, which varies as a function of current through the device. For any given amount of current and resistance, a carbon composition resistor develops greater flicker noise than any metal (film, wire, or foil) resistor.

In summary, avoid carbon composition resistors unless precision, stability, reliability, and noise are insignificant concerns. Carbon composition resistors are fine for building most prototype circuits, and for simple circuits in non-critical applications.

the highest-power audio amplifiers in existence, and for a very low material cost!

6.4 IEC standard component values

Components such as resistors, inductors, and capacitors are manufactured in several *standard values*, described by IEC standard 60063. Rather than having a single series of standard values, the IEC publishes lists called *E series* based on the number of unique values spanning a single *decade* (i.e. a 10:1 range).

The shortest of these series, called *E3* contains just three values: 10, 22, and 47. The next series is called *E6* with six unique values: 10, 15, 22, 33, 47, and 68. These values represent *significant values* for components, meaning the decimal point may be freely moved to create values spanning multiple decades. For example, "33" simply means one can expect to find components manufactured in values of 33, 3.3, 0.33, and 0.033 as well as 330, 3.3 k, 33 k, etc.

Although this may seem like a strange standard for component manufacturers to follow, there is a compelling logic to it. The terms of each series are closer-spaced at the low end than at the high end, and this allows for *series* and/or *parallel* combinations of components to achieve most any desired value. For example, in the E6 series we only have values with the significant figures 10, 15, 22, 33, 47, and 68, but this doesn't mean we are limited to *total* values with these significant figures. For example, if we needed 80 Ohms of resistance we could connect a 33 Ohm and 47 Ohm resistor together in series. 50 Ohms could be made from two 68 Ohm resistors in parallel (making 34 Ohms) plus a 15 Ohm and 1 Ohm resistor in series.

On the next page is a table showing the four most common E-series specified by IEC standard 60063.

E3	**E6**	**E12**	**E24**
10	10	10	10
			11
		12	12
			13
	15	15	15
			16
		18	18
			20
22	22	22	22
			24
		27	27
			30
	33	33	33
			36
		39	39
			43
47	47	47	47
			51
		56	56
			62
	68	68	68
			75
		82	82
			91

E48, *E96*, and *E192* series are also found in the IEC 60063 standard, used for components with tighter tolerance ratings than typical.

6.5 Small-gauge wire ampacities

The *ampacity* of a wire is its rated maximum current – literally the number of Amperes it may continually sustain without overheating. A wire's ampacity is fundamentally a function of three factors: (1) the rate of heat dissipated by the electric current passing through that wire based on wire resistance (by Joule's Law $P = I^2R$), (2) the wire's ability to shed heat to the surrounding environment, and (3) the high-temperature limit of the wire's insulation. Heat dissipation, of course, is directly related to the amount of current and the wire's resistance which is a function of gauge (cross-sectional area) and the type of metal (e.g. copper versus aluminum). Heat shedding is related to the outer surface area of the insulated conductor as well as the material(s) it contacts. For this reason, wires buried in earth or suspended alone in open air have greater ampacity ratings than wires bundled together in an enclosed raceway (e.g. conduit, wire duct). This means wire ampacity varies with the manner in which it is installed as well as its structure and composition.

Electrical safety standards documents contain conservatively-rated ampacity values for various wire sizes, insulation types, and arrangements. In the United States, the National Fire Protection Association (NFPA) is well-respected for its electrical safety standards, including NFPA 70 (*National Electrical Code*, or *NEC*) and NFPA 79 (*Electrical Standard for Industrial Machinery*). Article 310 of the National Electrical Code ("Conductors for General Wiring") specifies wire ampacities for residential, commercial, and industrial power distribution systems. Chapter 12 within the NFPA 79 standard ("Conductors, Cables, and Flexible Cords") specifies wire ampacities for electrical wiring within industrial machinery.

Conductors used for small electrical and electronic projects are typically much smaller (i.e. higher *American Wire Gauge* number) than those specified in Article 310 of the National Electrical Code because the NEC focuses on *facility* power wiring. NFPA 79, with its focus on the internal wiring of machinery, specifies characteristics of wires over a wider range than the NEC. The following table summarizes some specifications for smaller-gauge single copper conductors. Note that the DC resistance values assume room temperature (25 ^{o}C) while the ampacity values assume a temperature no greater than 75 ^{o}C:

AWG size	**Cross-sectional area**	**DC resistance per 1000 ft**	**Ampacity**
30 gauge	0.051 mm^2	109 Ω @ 25 ^{o}C	0.5 Amperes
28 gauge	0.081 mm^2	69.0 Ω @ 25 ^{o}C	0.8 Amperes
26 gauge	0.129 mm^2	43.3 Ω @ 25 ^{o}C	1 Ampere
24 gauge	0.205 mm^2	27.3 Ω @ 25 ^{o}C	2 Amperes
22 gauge	0.324 mm^2	17.2 Ω @ 25 ^{o}C	3 Amperes
20 gauge	0.519 mm^2	10.7 Ω @ 25 ^{o}C	5 Amperes
18 gauge	0.823 mm^2	6.77 Ω @ 25 ^{o}C	7 Amperes
16 gauge	1.31 mm^2	4.26 Ω @ 25 ^{o}C	10 Amperes
14 gauge	2.08 mm^2	2.68 Ω @ 25 ^{o}C	15 Amperes
12 gauge	3.31 mm^2	1.68 Ω @ 25 ^{o}C	20 Amperes
10 gauge	5.261 mm^2	1.06 Ω @ 25 ^{o}C	30 Amperes

A formula useful for estimating resistance values of copper wire per thousand feet appears below:

$$R_{1000ft} = (1.06)\left(e^{0.232G-2.32}\right)$$

Where,

$R_{1000ft} \approx$ Copper wire DC resistance in Ohms per 1000 feet of wire length at 25 ^{o}C

$G =$ American Wire Gauge (AWG) number of the wire

#10 AWG copper wire exhibits approximately 1.06 Ohms of electrical resistance per 1000 feet of length at 25 degrees Celsius. To apply this formula to wire metals other than copper, just include a multiplication factor consisting of the new metal's specific resistance value divided by the specific resistance of copper in identical units of measurement and for the same temperature. For example, since aluminum metal has a specific resistance of 15.97 Ohms-cmil/ft and copper has a specific resistance of 10.09 Ohms-cmil/ft, just multiply 1.06 Ohms per thousand feet for #10 AWG copper by $\frac{15.97}{10.09}$ to get 1.68 Ohms per thousand feet for #10 AWG aluminum wire.

6.6 Ground in electric and electronic circuits

Ground and *grounding* within both electric power and electronic circuits are commonly misunderstood topics, largely because these terms can often have very different meaning depending on context. Here we will explore some of these different meanings and hopefully eliminate some of the confusion surrounding them.

The very first concept we must understand in order to comprehend what "ground" is in any circuit is that *voltage* is fundamentally a *relative* measurement of potential energy different *between two points*. This is really true of all forms of potential energy, because "potential" means energy that has not yet been put to work setting matter into motion, implying a final state yet to be realized. When we say an electrical charge carrier possesses potential energy (i.e. electrical potential), this means it *could* (potentially) release energy to do work if it were to fall into a lower state of energy. The difference in energy held by that electric charge carrier from its original (high-potential) state to some other lower-potential state will be the amount of energy released by that charge carrier to do work, with that amount of work done dependent on both the charge carrier's initial energy level and its final energy level. *Voltage* is the term we use to describe such a difference in electrical potential.

We say that voltage always exists "between two points" or "between two locations" in a circuit because voltage is the amount of potential energy either lost or gained by electric charge carriers from one position in a circuit to another. It is impossible to quantify how much energy will be gained or lost by charge carriers unless we know both the starting point and the ending point for those charge carriers. In order to quantify the absolute amount of potential energy possessed by anything, we would have to know where or how it could lose every bit of its stored energy to be left with zero capacity to do work[4]. This is really unknowable from a practical perspective, and so the best we can do is quantify gains or losses in potential energy between different states.

This fact about voltage is also why we label it with *pairs* of "+" and "−" symbols, the "+" symbol representing the point of *higher potential* and the "−" symbol representing the point of *lower potential*. We cannot place an absolute value on electrical potential at any single location because no one can say where the location of zero energy is in the universe for electric charges. The best we can do is to rate one location as having higher or lower electrical potential than another, quantifying only the difference in potential between those two locations.

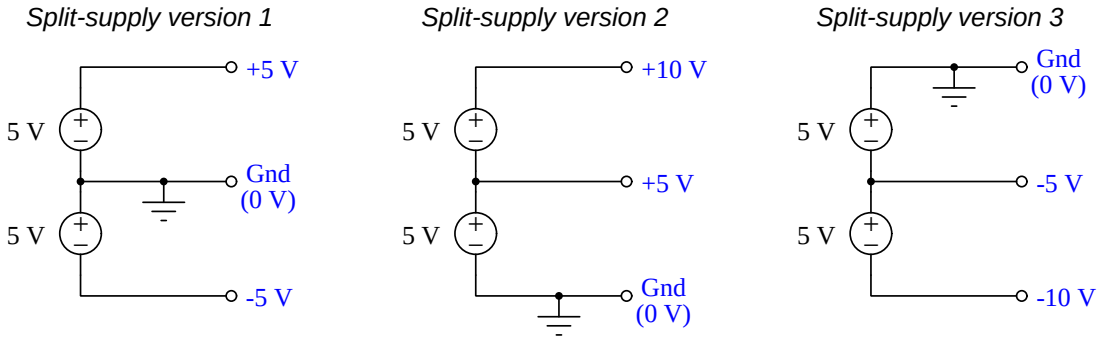
Now that we have reviewed this property of voltage and of potential energy in general, we are ready to explore what is meant by *ground* and *grounding*.

[4] Using gravitational potential energy as an example, a weight hoisted above the Earth's surface certainly possesses potential energy, and we might be tempted to quantify this potential energy by simply measuring its weight and its height above ground level and then multiplying those two quantities (i.e. potential energy equals force times distance). However, there are more places this weight could *potentially* fall than just ground level. That same weight, hoisted above the Earth's surface to the same height, will be assessed to have a far greater amount of potential energy if we consider it potentially falling down a deep hole rather than just falling to ground level. For that matter, one could even argue the weight has a *negative* quantity of potential energy with respect to what it would possess at the summit of the highest mountain! Potential energy, defined as the amount of work that *could* be done, necessarily depends on a system's initial condition *and* any number of different final conditions of which none are known to be truly zero-energy.

How do we rate the height of mountain peaks? Certainly, we may rate one mountain peak as being some number of meters higher or lower than another, but generally what people do instead is measure a mountain's peak height compared to *Mean Sea Level*. Since water is a liquid, and liquid tend to settle at equal heights under the influence of gravity when they are free to move about, the level of oceans throughout the world provide a relatively stable reference point for measurements of altitude. If we imagine a world without oceans, perhaps one with nothing but dry land and no open bodies of water anywhere, people living at different locations in this world would likely choose some flat-land reference points local (to them) for their measurements of nearby mountains, but these localized altitude measurements would be confusing if not meaningless for world-wide comparisons of mountain peaks.

Much the same is true of electrical and electronic circuits, where voltage is an important measure of electrical potential energy as well as a measure of signal strength where electricity is used as an analogue for representing other things[5]. One way to conveniently rate electrical potentials at different points in a circuit is by arbitrarily choosing one of those points to be the "zero-energy" reference point, and calling it *ground*. Ground in an electrical or electronic circuit is analogous to sea level for rating mountain peak heights or a *datum* or *benchmark* used for surveying land: simply a point of reference agreed-upon to be "zero" for the sake of ranking all other potentials to it.

A good example of this is an electrical network popularly known as a *split DC power supply*. Three different versions of this power supply network are shown with the same pair of 5-Volt DC sources, the only difference being the arbitrary location of the "Ground" (Gnd) point:

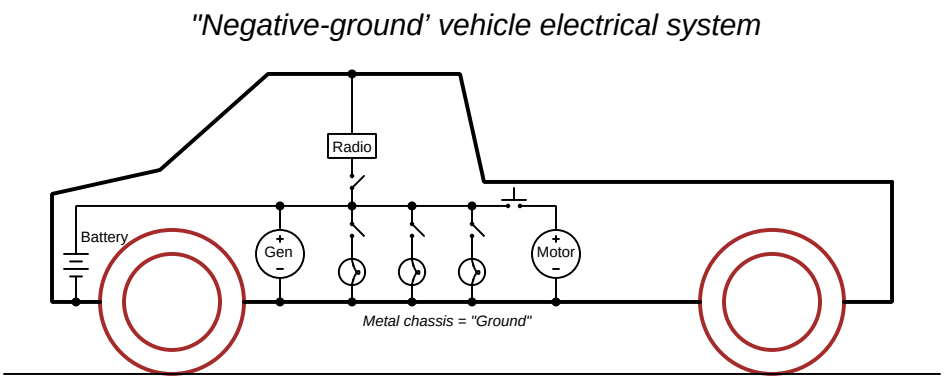


Each terminal's voltage label represents the amount of electrical potential there *relative to the "Ground" terminal*; i.e. "Ground" is simply a "sea-level" reference point against which all other potentials may be measured. The three different versions shown here illustrate just how arbitrary the location of "Ground" really is. Any load connected between the same pairs of terminals on each power supply would experience the same amount of voltage regardless of the "Ground" terminal assignment.

This is one meaning of the word "ground" in electric and electronic circuits: an arbitrary point of reference for the measurement and comparison of electrical power and signal potentials at different locations in the circuit.

[5] Many, many examples exist of voltage being used to represent non-electrical quantities. In digital computer systems, DC voltage levels represent binary "1" and "0" number states. In analog electronic sensor systems, voltage may represent temperature, speed, force, weight, sound pressure, or any number of other physical quantities.

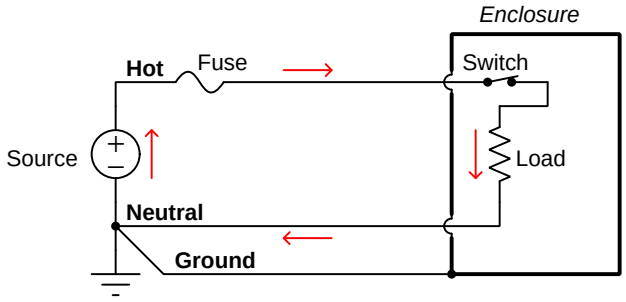
Another meaning of the word "ground" in circuits is a metallic surface used as a common conductor throughout some device or system for reasons of wiring economy. Automobiles with metal frames and chassis typically use their metallic bodies as an electrical conductor for nearly all circuits contained within. Doing so eliminates the need to install separate copper-wire conductors for every source and every load, thereby saving expense and weight:



Modern automotive electrical systems are "negative-ground" which means the vehicle chassis is always the lowest-potential point in any portion of the circuit. Interestingly, some early automobiles used "positive-ground" wiring which simply had the reverse polarity on all sources and loads: the vehicle chassis being the highest-potential point and all other points being either equal to it or at lower (−) potentials. This choice of polarity is really arbitrary, as electric circuits may be designed and built to function just as well either way. The "negative-ground" standardization we see today is really nothing more than automobile manufacturers agreeing to wiring their different vehicles the same way in order to enjoy interoperability of components.

This usage of the word *ground* – describing the metal chassis of some complex system exploited as a common electrical conductor for multiple circuits – is not incompatible with the previous usage of *ground*: a point of reference in a circuit arbitrarily defined to be "zero" potential. An automotive technician troubleshooting circuit faults in a vehicle often connects the black test lead of their voltmeter to the metal chassis, expecting to measure positive or zero voltage values on that meter when probing circuit test points with the red test lead. In a negative-ground electrical system, the chassis' electrical potential is *defined* as zero for the purpose of specifying voltages at other points in the circuit(s).

Yet another electrical meaning of the word "ground" is associated with *safety*, in which one metallic conductor of a power circuit is made electrically common to the Earth through a *grounding rod* buried in the soil. In the following circuit, the ground symbol in the lower-left corner is not merely a reference marker intended for anyone viewing the schematic diagram, but actually represents a metal rod driven deep into the soil and connected to one terminal of the voltage source with intent to achieve equipotentiality with the Earth:



Here the purpose of "grounding" is more important than merely establishing a reference point for voltage measurements. Instead, designating the conductor attached to this metal rod as "Ground" and attaching it to any conductive surface on or around an otherwise energized electrical appliance forces that surface to be equipotential to the same Earth that any humans and animals are standing on. This greatly mitigates the risk of electric shock should there be an internal fault within that appliance by making it impossible to have a difference of potential (i.e. voltage) between the grounded surface and the soil.

The following photograph shows the grounding rod for a commercial building, a large-gauge bare copper conductor clamped to the top of the rod which leads into the building's electrical room:

Ground wires in electric power systems should never carry current during normal operation. In fact, the presence of current through a ground conductor indicates a problem in the system! Note the two current-bearing power conductors in the previous schematic, specifically how the current-carrying conductor made common to Earth ground is called the *neutral*, while the other (non-grounded) power conductors is called *hot* by comparison. The Hot/Neutral designations always refer to which is grounded and which is not, rather than polarity. For example, if we were to reverse

the polarity of the DC voltage source shown in that schematic, the upper conductor (now −) would still be considered "hot" and the lower conductor (now +) would still be considered "neutral".

6.7 Occam's Razor as a general diagnostic principle

Sir William of Ockham was an English theologian who lived from 1287 to 1347, and whose name is attached (albeit often with different spellings) to a logical principle supremely useful in technical diagnostic work. Simply put, Occam's Razor states that the likeliest explanation for anything is that which employs the fewest assumptions. The word "razor" simply refers to the mental task of eliminating (i.e. shaving away) unnecessary assumptions until we are left with the most probable explanation for something.

