V = IR
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Chapter 1

Introduction

A strangely under-represented topic in most introductory electricity and electronics curricula is how to design a practical circuit given a collection of components and basic criteria for circuit function. An important sub-set of this topic is how to wire together components to form a practical circuit based on an existing design. The cognitive work necessary to complete such tasks are less quantitative than one might think, instead relying heavily on qualitative assessments of component function as well as solid application of foundational principles such as Kirchhoff’s Laws, series and parallel networks, and the distinction between electrical sources and loads. This learning module seeks to remedy this sad state of affairs by providing basic guidelines for designing simple circuits and determining connections between components where the components do not lend themselves well to arbitrary positioning.

Important concepts related to this topic include properties of series networks, properties of parallel networks, proper meter usage, electrically common points, Kirchhoff’s Laws, sources versus loads, strain gauge sensors, terminal blocks, electrical grounding, shunt resistors, oscilloscopes, short-circuit, fault current, Hot and Neutral conductors, ground voltage, and electrical noise.

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

- Where might a series connection suit our purposes when designing a circuit?
- Where might a parallel connection suit our purposes when designing a circuit?
- Why does the identification of a component as either a source or a load assist us with properly connecting it to other components to form a circuit?
- What advantages do terminal blocks offer for constructing circuits?
- What does it mean to “ground” something in a circuit?
- How might we encounter trouble when connecting grounded test instruments to grounded circuits?
- Where might Ohm’s Law prove useful in circuit design?
• What is the purpose of a shunt resistor?

• What are some of the practical steps we might take to translate a schematic diagram into physical connections between components?

• How does a differential voltage measurement differ from a ground-referenced voltage measurement?

• How might we calculate the magnitude of a particular fault current based on component values?

• What is “noise” in an electrical circuit?

An important problem-solving strategy employed multiple times in the Tutorial is annotation of a diagram with lines, numbered points, and other visual cues. Tracing the path of fault current for a short-circuit fault is one example of this, as is tracing which points have been connected together on a schematic diagram as you sketch wires on a pictorial diagram.

A very common misconception among students new to electricity is that the Earth has some sort of affinity for electricity. Often you will encounter people who say things like electric current always seeks ground when no such tendency exists. What is true is that most electric power circuits bond one conductor to be electrically common to the Earth, and for this reason it becomes possible for electric current to pass through the Earth in the event of a “ground fault” with one of the un-grounded conductors. Perhaps this is the origin of the misconception.
Chapter 2
Tutorial

First, a review of foundational circuit principles.

Three fundamental measures of electricity are voltage \( V \), current \( I \), and resistance \( R \). Voltage is defined as the amount of energy either gained or lost by electric charge carriers between two different locations. Current is defined as the rate of charge carrier flow. Resistance is defined as the amount of voltage drop (i.e. energy lost per charge carrier) for a given amount of current (flow). Ohm’s Law relates these three variables mathematically:

\[
V = IR \quad I = \frac{V}{R} \quad R = \frac{V}{I}
\]

The combination of voltage and current is power \( P \): the amount of energy either gained or lost per charge carrier multiplied by the number of charge carriers passing through over time equals the rate of energy gained or lost over time. Joule’s Law mathematically relates power to voltage, current, and resistance:

\[
P = IV \quad P = I^2R \quad P = \frac{V^2}{R}
\]

Electrical components designed to boost the energy level of charge carriers passing through are referred to as sources. Components extracting energy from passing charge carriers are called loads. The identity of any component as either a source or a load is evident by comparing the voltage polarity marks versus direction of current. If current enters a component on the “−” side and exits on the “+” side, it means the charge carriers enter at a lower energy level and exit at a higher energy level, which makes that component a source. If current enters a component on the “+” side and exits on the “−” side, it means the charge carriers enter at a higher energy level and exit at a lower energy level, which makes that component a load.