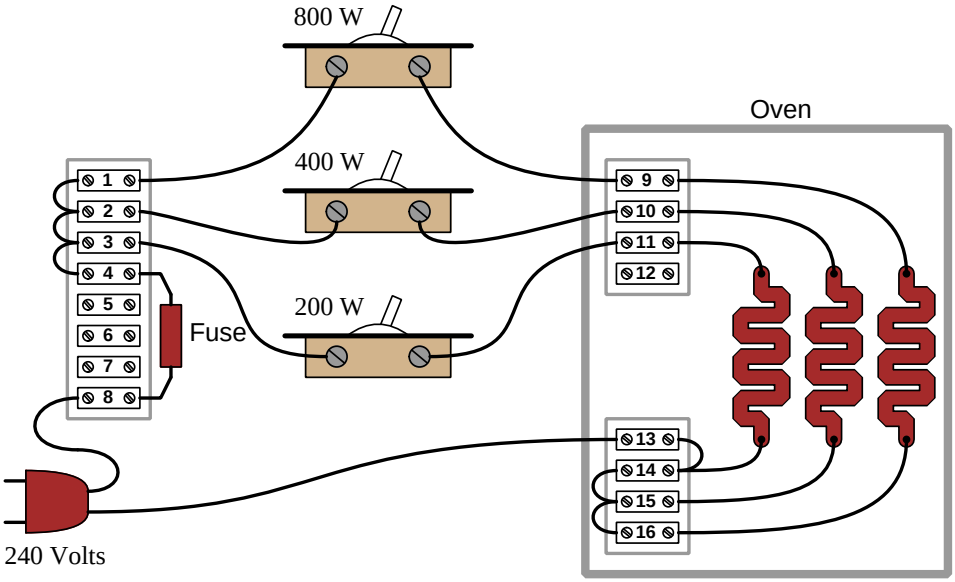
Let's consider a common example everyone can surely relate to: misplacing something. Suppose you are leaving your home to go to work, school, or some other destination, and on your way out the door you realize you are missing some important item such as your keys, your wallet or purse, your hat, etc. Realizing this, you return inside your home to find this item, but to your dismay it is not where you usually leave it. Why is this item missing, and where may you find it? Multiple explanations are possible, just a few of them listed here:

1. You were distracted while previously handling this item, and set it somewhere you usually don't
2. Someone who lives with you borrowed this item
3. A thief broke into your house and stole this item
4. An interstellar species traveled light-years across space and decided to teleport your item to their spacecraft for research before returning to their home planet

How many independent assumptions are necessary for each of these explanations? For the first (distraction), there is only one assumption and that is your prior distraction. For the second there is the assumption that a house-mate would fail to notifty you of their borrowing the item. For the third one must assume that the thief left no clue as to their entry and apparently were only motivated to steal this one item and none else you would have noticed. For the fourth rests on a host of assumptions: the existence of intelligent creatures far from Earth, their ability to travel here and scoop up your item unnoticed, their motive for doing so, etc., etc.

If you found yourself in the position of lacking this item on your way out the door of your home, you may very likely consider the first two explanations as possible, but not give any serious consideration to the third or fourth because they are so far-fetched. What makes them far-fetched is not their assured impossibility, but rather their *improbability* based on the number of assumptions necessary. You *might* be inclined to entertain explantion #3, but only after a thorough search of your house and inquiries of your house-mates failed to reveal the item's whereabouts. No one would seriously consider explanation #4. Of the first two explanations, the first is probably more likely than the second unless you happen to live with careless and inconsiderate people who would fail to let you know they needed to borrow this item from you.

Now let's consider how we might apply the principle of fewest (or least-unlikely) assumptions to electrical troubleshooting. Consider the following electric oven schematic, where three different heating elements are controlled by corresponding toggle switches:



Suppose someone calls you over the telephone to request your diagnostic assistance with this oven. They tell you the 200-Watt switch didn't appear to work: when they turn on that switch by itself, the oven remains at room temperature. Based on this information, the following faults should immediately come to mind as possibilities:

- Failed-open 200-Watt toggle switch
- Failed-open 200-Watt heating element
- Dead 240 VAC power source
- Blown fuse
- Open terminal 3-4 wire
- Open terminal 3-switch wire
- Open terminal 13-plug wire
- Open terminal 13-14 wire
- Open terminal 14-element wire
- Open terminal 11-element wire
- Open terminal 11-switch wire

Now suppose while you're on your way to the oven to begin troubleshooting, you receive a second telephone call from the same person, this time informing you that they subsequently tried flipping every one of the toggle switches to find *none* of them work. Even with all three switches on, the oven remains at room temperature! Upon receiving this news, proper application of Occam's Razor would tell you that any of the previously-listed faults capable of incapacitating the whole oven are more likely than any fault that could only explain the 200-Watt element failing to heat up, since in order for such a specific fault to be true it must also be coincidentally accompanied by at least one more fault explaining why the other heating elements aren't working either. *Simply put, a single fault accounting for everything is more likely than multiple, coincidental faults where each one only accounts for part of the problem.*

By employing Occam's Razor in this way, we may "shave down" our list of likely faults to those single faults individually capable of preventing any of the heating elements from energizing:

- Dead 240 VAC power source
- Blown fuse
- Open terminal 3-4 wire
- Open terminal 3-switch wire
- Open terminal 13-plug wire
- Open terminal 13-14 wire

For example, it's far more likely that a single fault such as an open wire between terminals 3 and 4 is the cause of the trouble here, as opposed to multiple faults such as a failed-open 200-Watt heating element *and* a failed-open 400-Watt heating element *and* a failed-open 800-Watt heating element to account for none of the heating elements working. Mind you, it is not *impossible* that all three heating elements have failed open, just *less likely* than a single fault such as a loosened wire between terminals 3 and 4. Occam's Razor is all about *probability*, not certainty.

Note how much shorter this list is than the first one which we created when we only knew the 200-Watt element wasn't working! Shorter lists of possible faults are quicker to work through, and so by judiciously focusing on these most-probable faults we should be able to identify the problem in less time and with less effort. Limiting our search to the fewest faults capable of accounting for the most symptoms is key to efficient and timely diagnosis.

This is why, when troubleshooting a malfunctioning system, it is so important to collect data on the problem. With each test we perform, with each measurement we take, we learn new information helpful for "shaving" our list of possible causes to the fewest in number. This means it is wise for us to re-assess our list of possible causes with each new symptom and data point we collect.

A companion strategy when diagnosing faults in complex systems is to intentionally simplify the system (if possible), especially if the system in question is new (i.e. unproven) and therefore more likely to harbor multiple errors than a system that used to work just fine and suddenly stopped functioning. When I counsel students who find their breadboard-constructed circuits don't work when initially powered, I recommend the same: *build the simplest version of the circuit you can think of and get that simple version working before adding complexity to it.* Otherwise, if you build

the entire circuit from scratch in its full glory, it becomes more likely that you will have multiple, unrelated faults which will be more challenging to identify.

It's worth noting that the premise of Occam's Razor – that fewer faults are more likely than a multiplicity of faults – is true only when the multiple faults are unrelated to each other (i.e. coincidental). If, however, one form of fault subsequently leads to another fault, then it may be quite likely for a failed system to harbor those multiple faults. Considering our oven example, suppose the original failure was a *shorted* failure of the 200-Watt heating element. With the 200-Watt element failed-shorted, the fuse would immediately blow as soon as the 200-Watt toggle switch was flipped to its "on" position, leading to a non-functioning oven with *two* faults: a shorted 200-Watt heating element and a blown-open fuse. The blown fuse is not coincidental to the shorted 200-Watt element, but rather a direct consequence of it.

This leads to the concept of something called a *root cause*. A "root" cause is the source of subsequent failures, that will keep resulting in future failures if uncorrected. In the example just given of the shorted heating element and the blown fuse, the shorted element is the root cause and the blown fuse is a secondary cause: the shorted element explains why the fuse blew, but the blown fuse would explain why none of the other heating elements will energize despite their sub-circuits being in good condition.

Root causes may go even further than this simple example. Suppose after repairing the shorted 200-Watt heating element, we find it fails once more shortly thereafter. Now, our search for root cause becomes a search for the answer to why that one heating element keeps failing prematurely. Perhaps the oven is being used improperly, in such a way that causes physical damage to that 200-Watt element and makes it fail shorted. Perhaps our supplier of 200-Watt heating elements has an error in their manufacturing and/or quality-control processes such that we keep receiving defective heating elements. As you may well imagine, the search for root cause may extend far beyond the immediate scope of a malfunctioning oven, and may even involve entities beyond your responsibility or control. However, root causes being what they are, if uncorrected they will continue to spawn other failures.

Chapter 7

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is *independence*, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of *experimentation* and *computer simulation* (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of *metacognition* within these statements: they are designed to foster a regular habit of examining one's own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

[1] Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

[2] Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

General challenges following tutorial reading

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

7.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor's task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student's needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your *reasoning* than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that *you* are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

When applying Ohm's and Joules' Laws it is imperative to carefully define voltage, current, resistance, and power, and to not confuse any of these quantities with each other. Likewise, the units of measurement for each of these parameters are unique and not to be confused with each other.

[3] *Analytical* thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. *Synthetic* thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

7.1.1 Reading outline and reflections

"Reading maketh a full man; conference a ready man; and writing an exact man" – Francis Bacon

Francis Bacon's advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner's thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

☑ Briefly SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did not comprehend.

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☑ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☑ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☑ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☑ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

7.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

Energy

Conductors versus Insulators

Voltage

Current

Resistance

Volt (unit of measurement)

Ampere (unit of measurement)

Ohm (unit of measurement)

Electrical source

Electrical load

Electrically common points

Ohm's Law

Series connection

Parallel connection

Joule's Law

Dimensional analysis

Resistor

Electric shock

Bonding

One-Hand Rule

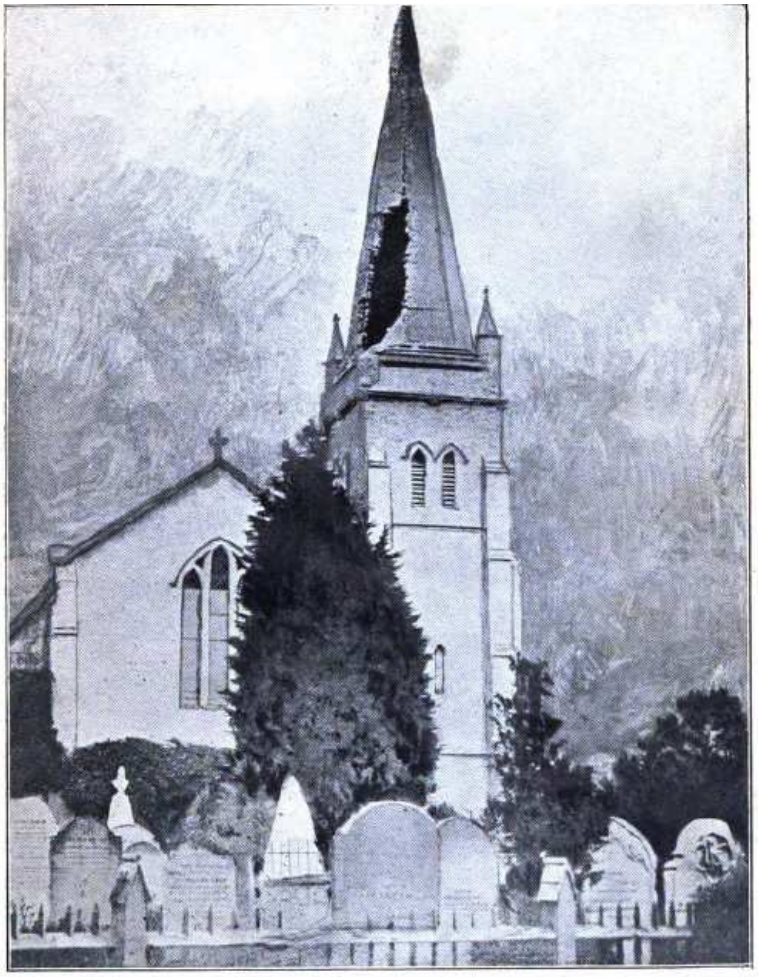
Arc

Arc flash

Lock-out Tag-out (LOTO)

7.1.3 Lightning damage to a church

The following photograph was taken from page 45 of a book written in 1911 called *The Autobiography Of An Electron*:



By permission of Dixon and Corbitt and R. S. Newall, Ltd. *Glasgow*

Damage Done by a Party of Electrons

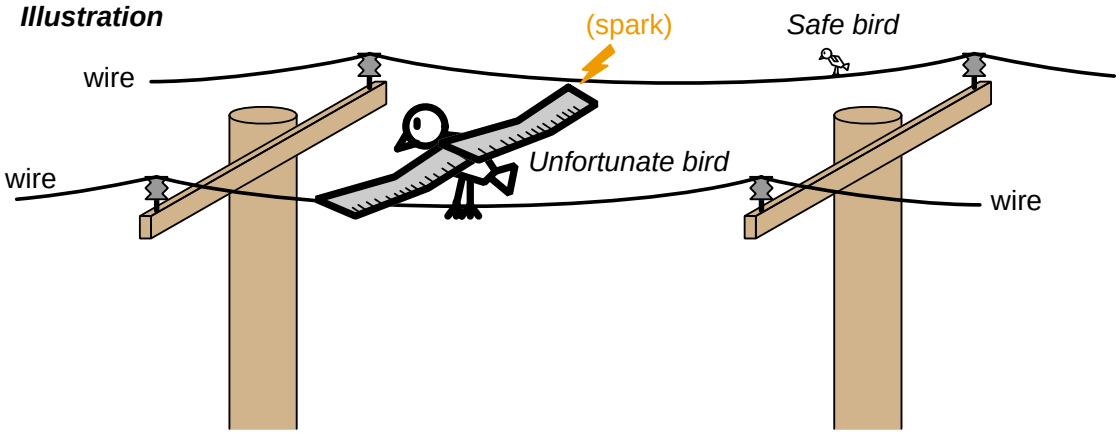
When a myriad of electrons is discharged suddenly from a cloud to the earth, it happens sometimes that considerable damage is done. The above photograph is of a church steeple damaged by lightning in 1875. No lightning-conductor was provided, so the electrons had to get to earth by way of the steeple itself, with the disastrous result as shown.

Explain how a "lightning-conductor" (otherwise known as a *lightning rod*) might have protected this church steeple from the damaging effects of a lightning strike. What is it, exactly, about a long metal rod anchored in the ground protruding to a height above the steeple that would have rendered a lightning strike harmless to the building?

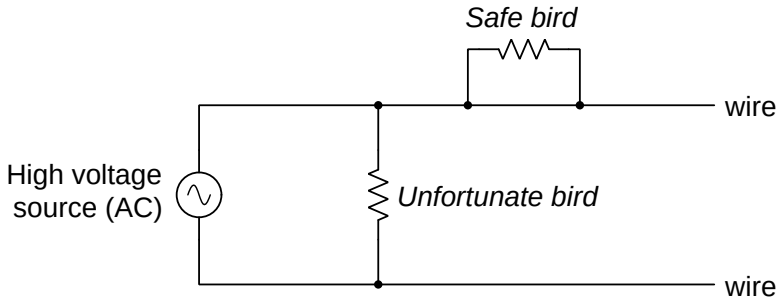
7.1.4 Birds on power lines

Birds do not receive an electric shock when perched on a single power line, even if both of their feet touch the wire. However, birds are immediately electrocuted if their wings *bridge* between two different power lines:

Illustration



Schematic diagram



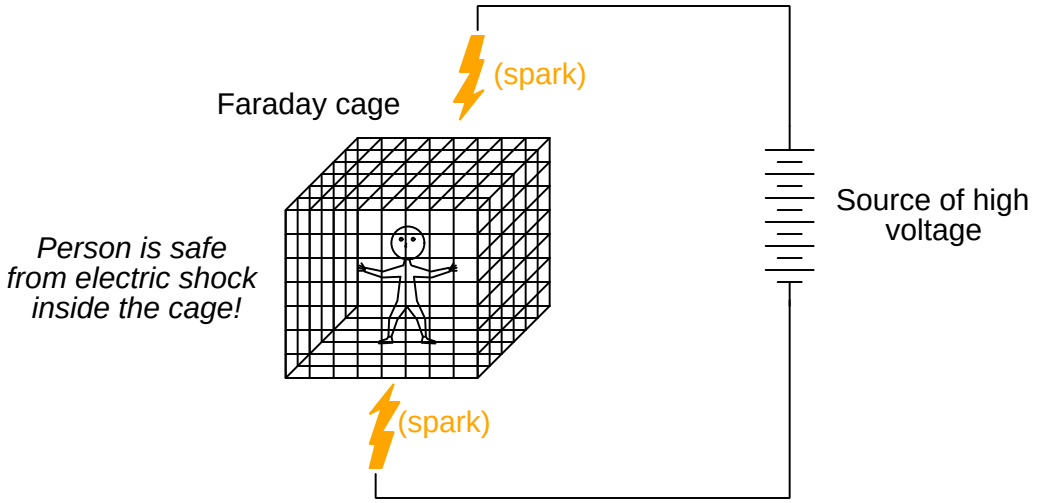
Explain why one bird is safe while the other is not.

Challenges

- Would a bird be in danger if just one wingtip brushed a power line, while the rest of the bird's body was suspended in mid-air flight?.
- Would there be any more or less danger if one of the power line conductors happened to be connected to Earth ground?.

7.1.5 Faraday cages

An apparatus known as a *Faraday cage* is useful for protecting people and/or objects from accidently becoming part of an electric circuit. Spectacular demonstrations have been made with people inside Faraday cages, while a high-voltage generator discharges large arcs from an electrode to the metal cage wires:



An extension of this concept is a Faraday *suit*, with wire mesh sandwiched between two layers of fabric cloth. The wire-mesh "cage" surrounding the person's body prevents them from being shocked by any external electric power source.