When electrical components are connected together, they form an electrical network. Connections between electrical components may be broadly divided into two categories: series and parallel. Each of these network types exhibits unique properties, and must be thoroughly understood before attempting to understand more complex types of electrical networks.
When electrical components are connected together such that they form a chain providing only one path for current, they are said to be connected in \textit{series} with each other:

\begin{center}
\begin{tikzpicture}
\draw (0,0) node[draw, circle, inner sep=0.2cm] (A) {} node[above] {Component \#1} -- (2,0) node[draw, circle, inner sep=0.2cm] (B) {} node[above] {Component \#2} -- (4,0) node[draw, circle, inner sep=0.2cm] (C) {} node[above] {Component \#3} -- cycle;
\draw[->, thick] (A) -- (B);
\draw[->, thick] (B) -- (C);
\draw[->, thick] (C) -- (A);
\end{tikzpicture}
\end{center}

With only one path for charge carriers to flow through each component, any continuous flow of electric charge carriers (i.e. current, \(I\)) through each component must be equal due to the Law of Electric Charge Conservation (electric charges can neither be created nor destroyed). Similarly, the Law of Energy Conservation – which states that energy can neither be created or destroyed – informs us that the energy gains or losses of electric charge carriers moving through each component accumulate to equal the total gain or loss in energy for the series network; that is to say, voltages across a set of series-connected components algebraically add to equal the series network’s total voltage. For the same reason, the total resistance (\(R\)) of a series network (defined as the amount of energy lost per charge carrier for a given rate of flow) is equal to the sum of all the individual component and wire resistances. Mathematically stating each of these series network properties:

\begin{align*}
I_{\text{total}} &= I_1 = I_2 \cdots = I_n \\
V_{\text{total}} &= V_1 + V_2 + \cdots + V_n \\
R_{\text{total}} &= R_1 + R_2 + \cdots + R_n
\end{align*}

Series connections are used in the measurement of electric current, to ensure the instrument designed to measure electric current (an \textit{ammeter}) will sense the exact same amount of current as the component being tested. A series connection between an ammeter and the component under test guarantees this equality of current:

\begin{center}
\textit{Ammeter connected in series, so as to experience the exact same current as the other components}
\end{center}

\begin{center}
\begin{tikzpicture}
\draw (0,0) node[draw, circle, inner sep=0.2cm] (A) {} -- (2,0) node[draw, circle, inner sep=0.2cm] (B) {} -- (4,0) node[draw, circle, inner sep=0.2cm] (C) {} -- (6,0) node[draw, circle, inner sep=0.2cm] (D) {} node[above] {A} -- cycle;
\draw[->, thick] (A) -- (B);
\draw[->, thick] (B) -- (C);
\draw[->, thick] (C) -- (D);
\end{tikzpicture}
\end{center}

Note that multiple locations are possible for the ammeter – \textit{any} location that is in-line with all components will yield the same measurement of current which is the value of current common to all components in this series network.
When electrical components are connected together such that they share the same two sets of electrically common points (i.e. their respective terminals are made equipotential by direct connection), they are said to be connected in parallel with each other:

![Parallel Connection Diagram]

The term *equipotential* means no energy is lost or gained by electric charge carriers moving between those connected points. Points connected together by a conductor of negligible resistance will be equipotential by virtue of that conductor’s low resistance. In the parallel network shown above, charge carriers on all the left-hand wires of the network exist at the same potential energy level, as do charge carriers on all the right-hand wires. Therefore, any *difference* of potential between the left and right wires must be the same. Therefore every component in a parallel network experiences the same potential difference (i.e. same voltage, $V$). In this example, any charge carriers moving from left to right through any of the components will lose the same amount of energy, regardless of which component they happen to pass through.

Current values through each component in a parallel network, however, may differ substantially. In fact, Ohm’s Law ($I = \frac{V}{R}$) guarantees this will be the case if the components in question happen to have differing resistance values ($R$) but all share the same voltage value ($V$). Given the Law of Charge Conservation, we may conclude that the total current for a parallel network must be equal to the algebraic sum of all component (“branch”) currents. Another property of parallel networks is that their total resistance is less than that of the lowest-resistance branch. Mathematically stating each of these parallel network properties:

$$V_{\text{total}} = V_1 = V_2 \cdots = V_n$$

$$I_{\text{total}} = I_1 + I_2 \cdots + I_n$$

$$R_{\text{total}} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} \cdots + \frac{1}{R_n}}$$

Parallel connections are used in the measurement of voltage, to ensure the instrument designed to measure voltage (a voltmeter) will sense the exact same amount of voltage as the component being tested. A parallel connection between a voltmeter and the component under test guarantees this equality of voltage.
Volts connected in parallel, so as to experience the exact same voltage as the other components.

Note that multiple locations are possible for the voltmeter – touching the voltmeter’s left-hand test lead to any point on the left-hand equipotential zone, and touching the voltmeter’s right-hand test lead to any point on the right-hand equipotential zone, will yield the same measurement of voltage which is the value of voltage common to all components in this parallel network.

A property common to all networks, series and parallel alike, is that total (i.e. source) power is equal to the sum of all load powers in a circuit. This is just an extension of the Law of Energy Conservation (that energy cannot be created or destroyed and so must be accounted for in all cases), because power is nothing more than energy transfer per unit time:

\[ P_{\text{total}} = P_1 + P_2 + \cdots + P_n \]

This holds true for all circuits operating under steady-state\(^1\) conditions, regardless of shape, because the Law of Energy Conservation is universal.

---

\(^1\)By “steady-state” we mean the quantities of voltage, current, and power remain constant over substantial periods of time. This caveat is based on the fact that energy is always and forever conserved, but power is not necessarily so. Imagine a scenario where a weight is slowly hoisted up to some elevation, and then released so that it falls to the ground: the amount of energy invested in the weight’s ascent is exactly equal to the amount of energy released by the weight as it falls (in the forms of air friction heating, and also energy delivered to the ground upon impact). However, the amount of power expended in slowly hoisting the weight far less than the amount of power delivered by the weight as it slams into the ground, simply due to the disparity in time intervals: the former happens over a long time interval, while the latter occurs over a very brief time interval. An analogous electrical scenario is that of a capacitor slowly energizing to some high voltage level, then rapidly de-energizing into a low-resistance load: the amount of energy invested in the capacitor is precisely equal to the amount of energy later delivered to that load, but the rates of power are quite unequal due to the timespan over which each action takes place. So, when analyzing any circuit operating under steady-state conditions we may regard power as a conserved quantity because everything occurs over the same span of time, but know that it is really energy that is conserved. If the circuit does not operate under steady-state conditions, source power and load power may in fact differ greatly.
Kirchhoff’s Voltage Law (KVL) states that the net change in energy for any charge moved around in a loop – i.e. moved from point to point, returning to the same location where it started – will always be zero. That is to say, as an electric charge gains and loses energy moving between these different points, it must always return to its original energy level after returning to its original location. Since energy gains and losses for electric charges is the definition of voltage, we may express KVL by saying that the algebraic sum of all voltages in a loop equals zero.

If we label points within a loop by letter (e.g. A, B, C, etc.) and denote each voltage within that loop by a letter subscript pair (e.g. \( V_{XY} \), the amount of energy gained or lost by a charge moving from Y to X), KVL becomes evident just by the subscripts. If we move a “test charge” from point A to point B and note the voltage (\( V_{BA} \)), then from point B to point C (\( V_{CB} \)), then all the way around the loop until we return to point A, the sum of those voltages must be the same as the amount of voltage moving from point A to point A (\( V_{AA} \)) – i.e. the amount of voltage between identical points. Of course, this must be equal to zero:

\[
V_{BA} + V_{CB} + V_{nC} \cdots + V_{An} = V_{AA} = 0
\]

KVL is true regardless of the path taken by the charge, as it is an expression of the Law of Energy Conservation (i.e. that energy cannot be created or destroyed, and therefore the amount of energy carried by an electric charge cannot simply appear or vanish, but must be accounted for in every step of that charge’s travels). The path traced need not be in the direction of real current in the circuit, and in fact need not follow any circuit conductors at all. It is perfectly permissible to trace a KVL loop that “jumps” between disconnected points in a circuit. In fact, this is what we often do when applying KVL to the calculation of voltage between points not directly spanned by one component.

Kirchhoff’s Voltage Law (KVL) is useful for calculating unknown voltage values between points in a circuit, if all the other voltage values between points in a loop happen to be known.