Explain how a Faraday cage/suit protects its occupant(s) from electric shock. Also, comment on whether or not a Faraday cage or a Faraday suit would protect its occupant(s) from electrically-induced *burns*.

Challenges

- Would a Faraday cage made of fiberglass or plastic bars work as well as one made of metal bars?
- Suppose one were to be enclosed inside of a metal *box* rather than a metal-bar *cage*. Would such a box protect against electric shock as well?
- Devise a way to determine the electrical resistance of an arc, such as that depicted on the illustration.

7.1.6 A brave man wearing a metal suit

Examine this photograph and caption, taken from page 129 of the book *The Autobiography Of An Electron* written in 1911:

By permission of Siemens Schuckert Werke Berlin

PROTECTION AGAINST A DISCHARGE OF ELECTRONS

When a man is encased completely in an over-all made of flexible metallic gauze he is proof against shock due to a discharge of high-tension electricity. The part played by electrons in the case of electric shock is explained in Chapter IV.

Explain how the metal "over-all" suit affords protection against electric shock.

What dangers *other* than electric shock might be imposed upon the wearer of this suit?

7.1.7 Dangerous voltages and currents for the human body

Professor Charles F. Dalziel of the University of California in Berkeley, on page 8 of his 1961 research paper entitled "Deleterious Effects of Electric Shock", makes the following statements:

> Although the deleterious effects of electric shock are due to the current actually flowing through the human body, in accidents the voltage of the circuit is usually the only electrical quantity known with certainty. While current and voltage are related by Ohm's law, the great variances in skin and contact resistances are so unpredictable that let-go voltages are relatively meaningless. On very high-voltage circuits, the skin and contact resistances break down instantly and thus they play only a minor role in limiting the current received by the victim. However, on the lower voltages the resistances at the contact locations become of increasing importance, and these resistances are of paramount importance on very low voltage circuits. Obviously, wet contacts create a most dangerous condition for receiving an electric shock, and let-go voltages under these conditions may be of limited interest.
>
> . . . From these and similar tests it is concluded that the maximum reasonable safe 60-cycle let-go voltages hand-to-hand are about 21 volts and hand to both feet, ankle deep in salt water, 10 volts. . . . Again the maximum reasonably safe d-c release voltages based on the 99-1/2 percentile are 104 volts hand to hand, and 51 volts hand to both feet ankle deep in salt water (5).

Explain why Dalziel concludes that "let-go voltages are relatively meaningless" while let-go *current* values are reliable safety parameters.

When electric circuits are classified according to their electric shock hazard, the first and most important parameter is typically voltage. Explain why a "high voltage" circuit is considered dangerous, even though (as Dalziel concludes) it is actually the amount of current passing through the human body that quantifies the threat.

Explain why Dalziel had his test subjects stand ankle-deep in salt water when testing for "let-go" voltages. What is the significance of *salt water* for an electrical test such as this?

Challenges

- The type of ground surface material (e.g. dirt, mud, crushed rock, asphalt, concrete) that a person stands on is relevant to electric shock hazard, as some materials conduct electricity more readily than others. Devise an experiment by which one might test the electrical conductivity of soil and other ground materials.

7.1.8 Heat dissipated by a resistance

If a person suffers burns as a result of electric current passing through their body, the worst of the burns tend to be on the skin rather than internal. This is because dry skin exhibits greater resistance (R) than wet internal organs, and power dissipation is proportional to resistance with all other factors being equal ($P = I^2R$).

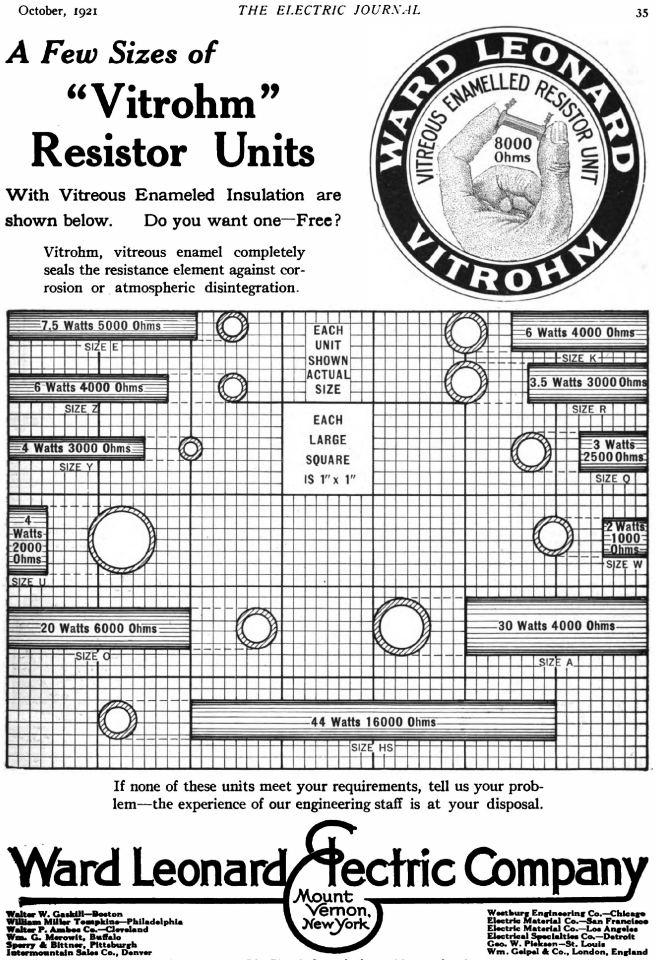
Another burn hazard is the heat emitted by an electric *arc*, where electricity from a voltage source of substantial potential (e.g. from an electric power system) passes through ionized air. We are told that electric arcs may reach spectacularly high temperatures (upwards of 35,000 ^{o}F!) due to their very *low* resistance from end-to-end.

Comparing these two statements, it may seem as though there is a contradiction. In one case we are told that electrical burns are worse on the skin of the body where resistance is *high*, and in the other case we are told that electric arcs reach such high temperatures because their resistance is so very *low*.

Explain why both of these statements are true, and how there is no contradiction between them.

7.1.9 Resistor sizes in 1921

Volume 18, Number 1 issue of *The Electric Journal* contains this advertisement for resistors, circa 1921:



Do you notice a relationship between resistance and physical size? Between power rating and physical size? Give an explanation for the relationship apparent in this scaled illustration of resistors.

Challenges

- Why is it important that these resistors were coated in enamel?

7.1.10 Loaded voltage and current sources

Consider two electrical sources, one outputting a constant voltage and the other outputting a constant current, both connected to variable resistor loads:

Does the voltage source output the greatest amount of power when its load resistor's value is low, or when its load resistor's value is high? In other words, what resistance value poses the "heaviest" load on the voltage source?

Does the current source output the greatest amount of power when its load resistor's value is low, or when its load resistor's value is high? In other words, what resistance value poses the "heaviest" load on the current source?

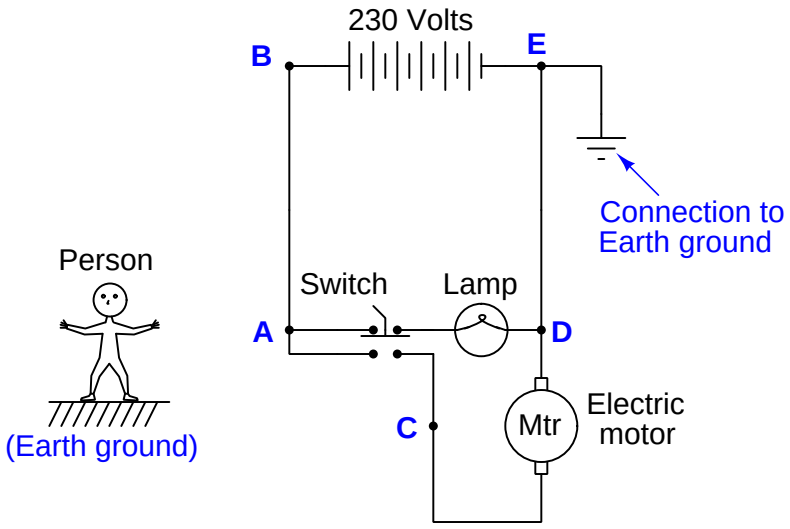
Identify the safest condition for each type of source: a *short-circuit* or an *open-circuit*.

Challenges

- How do you suppose a variable resistor is constructed?
- Answer all the questions in this problem without appealing to any mathematical formulae.

7.1.11 Assessing shock hazards in a circuit

Determine the states of the lamp and electric motor in this circuit with the switch left in the position shown. Then, determine whether or not a shock hazard exists for a person standing on the ground, touching any one of the points labeled in this circuit, citing any relevant electrical principles in defense of each answer:



- Point "A" – *hazard* or *no hazard*?
- Point "B" – *hazard* or *no hazard*?
- Point "C" – *hazard* or *no hazard*?
- Point "D" – *hazard* or *no hazard*?
- Point "E" – *hazard* or *no hazard*?

Would any of these hazard evaluations change if the 230 Volt source's polarity were reversed, so that point "B" was negative and point "E" was positive?

Challenges

- Apply color-highlighting to these circuits to show where the high-potential points are versus the low-potential points, as described in one of the Case Tutorial sections of this module.
- Describe how a voltmeter might be used to assess whether or not a shock hazard was posed touching any of these points, prior to making bodily contact with them.
- Would any of the "dangerous" points be safe to touch if the switch were in the other position?

- Would any of the "dangerous" points be safe to touch if the person stood on a dry rubber (non-conducting) mat rather than on the ground?
- Would any of the "dangerous" points be safe to touch if the ground were moved from point E to point B?

7.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

[4] In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

[5] This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers*. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

7.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($W/m^2 \cdot K^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

7.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), *spreadsheet* software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell `B3`, cell `A8`). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[6] would in an algebraic formula.

When this spreadsheet is executed, the numerical value `39.74576` will appear in cell `B3` rather than the formula `= B1 / B2`, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell `B1` or a different value for time is entered into cell `B2`, cell `B3`'s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell `B3` may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in `B1` and `B2`. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

[6] Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[7] arithmetic operations available for your use in a spreadsheet include the following:

- Addition (`+`)
- Subtraction (`-`)
- Multiplication (`*`)
- Division (`/`)
- Powers (`^`)
- Square roots (`sqrt()`)
- Logarithms (`ln()` , `log10()`)

Parentheses may be used to ensure[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[9] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells `B3`, `B4`, and `B5`, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells `B3` through `B5`. The numerical values appearing in cells `B1` and `B2` will be automatically updated by the computer immediately following any changes made to the coefficients.

[7] Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

[8] Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

[9] Reviewing some algebra here, a *root* is a value for x that yields an overall value of zero for the polynomial. For this polynomial ($9x^2 + 5x - 2$) the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells `B1` and `B2`, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

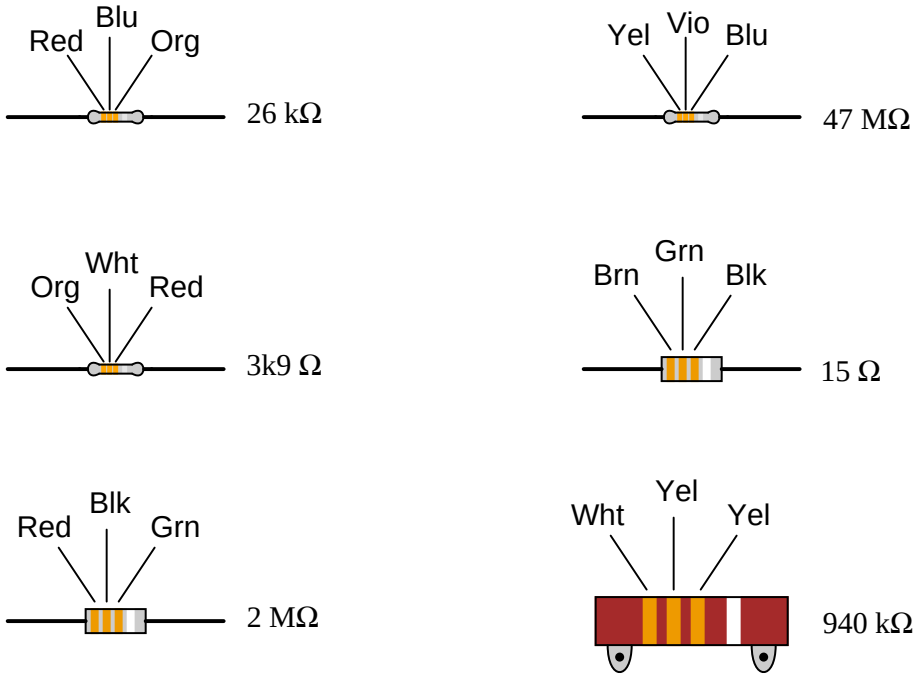
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference each other in the formulae.

Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

[10] My personal preference is to locate all the "given" data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

7.2.3 4-band resistor color codes

Observe the following "4-band" resistors, their color codes, and corresponding resistance values (note that the last color band is omitted, since it deals with precision and not nominal value):



What patterns do you notice between the color codes (given as three-letter abbreviations, so as to avoid interpretational errors resulting from variations in print quality), the resistance values, and the physical sizes of the resistors?

Challenges

- What does the physical size of a resistor represent, if not resistance?

7.2.4 4-band resistor tolerances

Determine the nominal resistance values of these resistors, given their band colors, and also express the allowable tolerance in Ohms. For example, a 25 kΩ resistor with a 10% tolerance rating would have an allowable tolerance of +/- 2.5 kΩ.

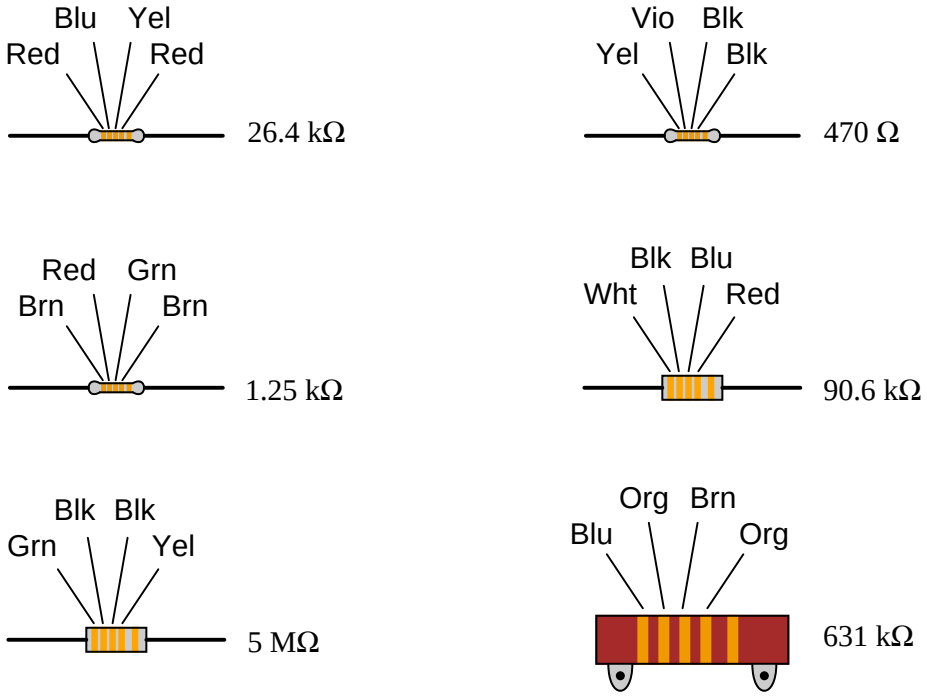
- Red, Org, Blu, Gld =
- Brn, Blk, Grn, Sil =
- Blu, Blk, Brn, Gld =
- Yel, Vio, Red, Sil =
- Grn, Brn, Yel =
- Wht, Blu, Blk, Sil =
- Gry, Grn, Org, Gld =
- Org, Org, Gld =
- Vio, Red, Sil, Gld =
- Brn, Red, Blk, Sil =

Challenges

- Approximate each of these answers without using a calculator.

7.2.5 5-band resistor color codes

Observe the following "5-band" resistors, their color codes, and corresponding resistance values (note that the last color band is omitted, since it deals with precision and not nominal value):



What patterns do you notice between the color codes (given as three-letter abbreviations, so as to avoid interpretational errors resulting from variations in print quality) and the resistance values of each resistor? Why do precision resistors use a "5-band" color code instead of a "4-band" color code?

Challenges

- What does the physical size of a resistor represent, if not resistance?

7.2.6 5-band resistor tolerance check

Determine whether or not the following resistors measure within the resistance range specified by their color codes:

- (Org, Org, Red, Blk, Blu) Measured resistance = 332.5 Ω
- (Brn, Blk, Blk, Gld, Red) Measured resistance = 9.7 Ω
- (Blu, Vio, Brn, Red, Grn) Measured resistance = 67.43 kΩ
- (Red, Wht, Grn, Yel, Vio) Measured resistance = 2.949 MΩ
- (Yel, Vio, Org, Gld) Measured resistance = 44.68 kΩ
- (Gry, Red, Brn, Sil) Measured resistance = 905 Ω
- (Grn, Blu, Gld) Measured resistance = 6.73 Ω
- (Vio, Brn, Red, Gld, Brn) Measured resistance = 70.82 Ω
- (Wht, Org, Blu, Brn, Grn) Measured resistance = 9.38 kΩ
- (Red, Blk, Wht, Grn, Vio) Measured resistance = 20.86 MΩ

Assume that all five-band resistors listed here use the *precision* color code as opposed to the military 5-band code where the fifth band indicates resistor reliability.

Challenges

- What might be some causes for a resistor being out of tolerance?

7.2.7 Voltage, Current, and Resistance calculations

Calculate the missing quantity (either V, I, or R) for each of the following scenarios describing a single-source, single-resistor circuit:

- Resistor = Green-Black-Red-Gold ; Voltage = 12.6 Volts
- Voltage = 208 Volts ; Resistance = 40.7 Ohms
- Voltage = 117 Volts ; Resistor = Orange-Orange-Red-Gold
- Resistance = 22 kΩ ; Voltage = 3.9 V
- Current = 23 Amperes ; Resistance = 8.1 Ohms
- Voltage = 38.1 Volts ; Current = 4.7 Amperes
- I = 2.8 A ; V = 155 V
- R = Orange-White-Orange-Gold ; I = 250 mA

Challenges

- Re-write some of the above values using *scientific notation* (e.g. 208 Volts = 2.08×10^2 Volts).
- Take any one of the listed conditions and vary one of the parameters arbitrarily while holding one of the other parameters constant. Which way will the third parameter change as a result? Will it increase, or decrease? Explain why it will do so, in conceptual terms.

7.2.8 Power, Voltage, Current, and Resistance calculations

Calculate the specified quantity (either P, V, I, or R) for each of the following scenarios describing a single-source, single-resistor circuit:

- Resistor = Yellow-Violet-Red-Gold ; Voltage = 16.2 Volts ; Power =
- Power = 35 Watts ; Current = 9.22 Amperes ; Resistance =
- Resistance = 78 mΩ ; Power = 12 μW ; Current =
- Voltage = 240 Volts ; Resistor = Green-Green-Orange-Gold ; Power =
- Power = 1500 Watts ; Voltage = 116 Volts ; Current =
- Current = 1.445 mA ; Power = 55 mW ; Voltage =
- Resistor = Brown-Red-Orange-Gold ; Current = 340 mA ; Power =
- Voltage = 960 V ; Power = 45 kW ; Resistance =

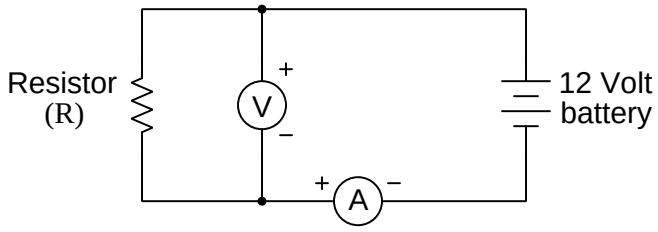
Next, identify strategies for verifying the correctness of your answers.

Challenges

- Re-write some of the above values using *scientific notation* (e.g. 12 kΩ = 1.2×10^4 Ω).
- Take any one of the listed conditions and vary one of the parameters arbitrarily while holding one of the other parameters constant. Which way will the third parameter change as a result? Will it increase, or decrease? Explain why it will do so, in conceptual terms.

7.2.9 Voltage, Current, and Resistance in a simple circuit

Calculate the value of this resistor shown in the following schematic diagram, in *Ohms* (Ω), given the voltage and current values registered by the two meters:



Voltmeter indication = 12.3 Volts
Ammeter indication = 4.556 milliAmperes

Next, apply the following foundational concepts to this circuit, explaining where each of them fit:

- Conservation of Energy
- Conservation of Electric Charge
- Definition of voltage
- Definition of current
- Sources versus loads
- Properties of electrically common points
- Series connection
- Parallel connection

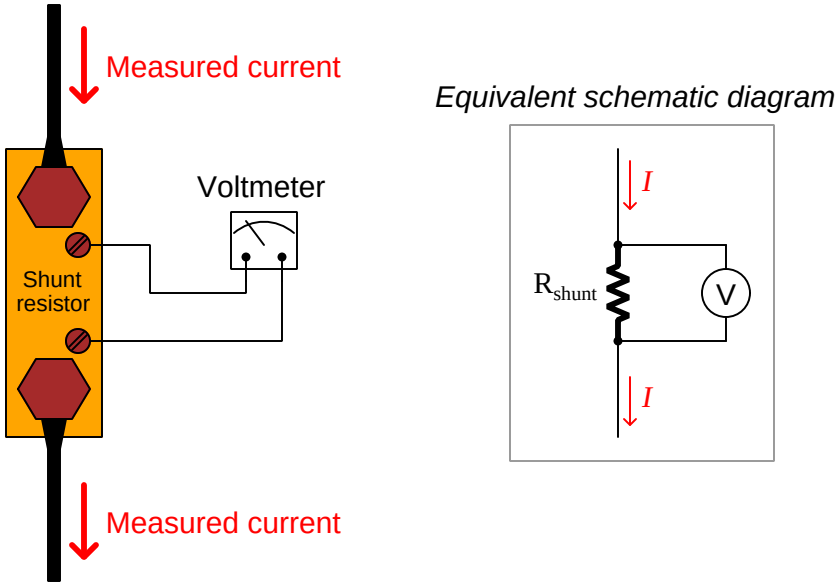
Challenges

- Identify which components in this circuit function as *sources* and which function as *loads*.
- Sketch arrows showing the directions of all currents in this circuit.
- Sketch (+) and (−) symbols to mark voltage polarity for both the battery and the resistor.

7.2.10 Shunt resistor used to measure current

Precision *shunt* resistors are often used as current-sensing elements, being designed to drop very precise amounts of voltage as large electric currents pass through them. By measuring the amount of voltage dropped by a shunt resistor, one is able to determine the amount of current going through it by using Ohm's Law. A photograph of a shunt resistor appears here:

Pictorial and schematic diagrams show how a shunt resistor is used in conjunction with a voltmeter to measure a large current value:



One reason to use a shunt resistor for current measurement rather than an ammeter is *economy*. High current values require large-gauge metal wire to safely convey, which means if the meter must be located a significant distance away from the circuit in question, an ammeter would require long lengths of expensive wire to convey all that current from the circuit, to the ammeter, and back again to the rest of the circuit. Using a shunt resistor means we may use relatively inexpensive (i.e. small-gauge) wire to connect a remotely-located voltmeter to the shunt installed in the high-current circuit.

Shunt resistors are also useful for improving *safety* for circuits where occasional current measurement is necessary by maintenance personnel using multimeters. Explain why this is.

Suppose that a shunt resistance is labeled with the following rating: `50 mV @ 150 A`. Calculate the resistance of this shunt, in Ohms. Express your answer in metric notation, scientific notation, and plain decimal notation.

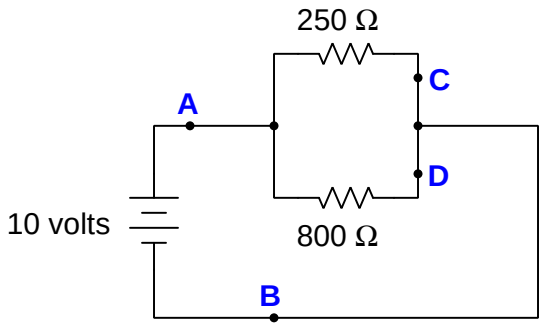
Also, identify whether the shunt resistor functions as a *source* or as a *load*, and sketch voltage polarity symbols (+, −) at each of the resistor's ends based on the direction of current shown.

Challenges

- Explain why large-gauge (i.e. thick) wire is preferable to small-gauge (i.e. thin) wire for carrying high currents.
- Closely examine the photograph of the shunt resistor, and note the materials it's made of. Which portions of the shunt resistor assembly are electrically conductive, and which portions are not? Explain your reasoning.
- Shunt resistors are commonly *hand-trimmed* to a precise resistance value by an assembly worker using a metal file to shave metal off the sides of the thin sheets seen in the photograph. Does shaving metal off of these sheets *increase* the shunt's resistance or *decrease* it?

7.2.11 Path of least resistance

A common saying about electricity is that *"electric current always takes the path of least resistance."* Explain how this proverb relates to the following circuit, where electric current from the battery encounters two alternate paths, one being less resistive than the other:



Will current *only* flow through the lesser-valued resistor? If so, why? If not, why not?

Determine the voltage existing between the following pairs of points in the circuit:

- $V_{AB} =$
- $V_{CD} =$
- $V_{BD} =$
- $V_{AC} =$

Determine the direction and magnitude of electric current (I) at each of the labeled points in the circuit:

- $I_A =$
- $I_B =$
- $I_C =$
- $I_D =$

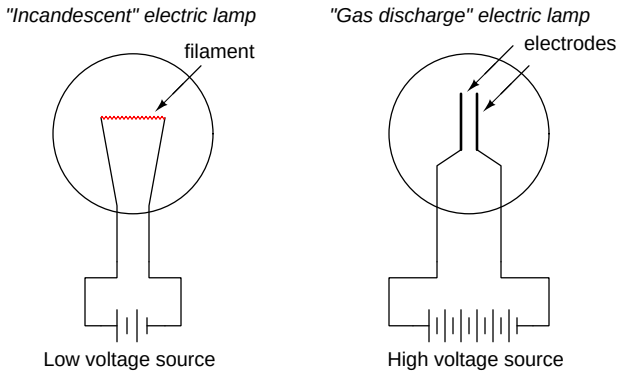
Challenges

- Will the two resistors experience equal or different voltages across their terminals?
- Will the two resistors experience equal or different power dissipation?
- Determine the effects of the wire breaking at point A.

- Determine the effects of the wire breaking at point B.
- Determine the effects of the wire breaking at point C.
- Determine the effects of the wire breaking at point D.

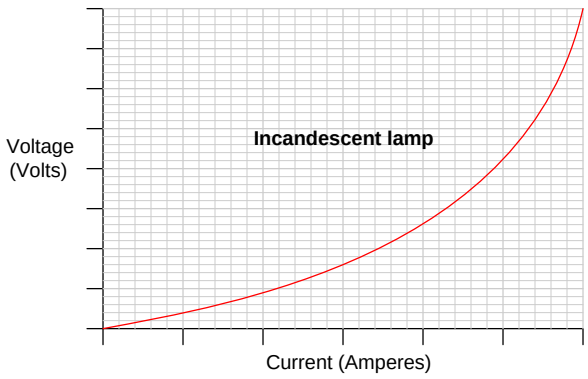
7.2.12 Lamp characteristics

One style of electric lamp, very different from the "incandescent" design which works on the principle of a super-heated wire filament emitting light, is called a *gas discharge lamp*. In this design of lamp, light is produced by the direct "excitation" of low-pressure gas molecules as electric current passes between two electrodes:

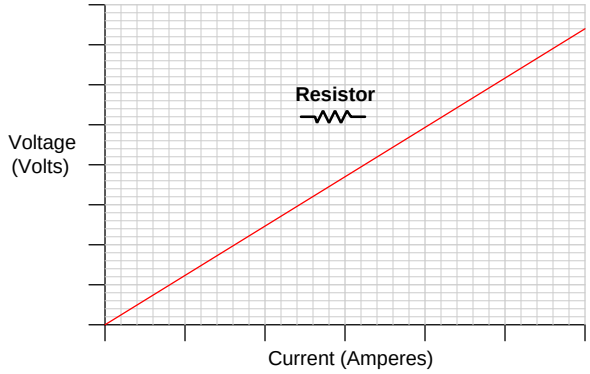


Incandescent lamps tend to emit a broad spectrum of light colors, while gas discharge lamps tend to emit a much narrow spectrum of colors. One very common style of gas discharge lamp is the so-called *neon lamp* traditionally used as illumination for business signs. Neon gas glows with a characteristic pink-orange color when excited by an electric current. Other gases glow with different colors, for example hydrogen gas which glows deep red when electrically excited. Thus, the wide range of colors available from "neon" lamps is actually due to gases other than neon filling the glass tubes.

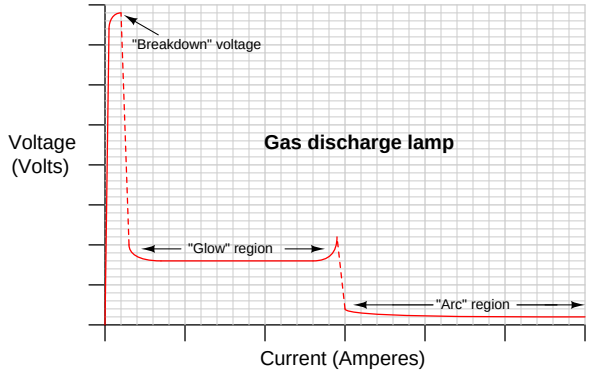
Both types of electric lamps have interesting voltage/current plots, neither one being identical to the linear (straight-line) voltage/current plot of a resistor. First, the voltage/current plot for an incandescent lamp:



Next, the voltage/current plot for a plain resistor:



Lastly, the voltage/current plot for a gas discharge lamp:



Closely examine the voltage/current graphs for each type of electric lamp and compare both to the resistor's graph. Note that *neither* type of lamp exhibits a constant amount of electrical resistance, but rather each lamp's electrical resistance is highly variable. What feature of the resistor's graph indicates it has constant electrical resistance?

Identify where resistance is *least* and also where resistance is *greatest* in each of the two lamp characteristic graphs.

Challenges

- The slope of the gas discharge lamp's graph is extremely steep at its left-hand end. Explain why the graph is so steep at that end, based on what you know about gases and electrical conductivity.
- Explain what is physically occurring at the "breakdown voltage" point of the gas discharge lamp's graph. What exactly is happening to the gas molecules at that voltage value?

- One application of gas discharge lamps is as a *voltage regulator*: maintaining a constant voltage despite significant variations in current. Identify places on the graph for the gas discharge lamp where it manifests this behavior.
- An important mathematical concept both in algebra and calculus is the *slope* of a graph at different points along it. What exactly does the slope of any of these graphs represent, in electrical terms?
- Some electrical components exhibit a characteristic called *negative resistance*. Gas discharge lamps are one such example. What do you suppose "negative resistance" is, and where on the gas discharge lamp's graph might we see an example of it.

7.2.13 Interpreting a SPICE analysis

A computer program called SPICE was developed in the early 1970's, whereby a text-based description of an electric circuit (called a *netlist*) could be entered into a computer, and then computer would be directed to apply fundamental laws of electric circuits to the netlist circuit description according to algorithms coded in SPICE.

Here is a netlist text for a simple one-source, one-resistor circuit:

```
* Simple one-source, one-resistor circuit
v1 1 0 dc 12
r1 1 0 3300
.op
.end
```

One of the fundamental concepts in SPICE programming is that connections between components in the virtual circuit to be analyzed are specified by identifying *node* numbers. All points in the circuit known to be equipotential must bear the same number. In this particular example, the only nodes in existence are `1` and `0`.

Knowing this fact, sketch a simple circuit diagram showing the source and resistor connected as specified by the SPICE netlist, labeling each wire in your diagram with its corresponding node number.

Based on the information contained in the netlist text, what else can you determine about the circuit? Is it possible to discern the voltage value of the source, in Volts? Is it possible to determine the resistance value of each resistor, in Ohms? Is there a current value specified anywhere in the netlist? Based on the component parameters you can identify in this netlist, perform your own calculations using Ohm's and Joule's Laws to predict all other values in this circuit.

When SPICE (software version 2G6) processes the contents of this "netlist" file, it generates the following text output:

```
1*******09/01/16 ********  spice 2g.6    3/15/83 ********08:42:22*****

0* simple one-source, one-resistor circuit

0****     input listing                    temperature =   27.000 deg c

0******************************************************************************

 v1 1 0 dc 12
 r1 1 0 3300
 .op
 .end
1***09/01/16 ***  spice 2g.6    3/15/83 ************08:42:22************

0* simple one-source, one-resistor circuit
0**** small signal bias solution          temperature = 27.000 deg c

0******************************************************************************

  node   voltage
 (  1)   12.0000

     voltage source currents

     name       current
     v1       -3.636E-03

     total power dissipation   4.36E-02  watts
0
         job concluded
0         total job time            0.00
```

Interpret the output of SPICE to the best of your ability. Identify all parameters that you can, and see if the results of the computer's analysis agree with your own calculations.

Challenges

- The output shown here lists a voltage of 12.000 at node 1. Since we know there is no such thing as voltage at a single point, what do you suppose the single reference node of 1 means?
- SPICE utilizes *power-of-ten* notation for small and large values. The standard representation of this in a plain-text format is a capital letter `E` followed by the power value. Identify any such figures in the SPICE output listing, and express them in regular decimal notation.
- Modify this SPICE netlist to utilize a voltage source with a value of 25.6 Volts instead of 12 Volts.
- Modify this SPICE netlist to reverse the polarity of the voltage source.
- Modify this SPICE netlist to utilize a resistor with a value of 4.5 MΩ instead of 3.3 kΩ.

7.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

7.3.1 Properties of connected points

Identify which of these are true statements:

1. Between two points directly connected to each other by a low-resistance conductor, there is guaranteed to be zero voltage.
2. If zero voltage is measured between two points, those points must be connected to each other by a low-resistance conductor.
3. Between two points that are not connected to each other at all, there is guaranteed to be voltage.
4. If substantial voltage is measured between two points, those points cannot be directly connected to each other by a low-resistance conductor.