Kirchhoff’s Current Law (KCL) states that charge carriers entering a point must exit that point, which is a consequence of the Law of Electric Charge Conservation (i.e. that electric charges cannot be created or destroyed, but must be accounted for in all cases). That is to say, the total amount of current entering a point (or “node”) in a circuit must be the same as the total amount of current exiting that same point. This is true regardless of the number of conductive paths connecting at that point. We may express KCL by saying that the algebraic sum of all currents at a node equals zero:

\[
I_1 + I_2 + I_3 \cdots + I_n = 0
\]

Kirchhoff’s Current Law (KCL) is useful for calculating unknown currents in a circuit, if all the other currents entering and/or exiting a points in the circuit happen to be known.

Now that we have reviewed some important foundational concepts, let us move to the topic at hand: how to design simple circuits to achieve stated goals. This will largely be done by example, and with persistent reference to these foundational concepts.
2.1 Constant-voltage and constant-current circuits

Let us consider a case where we have three electrical components which must be energized from the same power source, and must all receive the same amount of voltage that is relatively constant regardless of fluctuations in load. The loads in question here are a DC electric motor, and LED lamp assembly, and a heating element, all rated for 110 Volts DC. These three components are fixed in location:

The requirement of constant voltage for these loads necessitates a voltage source as the power supply for this circuit, because it is the nature of a voltage source to maintain (relatively) constant voltage at its terminals despite variations in current. We may also conclude that these four components (one voltage source and three loads) must connect in parallel with each other, since we have been told they must all share the same amount of voltage, and we know that parallel connections guaranteed equal voltage for the connected components. Furthermore, two of these loads are polarized as indicated by the + and − polarity symbols next to their terminals, indicating which terminals on those loads must be made electrically common to the + and − terminals of the voltage source.

Inserting a voltage source to the illustration and connecting all four components in parallel to each other yields a circuit that looks something like the following. Note the annotations added for voltage (across the non-polarized heater), current (through all components and wires), and source/load status which is always a good habit:

It is important to note that the circuit design presented here is by no means the only one possible. Any circuit design placing these four components in parallel with each other, while respecting the polarity of the polarized loads, is a valid solution.
Let us consider another case where three strain gauges must be energized with the same amount of constant current, with the amount of strain sensed by each gauge sensed by a voltmeter:

The necessity for each strain gauge to receive the same amount of constant tells us they must be connected in series with each other, because only a series network is able to guarantee equality of current through all connected components. The requirement for this current to be constant forces us to use a current source rather than a voltage source to energize the strain gauges. However, each voltmeter must sense the voltage dropped by its respective strain gauge, and the only way to guarantee a voltmeter senses the same voltage as a particular component is to connect the voltmeter in parallel with the sensed component. Thus, what we will need here is a series-parallel circuit; each voltmeter connected in parallel with one strain gauge, and then each of these parallel networks connected in series with each other and with a current source.

Furthermore, the polarization of the DC voltmeters places another constraint on our design: the direction of current through each strain gauge must be such that the right-hand terminal is positive and the left-hand terminal is negative. Knowing that both resistors and voltmeters act as electrical loads, we may then conclude that the direction of current (conventional flow notation) must be from right to left. Electrical charge carriers enter loads at higher energy levels than they exit, and so a right-to-left current direction through these loads will ensure + on right and − on left.

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A “strain gauge” is a small sensor translating physical tension and compression into a variable resistance signal. Strain gauges are often used in research and development laboratories for measuring microscopic deformation of mechanical objects. They consist of small wire grids laid atop an insulating pad which is then bonded to the mechanical object. Any compression or stretch of the mechanical object causes the strain gauge’s wire to shorten or lengthen, respectively, and this causes small changes in the strain gauge’s end-to-end electrical resistance.
One solution, but certainly not the only solution, for this strain gauge circuit is shown in the following illustration:

True to its name, the current source will work to maintain a constant amount of current through the circuit regardless of variations in resistance. This means as the strain gauges increase and decrease in resistance, the current will remain steady and the voltage drop across the varying strain gauge will directly track with those resistance changes. Note how this behavior differs from that of voltage sources, which act to maintain constant voltage over a wide range of load current. As usual, annotations of voltage, current, and source/load identity prove useful to organize our thoughts and verify that the circuit design is sound.