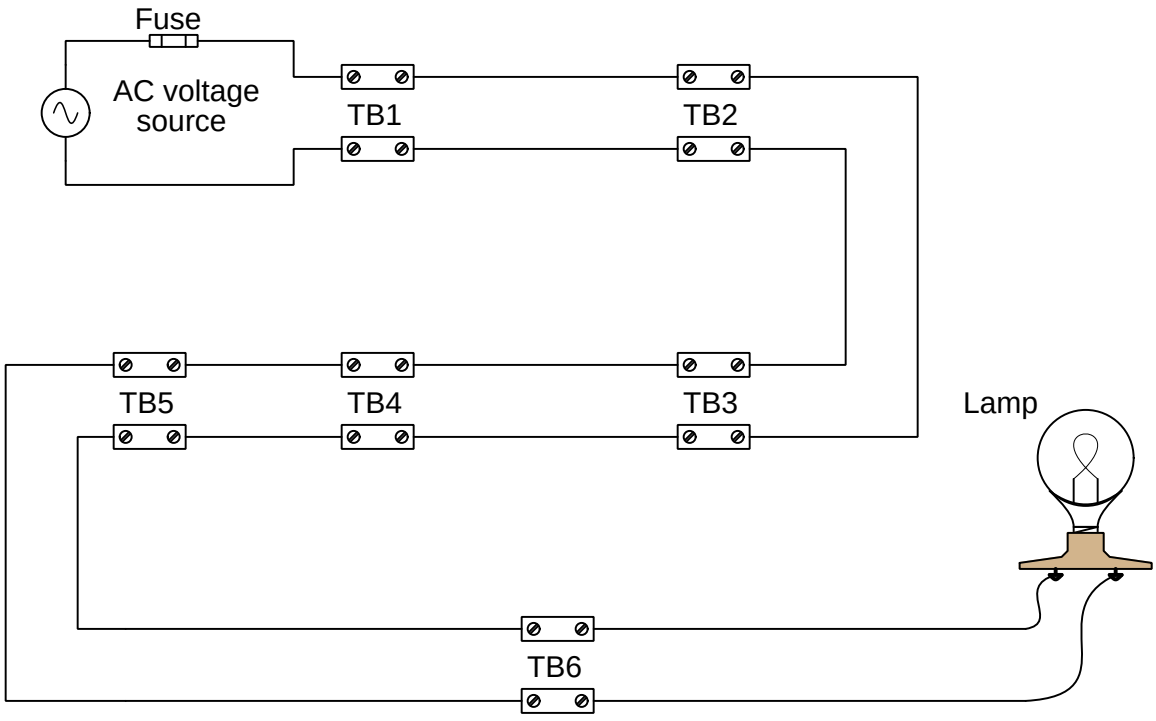
Explain how a sound understanding of these principles will help you diagnose circuit faults.

Challenges

- Devise a set of experiments to prove or disprove each of the statements listed above.

7.3.2 Voltmeter tests in a simple lamp circuit

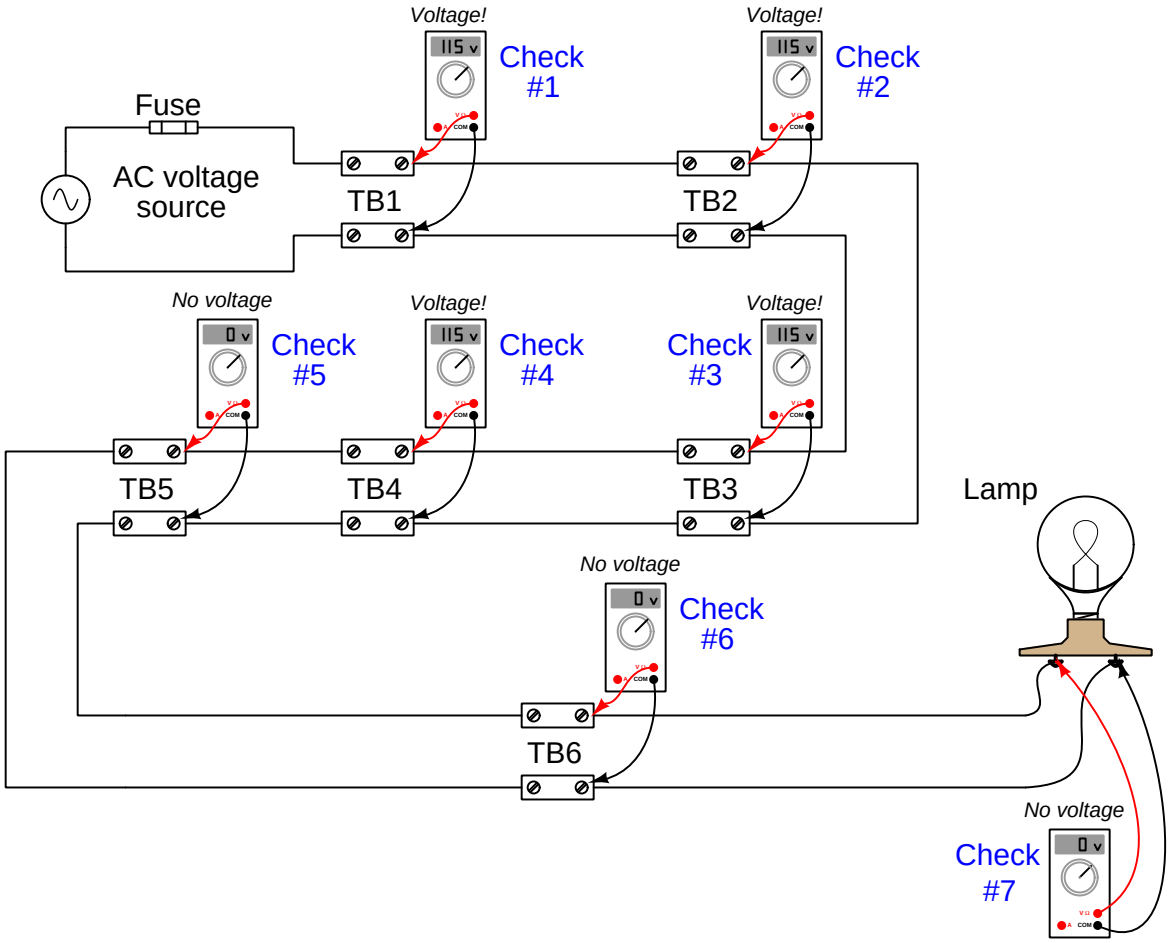
An electrician is troubleshooting a faulty lamp circuit, where the power source and lamp are far removed from one another:



As you can see in the diagram, there are several terminal blocks ("TB") through which electrical power is routed to the lamp. These terminal blocks provide convenient connection points to join wires together, enabling sections of wire to be removed and replaced if necessary, without removing and replacing *all* the wiring.

The electrician uses a voltmeter to check for the presence of voltage between pairs of terminals in the circuit. The terminal blocks are located too far apart to allow for voltage checks between blocks (say, between one connection in TB2 and another connection in TB3). The voltmeter's test leads are only long enough to check for voltage between pairs of connections at each terminal block.

In the next diagram, you can see the electrician's voltage checks, in the sequence that they were taken:



Based on the voltage indications shown, can you determine the location of the circuit fault? What about the electrician's choice of steps – do you think the voltage measurements taken were performed in the most efficient sequence, or would you recommend a different order to save time?

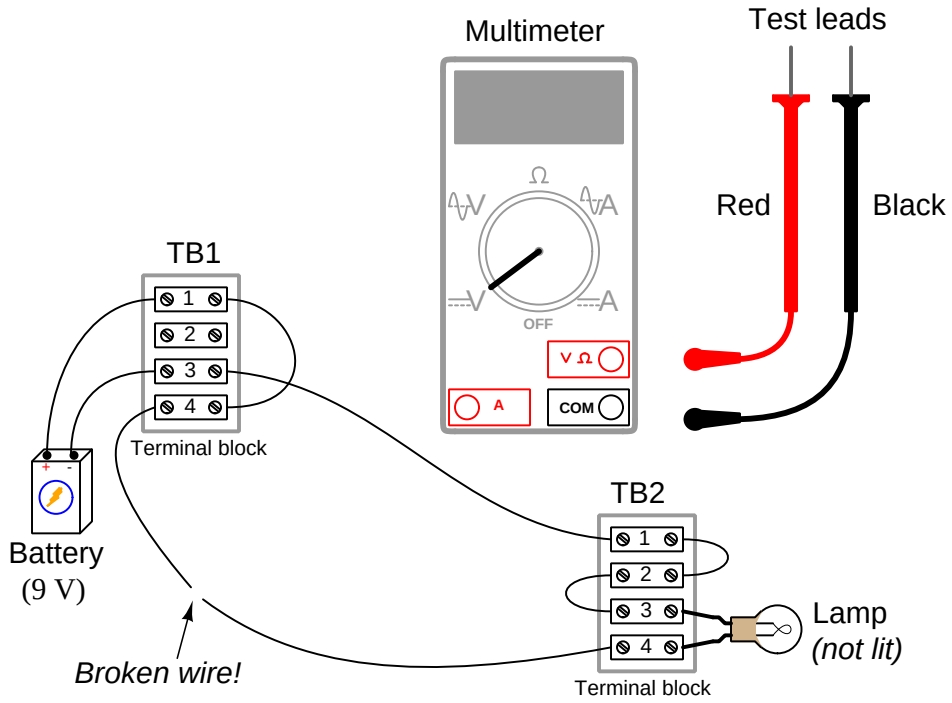
Challenges

- Would an ammeter measurement of *current* in this circuit have been helpful?

- Does the fact that this is an AC (alternating current) rather than DC (direct current) affect our diagnostic decision-making at all? Why or why not?

7.3.3 Using a voltmeter in a failed-open circuit

The following circuit contains an "open" fault in the wire connecting terminals TB1-4 and TB2-4, and the only piece of test equipment is a digital multimeter (DMM):



First, identify which jacks the two test leads should plug into on the DMM to measure DC voltage.

Next, identify how much voltage the DMM would register connected between the following pairs of points:

- Red lead on TB1-1 and Black lead on TB1-3 =
- Red lead on TB1-4 and Black lead on TB2-4 =
- Red lead on TB2-3 and Black lead on TB2-1 =
- Red lead on TB2-1 and Black lead on TB1-1 =
- Red lead on TB2-4 and Black lead on TB1-1 =

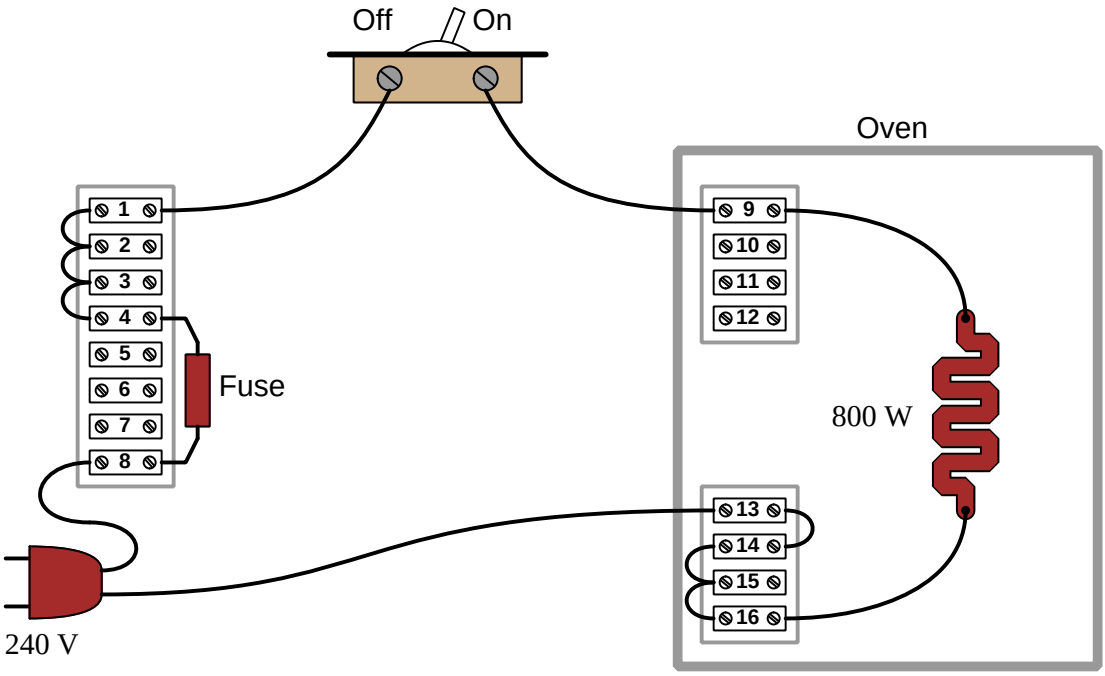
Lastly, which of these voltage measurements *proves* the location of the fault, supposing it were not plainly visible (e.g. the metal wire might be broken underneath the intact insulation)?

Challenges

- One of the challenges presented in this question is the somewhat disorienting layout of wires connecting terminals together. Identify a problem-solving strategy one might employ to simplify the solution of this problem and allow one's mind to concentrate only on voltage measurements and not be distracted by crossing wires.
- Describe the effect(s) of connecting a digital *ammeter* between the same test points.

7.3.4 Malfunctioning oven

This electric oven has a problem somewhere – with the switch "On" and the plug inserted into a 240 Volt power receptacle, it refuses to heat up. The fuse, which is supposed to automatically "open" to stop current if it becomes excessive, is rated at 5 Amperes:



Suppose a technician uses a digital multimeter (DMM) to measure voltage between the following pairs of terminals, in the order presented. Assume the plug is still inserted in the 240 Volt receptacle, and the switch is still in the "On" position:

1. Meter connected between 9 and 15 = 0 Volts
2. Meter connected between 9 and 13 = 0 Volts
3. Meter connected between 4 and 13 = 240 Volts
4. Meter connected between 4 and 8 = 0 Volts
5. Meter connected between 4 and 1 = 0 Volts
6. Meter connected between 1 and 9 = 240 Volts
7. Meter connected between 1 and 13 = 240 Volts

Identify what, if anything, each test (in order) proves about the nature and/or location of the fault.

Challenges

- Devise a more efficient set of tests to locate the fault.
- What circumstances might lead to the fuse "blowing" open?.
- Suppose someone told you the fuse's terminals would be safe to touch with your finger because there should be negligible voltage dropped across an intact fuse. Explain why this is a misguided conclusion.

Chapter 8

Projects and Experiments

The following project and experiment descriptions outline things you can build to help you understand circuits. With any real-world project or experiment there exists the potential for physical harm. *Electricity can be very dangerous in certain circumstances, and you should follow proper safety precautions at all times!*

8.1 Recommended practices

This section outlines some recommended practices for all circuits you design and construct.

8.1.1 Safety first!

Electricity, when passed through the human body, causes uncomfortable sensations and in large enough measures[1] will cause muscles to involuntarily contract. The overriding of your nervous system by the passage of electrical current through your body is particularly dangerous in regard to your heart, which is a vital muscle. Very large amounts of current can produce serious internal burns in addition to all the other effects.

Cardio-pulmonary resuscitation (CPR) is the standard first-aid for any victim of electrical shock. This is a very good skill to acquire if you intend to work with others on dangerous electrical circuits. You should never perform tests or work on such circuits unless someone else is present who is proficient in CPR.

As a general rule, any voltage in excess of 30 Volts poses a definitive electric shock hazard, because beyond this level human skin does not have enough resistance to safely limit current through the body. "Live" work of any kind with circuits over 30 volts should be avoided, and if unavoidable should only be done using electrically insulated tools and other protective equipment (e.g. insulating shoes and gloves). If you are unsure of the hazards, or feel unsafe at any time, stop all work and distance yourself from the circuit!

A policy I strongly recommend for students learning about electricity is to *never come into electrical contact*[2] *with an energized conductor, no matter what the circuit's voltage*[3] *level!* Enforcing this policy may seem ridiculous when the circuit in question is powered by a single battery smaller than the palm of your hand, but it is precisely this instilled habit which will save a person from bodily harm when working with more dangerous circuits. Experience has taught me that students who learn early on to be careless with safe circuits have a tendency to be careless later with dangerous circuits!

In addition to the electrical hazards of shock and burns, the construction of projects and running of experiments often poses other hazards such as working with hand and power tools, potential

[1] Professor Charles Dalziel published a research paper in 1961 called "The Deleterious Effects of Electric Shock" detailing the results of electric shock experiments with both human and animal subjects. The threshold of perception for human subjects holding a conductor in their hand was in the range of 1 milliampere of current (less than this for alternating current, and generally less for female subjects than for male). Loss of muscular control was exhibited by half of Dalziel's subjects at less than 10 milliamperes alternating current. Extreme pain, difficulty breathing, and loss of all muscular control occurred for over 99% of his subjects at direct currents less than 100 milliamperes and alternating currents less than 30 milliamperes. In summary, it doesn't require much electric current to induce painful and even life-threatening effects in the human body! Your first and best protection against electric shock is maintaining an insulating barrier between your body and the circuit in question, such that current from that circuit will be unable to flow through your body.

[2] By "electrical contact" I mean either directly touching an energized conductor with any part of your body, or indirectly touching it through a conductive tool. The only physical contact you should ever make with an energized conductor is via an electrically insulated tool, for example a screwdriver with an electrically insulated handle, or an insulated test probe for some instrument.

[3] Another reason for consistently enforcing this policy, even on low-voltage circuits, is due to the dangers that even some low-voltage circuits harbor. A single 12 Volt automobile battery, for example, can cause a surprising amount of damage if short-circuited simply due to the high current levels (i.e. very low internal resistance) it is capable of, even though the voltage level is too low to cause a shock through the skin. Mechanics wearing metal rings, for example, are at risk from severe burns if their rings happen to short-circuit such a battery! Furthermore, even when working on circuits that are simply too low-power (low voltage and low current) to cause any bodily harm, touching them while energized can pose a threat to the circuit components themselves. In summary, it's generally wise (and *always* a good habit to build) to "power down" *any* circuit before making contact between it and your body.

contact with high temperatures, potential chemical exposure, etc. You should never proceed with a project or experiment if you are unaware of proper tool use or lack basic protective measures (e.g. personal protective equipment such as safety glasses) against such hazards.