Like the three-load, constant-voltage circuit shown previously, multiple correct solutions exist for this strain gauge circuit. The exact location of the current source in the series loop, for example, is irrelevant. The ordering of the three strain gauges is likewise arbitrary, although physical location will make some orderings easier to build than others.
2.2 Terminal block circuit construction

A common circuit construction technique is to use terminal blocks as connection points between component terminals and wires. A “terminal block” is a metallic screw or spring connector mounted within or on top of an insulating body, providing robust electrical and mechanical attachment. Terminal blocks are manufactured in a wide range of styles, and they are quite popular for industrial circuits where the ability to reconfigure circuits is advantageous.

Plastic-framed terminal blocks built to snap on to standard-dimension metal rail (commonly called DIN rail) are particularly popular for industrial purposes, the following photograph and illustration showing an example of a terminal block assembly with twelve general-purpose four-terminal blocks located adjacent to a fuse-holder block on a single piece of DIN rail:

Terminal blocks, while physically convenient for circuit construction, are often mentally challenging for circuit design because the connection points lie along a straight line which is unlike most schematic diagrams. Translating a logically simple schematic diagram into a physically simple terminal block circuit is definitely a skill, and one well worth developing for any practitioner of electricity and electronics.

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*An interesting anecdote from my own education in electricity was the use of a “Science Fair” 150-in-one Experimenter’s Kit sold by Radio Shack in the United States. This project kit consisted of an assortment of electronic components such as resistors, capacitors, transistors, switches, meters, etc. mounted to a cardboard base, each component having a set of metal-coil springs attached to its terminals. Connections between components were made with pieces of stranded copper wire, each wire end inserted between the coils of one spring. The fixed location of the components forbid anyone using this kit to build the circuit exactly as it appeared in the schematic diagram, and it forced this independent learner to gain that skill of mapping schematic to physical layout. This skill is often overlooked in modern electronics education, and the prevalence of solderless breadboards allowing for arbitrary placement of components actually hampers this learning.*
A good illustrative example of the challenge of translating a schematic diagram into a terminal block circuit is a bridge rectifier, which is a type of circuit used to convert alternating current (AC) into direct current (DC). The schematic diagram is shown on the left-hand side and an illustration of four rectifying diodes ($D_1$ through $D_4$) attached to eight terminal blocks is shown on the right:

Two practical strategies for constructing this bridge rectifier circuit include (1) labeling each terminal block with a unique number and labeling each component in the schematic the same; and (2) over-tracing each wire in the schematic diagram after placing a wire between terminals in the real circuit. It is helpful to know that the “striped” end of each diode corresponds to the “line” end of its schematic symbol.

First, labeling all terminal blocks and component terminals with numbers:

From this we can see we will need to connect terminal blocks 1 and 2 together, 4 and 5 together, 3 and 7 together, and 6 and 8 together. The AC source’s terminals will then connect between 4/5 and 3/7, while the DC load’s positive goes to 6/8 and its negative to 1/2.
The following images show these connection being made. First, inserting “jumper” wires to connect the four diodes into a bridge configuration. Note the sketching of colored lines adjacent to wires in the schematic diagram to record which connections have been made:

Next, connecting the AC source:

Lastly, connecting the DC load:
### 2.3 Grounded circuits

The concept of electrical *grounding* is surprisingly complex, the term “ground” originating from the concept of making one point in an electrical circuit electrically common to (and therefore equipotential with) the actual soil upon which we stand. An alternative term for this is *earthing*, for reasons made obvious by the word itself. One reason for establishing an Earth-potential point in an electric circuit is safety for those working around it: ensuring that at least one point in that circuit is safe to touch while energized, because no substantial voltage can exist between the grounded conductor of that circuit and the Earth. However, the term “ground” has generally come to mean any point within an electric circuit deemed to be a stable reference for defining voltage, irrespective of safety.