Some other safety-related practices should be followed as well:

- All power conductors extending outward from the project must be *firmly* strain-relieved (e.g. "cord grips" used on line power cords), so that an accidental tug or drop will not compromise circuit integrity.
- All electrical connections must be sound and appropriately made (e.g. soldered wire joints rather than twisted-and-taped; terminal blocks rather than solderless breadboards for high-current or high-voltage circuits). Use "touch-safe" terminal connections with recessed metal parts to minimize risk of accidental contact.
- Always provide overcurrent protection in any circuit you build. *Always.* This may be in the form of a fuse, a circuit breaker, and/or an electronically current-limited power supply.
- Always ensure circuit conductors are rated for more current than the overcurrent protection limit. *Always.* A fuse does no good if the wire or printed circuit board trace will "blow" before it does!
- Always bond metal enclosures to Earth ground for any line-powered circuit. *Always.* Ensuring an equipotential state between the enclosure and Earth by making the enclosure electrically common with Earth ground ensures no electric shock can occur simply by one's body bridging between the Earth and the enclosure.
- Avoid building a high-energy circuit when a low-energy circuit will suffice. For example, I always recommend beginning students power their first DC resistor circuits using small batteries rather than with line-powered DC power supplies. The intrinsic energy limitations of a dry-cell battery make accidents highly unlikely.
- Use line power receptacles that are GFCI (Ground Fault Current Interrupting) to help avoid electric shock from making accidental contact with a "hot" line conductor.
- Always wear eye protection when working with tools or live systems having the potential to eject material into the air. Examples of such activities include soldering, drilling, grinding, cutting, wire stripping, working on or near energized circuits, etc.
- Always use a step-stool or stepladder to reach high places. Never stand on something not designed to support a human load.
- When in doubt, *ask an expert.* If anything even seems remotely unsafe to you, do not proceed without consulting a trusted person fully knowledgeable in electrical safety.

8.1.2 Other helpful tips

Experience has shown the following practices to be very helpful, especially when students make their own component selections, to ensure the circuits will be well-behaved:

- Avoid resistor values less than 1 kΩ or greater than 100 kΩ, unless such values are definitely necessary[4]. Resistances below 1 kΩ may draw excessive current if directly connected to a voltage source of significant magnitude, and may also complicate the task of accurately measuring current since any ammeter's non-zero resistance inserted in series with a low-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Resistances above 100 kΩ may complicate the task of measuring voltage since any voltmeter's finite resistance connected in parallel with a high-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Similarly, AC circuit impedance values should be between 1 kΩ and 100 kΩ, and for all the same reasons.

- Ensure all electrical connections are low-resistance and physically rugged. For this reason, one should avoid *compression splices* (e.g. "butt" connectors), solderless breadboards[5], and wires that are simply twisted together.

- Build your circuit with **testing** in mind. For example, provide convenient connection points for test equipment (e.g. multimeters, oscilloscopes, signal generators, logic probes).

- Design permanent projects with **maintenance** in mind. The more convenient you make maintenance tasks, the more likely they will get done.

- **Always document and save your work**. Circuits lacking schematic diagrams are more difficult to troubleshoot than documented circuits. Similarly, circuit construction is simpler when a schematic diagram precedes construction. Experimental results are easier to interpret when comprehensively recorded. Consider modern videorecording technology for this purpose where appropriate.

- **Record your steps** when troubleshooting. **Talk to yourself** when solving problems. These simple steps clarify thought and simplify identification of errors.

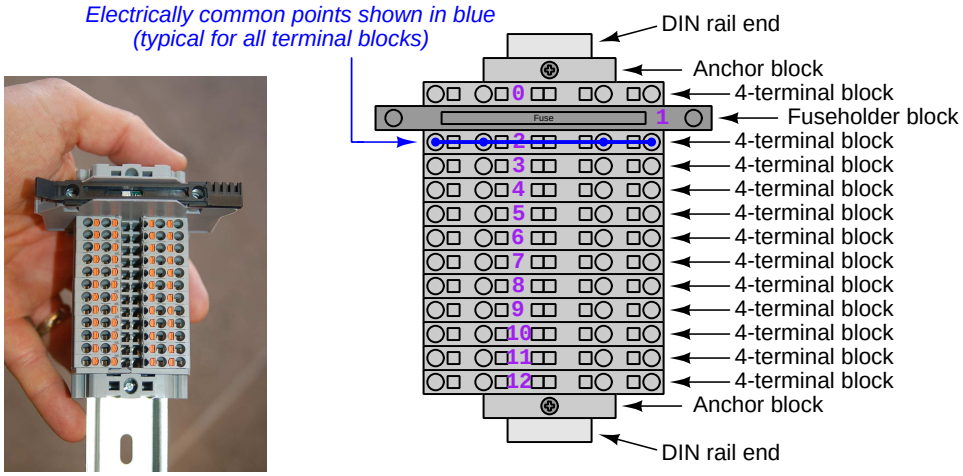
[4] An example of a necessary resistor value much less than 1 kΩ is a *shunt resistor* used to produce a small voltage drop for the purpose of sensing current in a circuit. Such shunt resistors must be low-value in order not to impose an undue load on the rest of the circuit. An example of a necessary resistor value much greater than 100 kΩ is an electrostatic *drain resistor* used to dissipate stored electric charges from body capacitance for the sake of preventing damage to sensitive semiconductor components, while also preventing a path for current that could be dangerous to the person (i.e. shock).

[5] Admittedly, solderless breadboards are very useful for constructing complex electronic circuits with many components, especially DIP-style integrated circuits (ICs), but they tend to give trouble with connection integrity after frequent use. An alternative for projects using low counts of ICs is to solder IC sockets into prototype printed circuit boards (PCBs) and run wires from the soldered pins of the IC sockets to terminal blocks where reliable temporary connections may be made.

8.1.3 Terminal blocks for circuit construction

Terminal blocks are the standard means for making electric circuit connections in industrial systems, and are also quite useful for student-built experiments, providing a robust alternative to solderless breadboards[6]. Terminal blocks provide highly reliable connections rated for significant voltage and current magnitudes, and they force the builder to think carefully about component placement which is an important mental practice. Terminal blocks designed to mount on standard 35 mm DIN rail[7] come in many types and capabilities.

Every student of electricity should build their own terminal block array consisting of several terminal blocks where each block has at least 4 connection points all electrically common to each other[8] and at least one terminal block that is a fuse holder for overcurrent protection. A pair of anchoring blocks hold all terminal blocks securely on the DIN rail, preventing them from sliding off the rail. Each of the terminals should bear a unique number starting from 0. An example is shown in the following photograph and illustration:



Screwless terminal blocks (using internal spring clips to clamp wire and component lead ends) are preferred over screw-based terminal blocks, as they reduce assembly and disassembly time, and also minimize repetitive wrist stress from twisting screwdrivers. Some screwless terminal blocks require the use of a special tool to release the spring clip, while others such as the Phoenix Contact model 3211019 blocks shown in the photograph provide buttons[9] for this task which may be pressed using the tip of any suitable tool such as a small screwdriver or multimeter test probe tip.

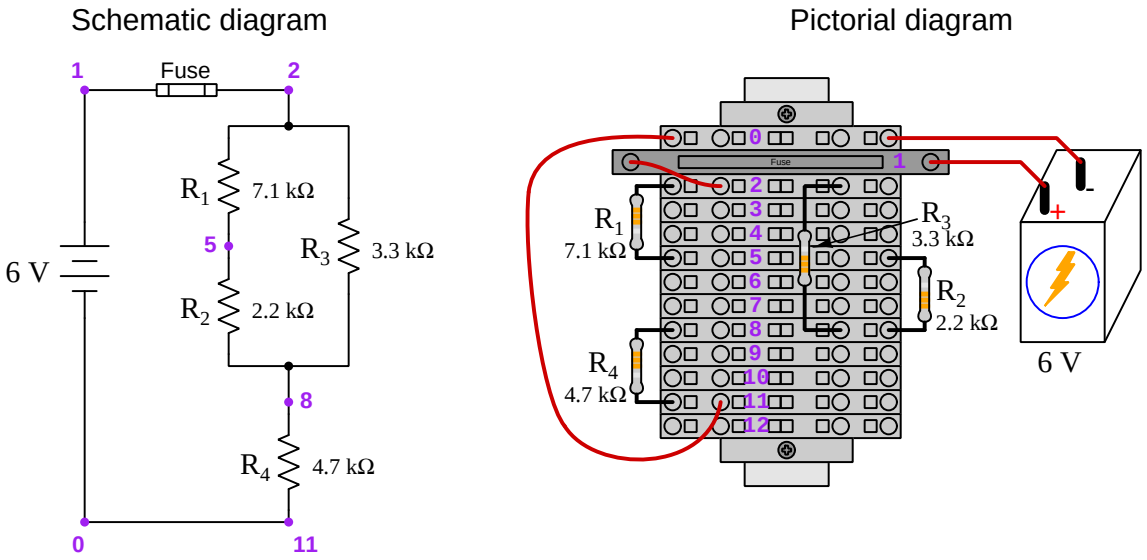
[6] Solderless breadboard are preferable for complicated electronic circuits with multiple integrated "chip" components, but for simpler circuits I find terminal blocks much more practical. An alternative to solderless breadboards for "chip" circuits is to solder chip sockets onto a PCB and then use wires to connect the socket pins to terminal blocks. This also accommodates *surface-mount* components, which solderless breadboards do not.

[7] DIN rail is a metal rail designed to serve as a mounting point for a wide range of electrical and electronic devices such as terminal blocks, fuses, circuit breakers, relay sockets, power supplies, data acquisition hardware, etc.

[8] Sometimes referred to as *equipotential*, *same-potential*, or *potential distribution* terminal blocks.

[9] The small orange-colored squares seen in the above photograph are buttons for this purpose, and may be actuated by pressing with any tool of suitable size.

The following example shows how such a terminal block array might be used to construct a series-parallel resistor circuit consisting of four resistors and a battery:



Numbering on the terminal blocks provides a very natural translation to SPICE[10] netlists, where component connections are identified by terminal number:

```
* Series-parallel resistor circuit
v1 1 0 dc 6
r1 2 5 7100
r2 5 8 2200
r3 2 8 3300
r4 8 11 4700
rfuse 1 2 0.01
rwire 0 11 0.01
.op
.end
```

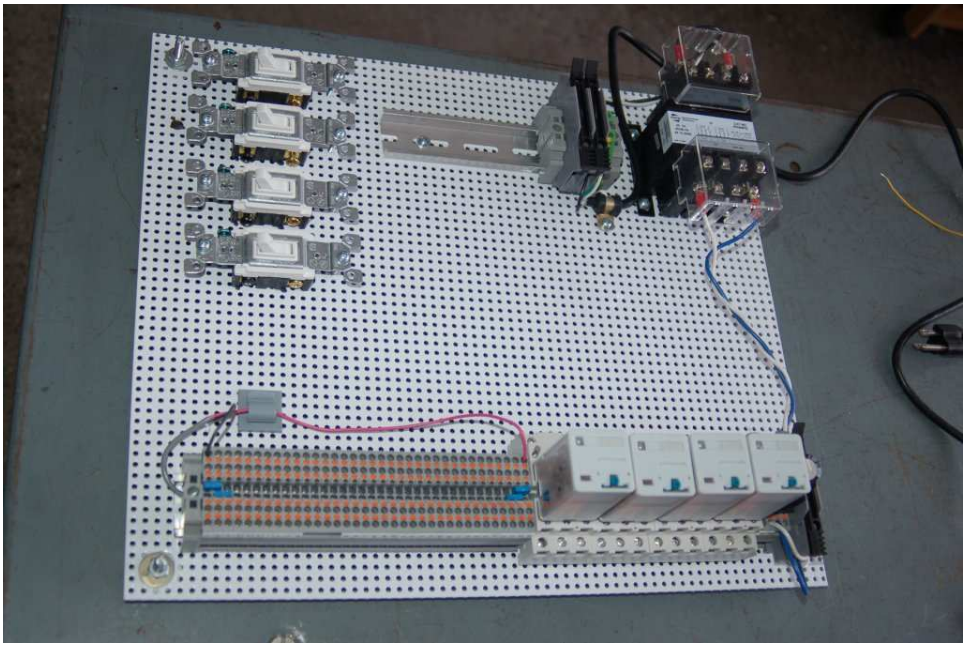
Note the use of two resistances `rfuse` and `rwire` to describe fuse resistance between terminals 1 and 2 and "jumper" wire resistance between terminals 0 and 11, respectively. Being resistances, SPICE requires a resistance value for each, and here we see they have both been set to an arbitrarily low value of 0.01 Ohm appropriate to their real-life resistance values.

Listing all components and wires along with their numbered terminals happens to be a useful documentation method for any circuit built on terminal blocks, independent of SPICE. Such a

[10] SPICE is computer software designed to analyze electrical and electronic circuits. Circuits are described for the computer in the form of *netlists* which are text files listing each component type, connection node numbers, and component values.

"wiring sequence" may be thought of as a *non-graphical description* of an electric circuit, and is exceptionally easy to follow.

An example of a more elaborate terminal block array is shown in the following photograph, with terminal blocks and "ice-cube" style electromechanical relays mounted to DIN rail, which is turn mounted to a perforated subpanel[11]. This "terminal block board" hosts an array of thirty five undedicated terminal block sections, four SPDT toggle switches, four DPDT "ice-cube" relays, a step-down control power transformer, bridge rectifier and filtering capacitor, and several fuses for overcurrent protection:



Four plastic-bottomed "feet" support the subpanel above the benchtop surface, and an unused section of DIN rail stands ready to accept other components. Safety features include electrical bonding of the AC line power cord's ground to the metal subpanel (and all metal DIN rails), mechanical strain relief for the power cord to isolate any cord tension from wire connections, clear plastic finger guards covering the transformer's screw terminals, as well as fused overcurrent protection for the 120 Volt AC line power and the transformer's 12 Volt AC output. The perforated holes happen to be on $\frac{1}{4}$ inch centers with a diameter suitable for tapping with 6-32 machine screw threads, their presence making it very easy to attach other sections of DIN rail, printed circuit boards, or specialized electrical components directly to the grounded metal subpanel. Such a "terminal block board" is an inexpensive[12] yet highly flexible means to construct physically robust circuits using industrial wiring practices.

[11] An electrical *subpanel* is a thin metal plate intended for mounting inside an electrical enclosure. Components are attached to the subpanel, and the subpanel in turn bolts inside the enclosure. Subpanels allow circuit construction outside the confines of the enclosure, which speeds assembly. In this particular usage there is no enclosure, as the subpanel is intended to be used as an open platform for the convenient construction of circuits on a benchtop by students. In essence, this is a modern version of the traditional *breadboard* which was literally a wooden board such as might be used for cutting loaves of bread, but which early electrical and electronic hobbyists used as platforms for the construction of circuits.

[12] At the time of this writing (2019) the cost to build this board is approximately $250 US dollars.

8.1.4 Conducting experiments

An *experiment* is an exploratory act, a test performed for the purpose of assessing some proposition or principle. Experiments are the foundation of the *scientific method*, a process by which careful observation helps guard against errors of speculation. All good experiments begin with an *hypothesis*, defined by the American Heritage Dictionary of the English Language as:

> An assertion subject to verification or proof, as (a) A proposition stated as a basis for argument or reasoning. (b) A premise from which a conclusion is drawn. (c) A conjecture that accounts, within a theory or ideational framework, for a set of facts and that can be used as a basis for further investigation.

Stated plainly, an hypothesis is an *educated guess* about cause and effect. The correctness of this initial guess matters little, because any well-designed experiment will reveal the truth of the matter. In fact, *incorrect* hypotheses are often the most valuable because the experiments they engender lead us to surprising discoveries. One of the beautiful aspects of science is that it is more focused on the process of *learning* than about the status of *being correct*[13]. In order for an hypothesis to be valid, it must be testable[14], which means it must be a claim possible to refute given the right data. Hypotheses impossible to critique are useless.

Once an hypothesis has been formulated, an experiment must be designed to test that hypothesis. A well-designed experiment requires careful regulation of all relevant variables, both for personal safety and for prompting the hypothesized results. If the effects of one particular variable are to be tested, the experiment must be run multiple times with different values of (only) that particular variable. The experiment set up with the "baseline" variable set is called the *control*, while the experiment set up with different value(s) is called the *test* or *experimental*.

For some hypotheses a viable alternative to a physical experiment is a *computer-simulated experiment* or even a *thought experiment*. Simulations performed on a computer test the hypothesis against the physical laws encoded within the computer simulation software, and are particularly useful for students learning new principles for which simulation software is readily available[15].

[13] Science is more about clarifying our view of the universe through a systematic process of error detection than it is about proving oneself to be right. Some scient*ists* may happen to have large egos – and this may have more to do with the ways in which large-scale scientific research is *funded* than anything else – but scientific *method* itself is devoid of ego, and if embraced as a practical philosophy is quite an effective stimulant for humility. Within the education system, scientific method is particularly valuable for helping students break free of the crippling fear of *being wrong*. So much emphasis is placed in formal education on assessing correct retention of facts that many students are fearful of saying or doing anything that might be perceived as a mistake, and of course making mistakes (i.e. having one's hypotheses disproven by experiment) is an indispensable tool for learning. Introducing science in the classroom – *real* science characterized by individuals forming actual hypotheses and testing those hypotheses by experiment – helps students become self-directed learners.

[14] This is the principle of *falsifiability*: that a scientific statement has value only insofar as it is liable to disproof given the requisite experimental evidence. Any claim that is unfalsifiable – that is, a claim which can *never* be disproven by any evidence whatsoever – could be completely wrong and we could never know it.