Making matters even more confusing is the fact that some circuits may possess different ground points for different purposes. For example, it is customary in electrical power system design to bond one of the current-carrying conductors to Earth for safety, but then individual devices (loads) connected to this power system may have points within them arbitrarily defined by the manufacturer as “ground”, and these points may or may not be exactly equipotential with the Earth. Another example of differing ground points is in some electronic systems where each type of electronic voltage signal (e.g. analog voltages, digital voltages) has its own separate reference point called “ground” (sometimes labeled AGND for analog ground and DGND for digital ground).

---

4Remember that voltage is fundamentally a *differential* quantity, defined as the amount of energy gained or lost by an electric charge carrier moving from one location to another. If some point in an electric circuit is defined as being “ground” it means we may intelligently speak of voltages being “at” any other single point in that circuit, ground being the implied reference point where the other test lead of the voltmeter would touch. By analogy, we may speak of a mountain peak as having a certain altitude, but what we really mean is the vertical distance between that mountain peak and sea level. Here, the level of the world’s oceans is taken to be the “ground” height reference for all mountains.

5Extending our mountain elevation analogy, not all bodies of water exist at equal height, and so a mountain peak’s altitude as measured from the “ground” reference of a nearby lake may not be the same as that same peak measured from the separate “ground” reference of the world’s oceans.

6An “analog” voltage is a signal where the magnitude of the voltage proportionately represents some other quantity such as potentiometer position, temperature, audio tone, etc.

7A “digital” or “discrete” voltage is one with only two valid states, typically called “high” and “low”, often representing the status of a switch (i.e. either on or off).
2.3. GROUNDED CIRCUITS

Grounding can be a constraint for circuit design when two or more components in the circuit must possess a grounded terminal. Consider the following circuit, where a grounded AC voltage source powers a single load, and a precision shunt resistor\(^8\) is used to make inferential current measurements. This “shunt resistor” is connected in series with the load so as to experience the exact same current as the load, and a voltmeter is connected in parallel with the shunt resistor so as to experience the shunt resistor’s voltage drop:

\[ I = \frac{V}{R} \]

The grounded AC power conductor is customarily called the “neutral” while the ungrounded conductor is called the “hot” (in reference to the danger of touching the latter while in contact with the Earth). A 0.1 Ω shunt resistor has been placed on the “hot” conductor to facilitate measurements of load current: simply take the AC voltmeter’s reading and divide by 0.1 to find the line current according to Ohm’s Law \( I = \frac{V}{R} \). This is both faster and safer than the alternative strategy of connecting an ammeter in series with the load to intercept its current. So far, the presence of a ground connection in the power circuit poses no problem for us in measuring load current.

---

\(^8\)The term “shunt” is a synonym for “parallel”, and is given to this resistor because the sensing instrument is a voltmeter connected in parallel (shunt) to that resistor.
If we wished to use an oscilloscope\textsuperscript{9} to sense the shunt resistor’s voltage drop, though, we would very quickly experience trouble. Oscilloscopes are essentially voltmeters, but are limited by the fact that most have their “reference” test lead connected to Earth ground through the metal frame of the oscilloscope to the power plug. Unlike a hand-held voltmeter which is electrically isolated from Earth ground, the “ground” clip test lead of an oscilloscope is bonded to Earth whether we want it to be or not. In other words, a hand-held voltmeter naturally facilitates differential voltage measurements while an oscilloscope’s construction assumes ground-referenced voltage measurements\textsuperscript{10}. Attempting to connect an oscilloscope’s test leads in parallel with the grounded AC circuit’s shunt resistor forms an unintentional short-circuit:

Such a short-circuit could pose significant danger to the person operating the oscilloscope. The resistance of the short-circuit current path is little more than the 0.1 Ω of the shunt resistor plus any wiring resistance connecting the oscilloscope to ground. This means the fault current could be quite substantial, perhaps enough to create an arc flash\textsuperscript{11}.

\textsuperscript{9}Oscilloscopes may be thought of as graphing voltmeters, displaying voltage on the vertical axis of a graph and time on the horizontal axis. They are extremely useful instruments, and are essential for a wide variety of electronic measurements.