[15] A very pertinent example of this is learning how to analyze electric circuits using simulation software such as SPICE. A typical experimental cycle would proceed as follows: (1) Find or invent a circuit to analyze; (2) Apply your analytical knowledge to that circuit, predicting all voltages, currents, powers, etc. relevant to the concepts you are striving to master; (3) Run a simulation on that circuit, collecting "data" from the computer when complete; (4) Evaluate whether or not your hypotheses (i.e. predicted voltages, currents, etc.) agree with the computer-generated results; (5) If so, your analyses are (provisionally) correct – if not, examine your analyses and the computer simulation again to determine the source of error; (6) Repeat this process as many times as necessary until you achieve mastery.

Thought experiments are useful for detecting inconsistencies within your own understanding of some subject, rather than testing your understanding against physical reality.

Here are some general guidelines for conducting experiments:

- The clearer and more specific the hypothesis, the better. Vague or unfalsifiable hypotheses are useless because they will fit *any* experimental results, and therefore the experiment cannot teach you anything about the hypothesis.
- Collect as much data (i.e. information, measurements, sensory experiences) generated by an experiment as is practical. This includes the time and date of the experiment, too!
- *Never* discard or modify data gathered from an experiment. If you have reason to believe the data is unreliable, write notes to that effect, but never throw away data just because you think it is untrustworthy. It is quite possible that even "bad" data holds useful information, and that someone else may be able to uncover its value even if you do not.
- Prioritize *quantitative* data over *qualitative* data wherever practical. Quantitative data is more specific than qualitative, less prone to subjective interpretation on the part of the experimenter, and amenable to an arsenal of analytical methods (e.g. statistics).
- Guard against your own bias(es) by making your experimental results available to others. This allows other people to scrutinize your experimental design and collected data, for the purpose of detecting and correcting errors you may have missed. Document your experiment such that others may independently replicate it.
- Always be looking for sources of error. No physical measurement is perfect, and so it is impossible to achieve *exact* values for any variable. Quantify the amount of uncertainty (i.e. the "tolerance" of errors) whenever possible, and be sure your hypothesis does not depend on precision better than this!
- Always remember that scientific confirmation is provisional – no number of "successful" experiments will prove an hypothesis true for all time, but a single experiment can disprove it. Put into simpler terms, *truth is elusive but error is within reach.*
- Remember that scientific method is about *learning*, first and foremost. An unfortunate consequence of scientific triumph in modern society is that science is often viewed by non-practitioners as an unerring source of truth, when in fact science is an ongoing process of challenging existing ideas to probe for errors and oversights. This is why it is perfectly acceptable to have a failed hypothesis, and why the only truly failed experiment is one where nothing was learned.

The following is an example of a well-planned and executed experiment, in this case a physical experiment demonstrating Ohm's Law.

```
Planning Time/Date = 09:30 on 12 February 2019

HYPOTHESIS: the current through any resistor should be exactly proportional
to the voltage impressed across it.

PROCEDURE: connect a resistor rated 1 k Ohm and 1/4 Watt to a variable-voltage
DC power supply.  Use an ammeter in series to measure resistor current and
a voltmeter in parallel to measure resistor voltage.

RISKS AND MITIGATION: excessive power dissipation may harm the resistor and/
or pose a burn hazard, while excessive voltage poses an electric shock hazard.
30 Volts is a safe maximum voltage for laboratory practices, and according to
Joule's Law a 1000 Ohm resistor will dissipate 0.25 Watts at 15.81 Volts
(P = V^2 / R), so I will remain below 15 Volts just to be safe.

Experiment Time/Date = 10:15 on 12 February 2019

DATA COLLECTED:
  (Voltage)    (Current)         (Voltage)   (Current)
   0.000 V   =  0.000 mA          8.100    =  7.812 mA
   2.700 V   =  2.603 mA          10.00 V  =  9.643 mA
   5.400 V   =  5.206 mA          14.00 V  =  13.49 mA

Analysis Time/Date = 10:57 on 12 February 2019

ANALYSIS: current definitely increases with voltage, and although I expected
exactly one milliAmpere per Volt the actual current was usually less than
that.  The voltage/current ratios ranged from a low of 1036.87 (at 8.1 Volts)
to a high of 1037.81 (at 14 Volts), but this represents a variance of only
-0.0365% to +0.0541% from the average, indicating a very consistent
proportionality -- results consistent with Ohm's Law.

ERROR SOURCES: one major source of error is the resistor's value itself.  I
did not measure it, but simply assumed color bands of brown-black-red meant
exactly 1000 Ohms.  Based on the data I think the true resistance is closer
to 1037 Ohms.  Another possible explanation is multimeter calibration error.
However, neither explains the small positive and negative variances from the
average.  This might be due to electrical noise, a good test being to repeat
the same experiment to see if the variances are the same or different.  Noise
should generate slightly different results every time.
```

The following is an example of a well-planned and executed *virtual* experiment, in this case demonstrating Ohm's Law using a computer (SPICE) simulation.

```
Planning Time/Date = 12:32 on 14 February 2019

HYPOTHESIS: for any given resistor, the current through that resistor should be
exactly proportional to the voltage impressed across it.

PROCEDURE: write a SPICE netlist with a single DC voltage source and single
1000 Ohm resistor, then use NGSPICE version 26 to perform a "sweep" analysis
from 0 Volts to 25 Volts in 5 Volt increments.

    * SPICE circuit
    v1 1 0 dc
    r1 1 0 1000
    .dc v1 0 25 5
    .print dc v(1) i(v1)
    .end

RISKS AND MITIGATION: none.

DATA COLLECTED:
       DC transfer characteristic  Thu Feb 14 13:05:08  2019
    ------------------------------------------------------------
    Index   v-sweep         v(1)            v1#branch
    ------------------------------------------------------------
    0       0.000000e+00    0.000000e+00    0.000000e+00
    1       5.000000e+00    5.000000e+00    -5.00000e-03
    2       1.000000e+01    1.000000e+01    -1.00000e-02
    3       1.500000e+01    1.500000e+01    -1.50000e-02
    4       2.000000e+01    2.000000e+01    -2.00000e-02
    5       2.500000e+01    2.500000e+01    -2.50000e-02

Analysis Time/Date = 13:06 on 14 February 2019

ANALYSIS: perfect agreement between data and hypothesis -- current is precisely
1/1000 of the applied voltage for all values.  Anything other than perfect
agreement would have probably meant my netlist was incorrect.  The negative
current values surprised me, but it seems this is just how SPICE interprets
normal current through a DC voltage source.

ERROR SOURCES: none.
```

As gratuitous as it may seem to perform experiments on a physical law as well-established as Ohm's Law, even the examples listed previously demonstrate opportunity for real learning. In the physical experiment example, the student should identify and explain why their data does not perfectly agree with the hypothesis, and this leads them naturally to consider sources of error. In the computer-simulated experiment, the student is struck by SPICE's convention of denoting regular current through a DC voltage source as being *negative* in sign, and this is also useful knowledge for future simulations. Scientific experiments are most interesting when things *do not* go as planned!

Aside from verifying well-established physical laws, simple experiments are extremely useful as educational tools for a wide range of purposes, including:

- Component familiarization (e.g. *Which terminals of this switch connect to the NO versus NC contacts?*)
- System testing (e.g. *How heavy of a load can my AC-DC power supply source before the semiconductor components reach their thermal limits?*)
- Learning programming languages (e.g. *Let's try to set up an "up" counter function in this PLC!*)

Above all, the priority here is to inculcate the habit of hypothesizing, running experiments, and analyzing the results. This experimental cycle not only serves as an excellent method for self-directed learning, but it also works exceptionally well for troubleshooting faults in complex systems, and for these reasons should be a part of every technician's and every engineer's education.

8.1.5 Constructing projects

Designing, constructing, and testing projects is a very effective means of practical education. Within a formal educational setting, projects are generally chosen (or at least vetted) by an instructor to ensure they may be reasonably completed within the allotted time of a course or program of study, and that they sufficiently challenge the student to learn certain important principles. In a self-directed environment, projects are just as useful as a learning tool but there is some risk of unwittingly choosing a project beyond one's abilities, which can lead to frustration.

Here are some general guidelines for managing projects:

- Define your goal(s) before beginning a project: what do you wish to achieve in building it? What, exactly, should the completed project *do*?
- Analyze your project prior to construction. Document it in appropriate forms (e.g. schematic diagrams), predict its functionality, anticipate all associated risks. In other words, *plan ahead.*
- Set a reasonable budget for your project, and stay within it.
- Identify any deadlines, and set reasonable goals to meet those deadlines.
- Beware of *scope creep*: the tendency to modify the project's goals before it is complete.
- Document your progress! An easy way to do this is to use photography or videography: take photos and/or videos of your project as it progresses. Document failures as well as successes, because both are equally valuable from the perspective of learning.

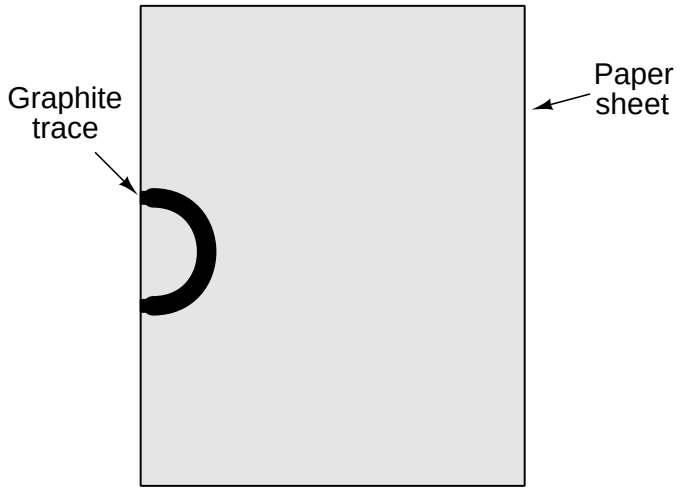
8.2 Experiment: pencil-trace resistance

In this experiment you will sketch a circuit on a piece of paper using a soft-graphite pencil, and measure its resistance using a digital multimeter (DMM) configured to measure resistance.

- A clean sheet of white notebook paper
- A soft-lead pencil (no harder than #2 "lead" hardness rating)
- A digital multimeter (DMM) capable of measuring resistance
- Alligator-clip style jumper wires to connect the meter to the paper

First and foremost, identify any potential hazards posed by this experiment. If any exist, identify how to mitigate each of those risks to ensure personal safety as well as ensure no components or equipment will be damaged.

Use the pencil to draw a thick U-shaped curve terminating on the edge of the paper sheet, like this:



Attach two of the alligator clip jumper wires, one to each end of the curve, being sure to make contact between the metal jaw of each alligator clip and the graphite mark. Connect the other ends of the jumper wires to the two test leads of your ohmmeter.

Record the resistance measurement registered by the ohmmeter. While the meter is still measuring resistance, use the pencil to "thicken" the curve, making it wider and/or darker in color. Note the effect[16] these alterations have on the ohmmeter's indication.

[16] This is an example of using a "control" within a scientific experiment. A *control* is a test scenario set up to gather baseline data for comparison against one or more differing scenarios. In this case, comparing the electrical resistance of a thickened pencil mark ("test") against its resistance when initially drawn ("control") allows us to see the difference this one change makes.

Draw another U-shaped curve somewhere else on the page, not intersecting with the first curve. Make this other trace either significantly shorter than or significantly longer than the first curve. Repeat the resistance measurement on this new curve, recording the value and comparing it against the first curve's resistance.

Repeat this process as many times as desired, noting the differences in resistance between the different curves.

Write your conclusions about the effect of the graphite mark's *length*, *width*, and *thickness* (darkness) on its end-to-end electrical resistance. Are there any consistent patterns apparent?

Be sure to document all data in a neat and well-organized format, easily understood by anyone viewing it. Be prepared to explain your reasoning at every step, and also to demonstrate the safe and proper use of all materials, components, and equipment. If a live demonstration is not practical, record your actions on video.

Challenges

- Explain why, to your best knowledge, the *length* of the graphite mark has the effect it does on end-to-end resistance.
- Describe a scientific experiment to demonstrate the effect of a graphite trace's *length* on end-to-end resistance. Specifically note how you would *control* for other variables in this experiment which could affect resistance.
- Explain why, to your best knowledge, the *width* of the graphite mark has the effect it does on end-to-end resistance.
- Describe a scientific experiment to demonstrate the effect of a graphite trace's *width* on end-to-end resistance. Specifically note how you would *control* for other variables in this experiment which could affect resistance.
- Explain why, to your best knowledge, the *thickness* (i.e. darkness) of the graphite mark has the effect it does on end-to-end resistance.
- Instead of always connecting the ohmmeter to the graphite mark using alligator clips at the paper's edge, try using the ohmmeter's test lead probes touching the graphite mark directly. Try moving the probe tips closer together along the curve. How do these changes affect the measured resistance value, and why do you think they do?
- Try replicating the pencil-line experiment with other writing instruments, such as ink pen or crayon. What results do you obtain? Explain why these results might vary from that of the pencil experiment.

8.3 Experiment: Ohm's Law in a single-resistor circuit

In this experiment you will confirm the validity of Ohm's Law as it applies to carbon composition resistors powered by a battery. For this experiment you will need:

- A primary-cell battery (6 or 9 Volts is sufficient)
- An assortment of carbon composition resistors between 1 kΩ and 100 kΩ
- A digital multimeter (DMM) capable of measuring DC voltage and DC current (milliAmperes) and resistance
- Alligator-clip style jumper wires to connect the battery to a resistor
- (Optional) A solderless breadboard or set of terminal blocks suitable for holding the resistor

First and foremost, identify any potential hazards posed by this experiment. If any exist, identify how to mitigate each of those risks to ensure personal safety as well as ensure no components or equipment will be damaged.

Choose at least three resistors with different resistor values, all between 1 kΩ and 100 kΩ. The reason for staying within these resistance limits has to do with safety as well as loading effects on the battery, and loading effects of your meter[17].

Decode the color-code bands on each resistor to determine its nominal resistance value as well as its tolerance. Then, use your DMM (set to measure resistance) to verify each resistor's actual resistance value. Document these values and calculate the error of each resistor in percent. For example, suppose we had a resistor marked Brown-Red-Orange-Gold (12 kΩ ± 5%) and it measured 11.5 kΩ. The error would be:

$$\frac{\text{Actual} - \text{Ideal}}{\text{Ideal}} \times 100\% = \frac{11500 - 12000}{120000} \times 100\% = -4.1667\% \text{ error}$$

Next, use your DMM to measure the battery's voltage. Document this value as well.

Use Ohm's Law to calculate the expected amount of current for each of the three resistors when connected to this battery. Document these predicted current values, as you will be comparing them with measured (empirical) values of current in the next step.

Sketch a complete schematic diagram of the circuit as you intend it to be built. Double-check the schematic to ensure there are no "opens" that will prohibit current where needed, and no "shorts" prohibiting necessary voltage drops and/or causing excessive current. After you are satisfied with your plan, construct the circuit.

[17] Here, the term "loading" has to do with certain portions of the circuit behaving as a load in ways that will skew the results. All batteries contain low amounts of internal resistance, and so choosing resistor values far greater than the typical resistance of a primary-cell battery ensures the amount of current in the circuit will not only be safe, but will also be low enough that the effect of voltage dropping across the battery's internal resistance will be small enough to ignore. Choosing resistor values less than 100 kΩ ensures the multimeter's internal resistance will be low enough in the ammeter mode (by comparison to the resistor) that it will not significantly skew circuit current.

Connect your DMM (set to measure DC current) *in-line* with the battery and resistor so as to form a single loop for current, and measure the current through each resistor in turn. Compare the measured current values with the predicted current values from the previous step. Sketch a schematic diagram showing the battery, resistor, and ammeter properly connected.

How well are the theoretical predictions of Ohm's Law supported by the empirical (measured) data from this experiment? Are there any noteworthy sources of error in this experiment?

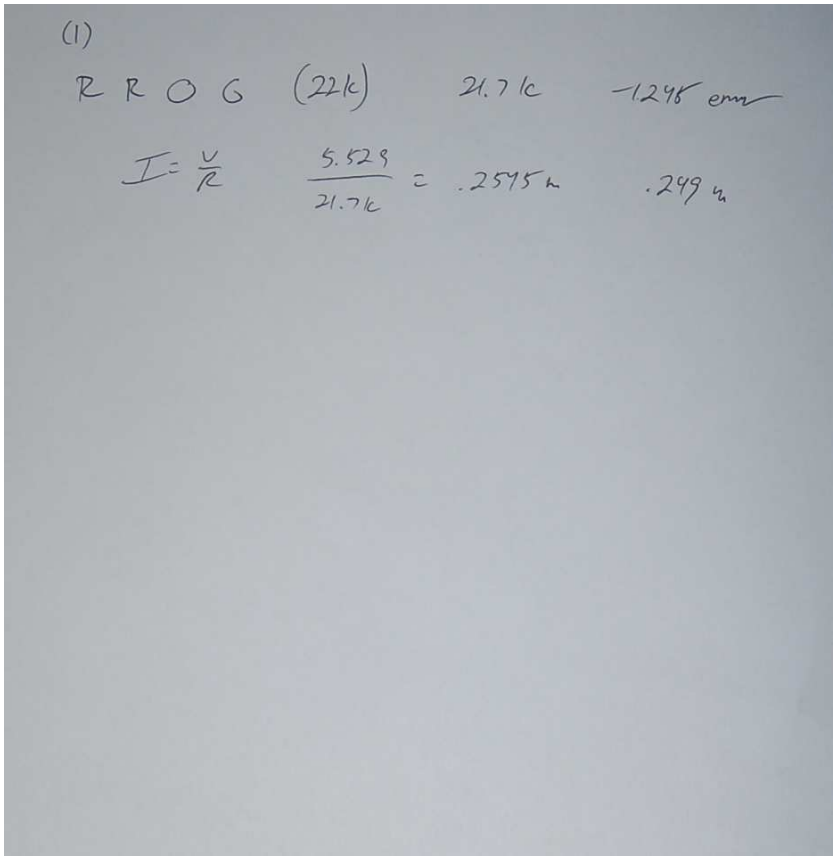
Be sure to document all data in a neat and well-organized format, easily understood by anyone viewing it. Be prepared to explain your reasoning at every step, and also to demonstrate the safe and proper use of all materials, components, and equipment. If a live demonstration is not practical, record your actions on video.

Challenges

- A good self-test of an ohmmeter is to connect its test leads directly together (otherwise known as "shorting" the leads because a direct connection is the shortest, lowest resistance electrical path possible). What should an ohmmeter register when its leads are shorted together? Why?
- Predict the effects of either *increasing* or *deceasing* the resistor's value.
- Predict the effects of either *increasing* or *deceasing* the source voltage value.
- Predict the effects of the resistor failing open.
- Predict the effects of the resistor failing shorted.
- Explain why you cannot obtain a reliable resistance measurement using an ohmmeter when the component in question is energized by a source.
- Sometimes you will find your multimeter yields a non-zero resistance measurement when you would expect it to measure zero or very nearly zero. Explain why this is.
- Identify any data points (empirical) that disagree with theory (prediction), and suggest sources of error.
- Explain why connecting an ammeter directly to the terminals of a voltage source such as a primary-cell battery is a bad idea.
- The manner in which you connect the DMM to a resistor to measure its resistance may introduce a measurement error. In particular, contacting each of the meter's test probes with your skin while simultaneously contacting the resistor's terminals places your body in "parallel" with the resistor, providing an alternate path for the meter's test current to flow. Will this measurement error be positive (i.e. registering more than the resistor's true value) or negative (registering less than the resistor's true value)? Explain your reasoning.

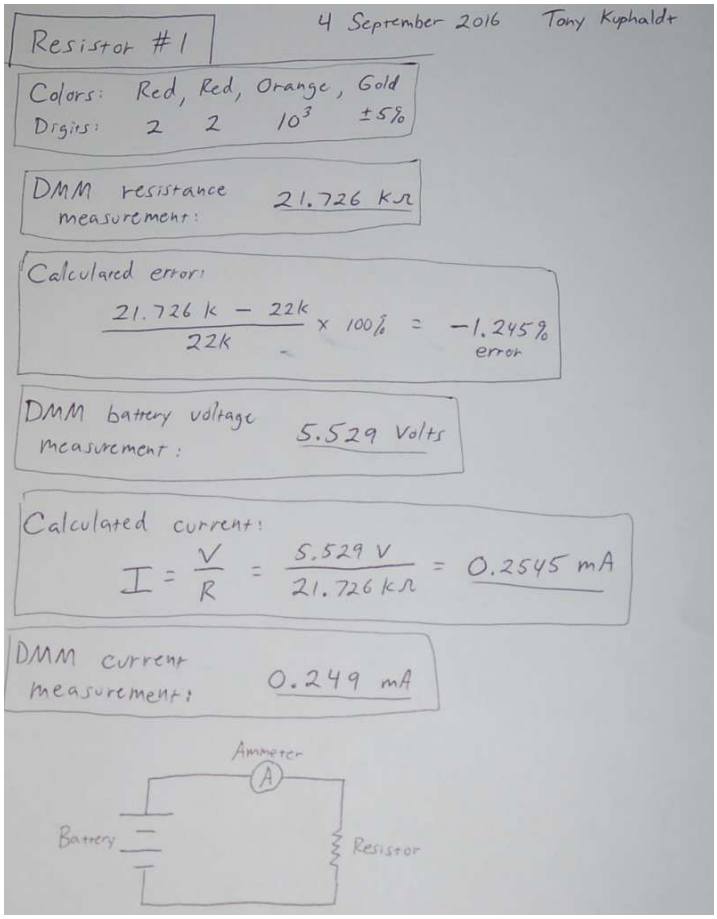
In order to clarify expectations on the quality of your lab documentation, here are three hand-written examples showing all the requested data for just one resistor (out of three required for this experiment). The first example shows poor documentation: sloppy writing, missing information, and generally a confusing presentation. The next two examples are both acceptable, showing all the requested calculations and data in a neat, easy-to-understand format. Bear in mind that computer-based documentation such as a *spreadsheet* is an excellent way to present data as well as perform calculations.

Poor documentation



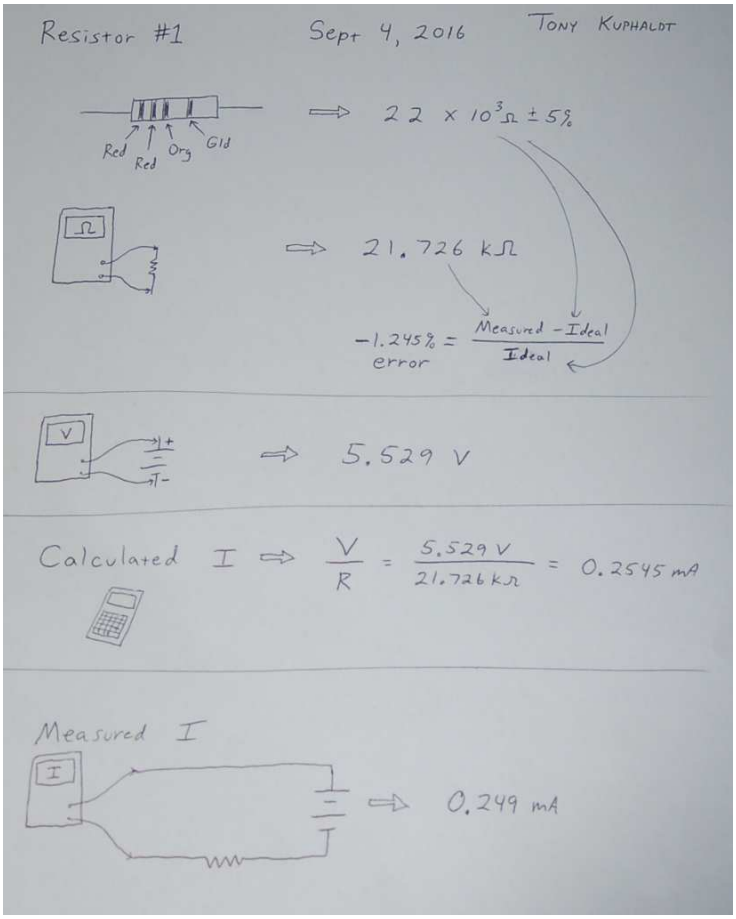
Note how unclear the numerical figures are, due to poor handwriting. Note also the lack of any mathematical work showing how calculated values were obtained. Note also how there are no "0" figures preceding decimal points for current (i.e. `.249 mA` rather than `0.249 mA`), which is bad practice because decimal points written or printed on paper may become smudged and lost – the zero character helps avoid this interpretational error in case the decimal point becomes smudged, because the extra space between that zero and the trailing digits will appear conspicuous.

Good documentation (first example)



The handwriting, while far from perfect, is clear and legible. All requested data is present and easy to locate.

Good documentation (second example, with an artistic touch)



This example makes use of simple artwork to differentiate between calculated and empirical values.

8.4 Experiment: investigating how an ohmmeter works

A meter designed to measure electrical resistance is called an *ohmmeter*. Most digital multimeters (DMMs) provide a resistance-measuring function which allows them to function as an ohmmeter. Voltmeters and ammeters (or DMMs configured to perform those functions) work by presenting a very small load to the circuit under test, using the energy extracted by that loading effect to present a measurement of voltage or current to the user.

Resistance measurements, however, do not work on the principle of extracted energy, since resistors possess no energy of their own for a meter to sense. This fact presents an interesting problem to solve: *how does an ohmmeter work?* To phrase the question differently, *what is an ohmmeter doing to sense the amount of resistance between its leads when there is no energy source?*

The purpose of this experiment is to determine how an ohmmeter (or a DMM configured to measure resistance) performs the task of sensing resistance between its test leads, given the fact that a resistance presents no energy of its own to be sensed by the meter. You will, of course, need an ohmmeter and a selection of resistors to measure with that meter.

In order for you to determine what the ohmmeter is doing to sense the resistance of any resistor (or other object) placed between its test leads, you will need another meter. This means you should probably work as a team with another student, sharing meters to perform this experiment.

First and foremost, identify any potential hazards posed by this experiment. If any exist, identify how to mitigate each of those risks to ensure personal safety as well as ensure no components or equipment will be damaged.

Formulate a hypothesis (i.e. an educated guess) as to how an ohmmeter functions to measure resistance. Then, devise an experimental procedure that will either confirm or disprove that hypothesis. As you conduct your experiment(s), be sure to document and analyze all results.

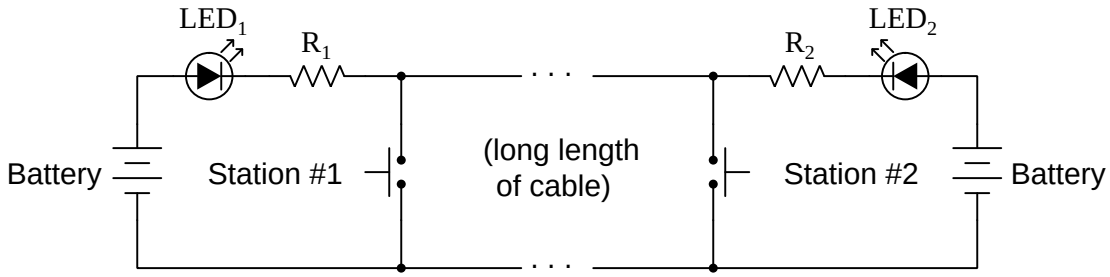
Be sure to document all data in a neat and well-organized format, easily understood by anyone viewing it. Be prepared to explain your reasoning at every step, and also to demonstrate the safe and proper use of all materials, components, and equipment. If a live demonstration is not practical, record your actions on video.

Challenges

- Explain why you cannot obtain a reliable resistance measurement using an ohmmeter when the component in question is energized by a source.
- Sometimes you will find your multimeter yields a non-zero resistance measurement when you would expect it to measure zero or very nearly zero. Explain why this is.
- How does the ohmmeter react to the test resistance increasing in value?

8.5 Project: simple telegraph

Build a telegraph system comprised of two stations (each one with a pushbutton switch for sending information and an LED for indicating what has been sent) connected by a long length of two-conductor cable:



Each station needs to be independent, so that the two may be positioned arbitrarily apart from each other with only the two-conductor cable connecting them. Each station should be constructed using terminal blocks to form all connections between components, as this will make suitably rugged assemblies. The selection of all components is left to the student as a design exercise. You will find a *datasheet* helpful in identifying the operating voltage and current requirements of the LED, necessary information for sizing the resistor.

This is an excellent project for two students to work on together, each student building their own station independently according to mutually-agreed voltage values.

Challenges

- Research *Morse Code*, and then explain how this form of communication could be used over this telegraph system.
- Explain the effect of the cable failing open somewhere between the two stations.
- Explain the effect of the cable failing shorted somewhere between the two stations.
- Could incandescent lamps be substituted for the two LEDs? Explain why or why not.
- Could one station utilize an incandescent lamp while the other station uses an LED? Explain why or why not.
- Could this telegraph system be expanded to include more than two stations? If so, is it possible to tell which station a received message originated from?

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.

- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.

- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.

- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: casting new concepts in one's own words, running mental experiments to perceive patterns and trends, etc. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product. Depth of understanding and permanence of memory are both directly related to mental effort during the learning process – i.e. *easy learning is shallow and fleeting.*

- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.

- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.

- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.

- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.

- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable**. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

B.4 Design of these learning modules

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[4] In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[5] Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TEX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

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Appendix F

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

26 August 2024 – minor edits to the Full Tutorial, and edits to the Introduction chapter.

20 August 2024 – added another section to the Introduction chapter specifically for challenges related to this module's topic.

26 June 2024 – divided the Introduction chapter into two sections, one for students and one for instructors, and added content to the instructor section recommending learning outcomes and measures.

5 February 2024 – added a new "Derivations and Technical References" section on Occam's Razor as a general troubleshooting principle. Also added a new Case Tutorial resistor color-code interpretational example in the "Example: Resistor values and tolerances" section.

18 January 2024 – added another sub-question and a Challenge question to the "Assessing shock hazards in a circuit" Conceptual Reasoning question.

25 June 2023 – added Technical Reference section on grounding.

14-15 June 2023 – minor edit to image_0088 (capitalization of the word "Volt" on the power source). Also added a new Case Tutorial section articulating a money-based analogy for voltage, current, power, and resistance.

8 June 2023 – added a Case Tutorial section showing the effects of opens and shorts in both electric and hydraulic circuits.

14 December 2022 – added a Technical References section on different types of resistors.

27 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

30 August 2022 – added another Case Tutorial section with Ohm's and Joule's Law examples using metric prefixes.

16 June 2022 – added error-calculation formula to section on resistors.

10 February 2022 – divided the Full Tutorial chapter into sections, and also simplified some of the text.

4 February 2022 – added some challenges in various questions to have students demonstrate strategies for checking their work.

30 January 2022 – added text to the "Shunt resistor used to measure current" Quantitative Reasoning question.

8-9 September 2021 – added Case Tutorial section on resistor color codes and tolerances.

2 September 2021 – added Technical Reference section on ampacities for small-gauge copper wires.

31 August 2021 – added Challenge question to the "Assessing shock hazards in a circuit" Conceptual Reasoning question.

18 July 2021 – minor additions to the Full Tutorial defining series and parallel, plus adding conceptual application to the "Voltage, Current, and Resistance in a simple circuit" Quantitative Reasoning question.

9 July 2021 – replaced some TeX-style italicizing markup with LaTeX-style.

22 June 2021 – added technical reference on resistor labeling.

11 March 2021 – added a tasteful mnemonic to the Full Tutorial for remembering resistor color codes.

11 February 2021 – corrected several instances where "Ohms" was uncapitalized.

27 January 2021 – minor additions to the Introduction chapter.

21 January 2021 – corrected a copy-and-paste error in the "Current source and resistors" Case Tutorial example, where I mistakenly referred to the current source as a 12-Volt battery.

24 September 2020 – added more content to the Introduction chapter, including a suggestion to write a "summary page" showing all variations of Ohm's Law and Joule's Law equations.

3 September 2020 – added Technical Reference section on metric prefixes.

24 August 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions. Also

made minor edits to the Full Tutorial to make it clear that the single-battery, single-heater circuit schematic used three different times represent three completely different component values.

20 August 2020 – minor edit to Simplified and Full Tutorial chapters regarding resistor power ratings (clarifying these as *maximum* values).

17 April 2020 – added a Technical Reference section on IEC standard component values (file techref_IEC60063.latex).

31 March 2020 – incorporated Historical Reference on "Early electrical safety" into its own LaTeX file.

9 November 2019 – added a quantitative question based on a 1921 advertisement for enamel-coated resistors. This advertisement happened to give dimensions of several resistors and their power ratings.

19 September 2019 – minor edit to footnote in the Case Tutorial chapter.

18 September 2019 – added a couple of index entries for "source" and "load".

14 September 2019 – added a Case Tutorial chapter.

26 August 2019 – added mention of difficult concepts to the Introduction.

3 January 2019 – included an historical reference to "body protector" devices intended to help prevent serious injury to electrical workers.

1 January 2019 – took all text and images discussing safety and put them into their own common file (common_safety.latex) to be easily included in other modules.

5 November 2018 – retitled Historical References section(s) so as to not be redundant to the "Historical References" chapter.

September 2018 – clarified a footnote from John Fleming's 1899 book *Electric Lamps and Electric Lighting* as being his footnote and not mine. Also edited the Introduction to make it more of a condensed tutorial, so that it functions as the "first-step" in a series of "vertical texts" on this topic. Also, renamed "Derivations and Technical References" chapter to "Historical References".

August 2018 – added some historical citations related to electrical safety, as well as several pages of text from John Fleming's 1899 book *Electric Lamps and Electric Lighting* defining fundamental concepts such as voltage, current, resistance, power, Ohm's Law, and Joule's Law. Also, made minor edits to Introduction chapter.

July 2018 – added Charles Dalziel to the list of References. Also added historical citations of Georg Simon Ohm's original treatise on his law.

April 2018 – added a Simplified Tutorial chapter, and also clarified some of the explanations and graphic images in the Full Tutorial chapter.

August 2017 – Incorporated the concept of electrically common points into the safety discussion.

July 2017 – Added explanatory comments about the use of a "control" within a scientific experiment. Capitalized all instances of the word "Earth".

June 2017 – Corrected typographical error in answer (mA rather than A) in the instructor version.

May 2017 – Added interpretation of the 4700 Ohm carbon resistor's value to the text, as a way to apply the color code.

March 2017 – Reworded the opening sentences of both "Voltage, Current, and Resistance Calculations" and "Power, Voltage, Current, and Resistance Calculations" quantitative questions.

March 2017 – Included mention of "series" and "parallel" meter connections in the Tutorial as well as the "Foundational Concepts" conceptual question to reinforce these important concepts. Also added a pair of Challenges to the "Path of Least Resistance" quantitative question in response to misconceptions noted with students determining voltages across the two resistors.

July 2016 – added metric expression of distance in addition to Imperial for arc flash hazard radius.

December 2016 – minor edits to graphic images, as well as more careful distinctions made between *electrically common* points versus *equipotential points* (electrically common points are always equipotential, but equipotential points are not necessarily electrically common).

October 2016 – created changelog for future use.

September 2016 – document first published.

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