\textsuperscript{10}Voltage, of course, is always measured between two points because voltage by definition is the amount of potential energy gained or lost by an electric charge moved from one specified location to another. What we mean by the term differential voltage (since all voltages are differential by their very nature) is that neither of the specified points are grounded. A ground-referenced voltage, by contrast, is one where only one point is specified and the other point is assumed to be ground. Any voltage-sensing instrument built like an oscilloscope where one of the test leads is internally connected to Earth ground, is designed to only measure ground-referenced voltages.

\textsuperscript{11}An “arc flash” is super-heated air resulting from a high-current electric arc.
In order to avoid such a short-circuit, we would need to connect the oscilloscope to the circuit in such a way that its grounded test clip never contacts a point in the circuit elevated from ground potential. If we simply omitted the ground clip and only touched the measurement probe to the circuit, we would avoid a short-circuit but we would also fail to measure the shunt resistor’s voltage drop – instead sensing the AC source voltage:

One solution\textsuperscript{12} to this measurement problem is to re-design the circuit, relocating the shunt resistor to a place more suitable to the oscilloscope’s limitations. We must resign ourselves to the fact that this oscilloscope is only capable of measuring voltage between the test lead tip and Earth ground, and so we need to move the shunt resistor to a place where one of its terminals is equipotential with Earth ground as well.

\textsuperscript{12}There do exist other solutions to this problem, including substitution of the ground-referenced oscilloscope with another instrument capable of performing differential (i.e. ungrounded) voltage measurements. Some oscilloscopes are built like hand-held multimeters and lack an Earth ground connection. Multi-channel oscilloscopes provide a differential mode where the ungrounded test leads of two channels may be used to perform a differential voltage measurement, the instrument essentially displaying the mathematical difference (subtraction) between two ground-referenced voltage measurements.
We see such a solution in this next illustration, having moved the shunt resistor to the “neutral” conductor instead of the “hot” conductor:

![Diagram showing the new solution]

It may help to model the oscilloscope as a voltmeter with one grounded test lead, as shown in this diagram:

![Diagram showing oscilloscope as a voltmeter]

However, even this re-design is not without its problems. As mentioned before, not all points labeled “Ground” are perfectly equipotential. It is possible that the two ground points shown in this circuit connect to two different metal rods driven into the Earth, with many meters’ worth of distance separating the two. Or, there may be a substantial length of current-carrying neutral conductor between the left-hand terminal of the shunt resistor and the AC source’s bottom terminal (although the diagram makes it look rather short), and this length of current-carrying conductor is bound to drop some voltage of its own by Ohm’s Law \( V = IR \). In either case, if we apply Kirchhoff’s Voltage Law to the “loop” formed of the oscilloscope, the shunt resistor, and the conductive pathways to ground, we see that the oscilloscope’s voltage is the algebraic sum of the shunt resistor’s voltage drop and whatever small amount of voltage might exist between the two ground points. The shunt
2.3. GROUNDED CIRCUITS

resistor’s drop is fairly small, and so it doesn’t take much “ground voltage” between the oscilloscope and the power circuit’s ground point to corrupt the voltage measurement.

An illustration of “ground voltage” is shown here, with this additional voltage modeled as its own source between the oscilloscope’s ground point and the circuit’s safety ground point:

Stepping around the loop formed by the oscilloscope, $V_{\text{ground}}$, and voltage dropped across $R_{\text{shunt}}$, we see that the voltage sensed by the oscilloscope must be the algebraic sum of the shunt resistor’s voltage and $V_{\text{ground}}$. It is common in electrical engineering to refer to such extraneous sources of voltage (or current) as electrical noise sources because they contribute interference to our measurement. Noise sources may be DC, AC, or some combination thereof.

It may seem out of place in an “Elementary Circuit Design” tutorial to be commenting on voltage measurement errors, but it should be apparent that the design and layout of a circuit influences how we may measure certain parameters within it. Similarly, the act of connecting any measurement instrument to a circuit necessarily alters (i.e. re-designs) that circuit. Following good practice, we may minimize adverse effects and achieve valid measurements. Just know that a re-design of the circuit itself may be needed to achieve a desired measurement.
Chapter 3

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 the tutorials and attempt to answer questions on their own prior to the instructor’s interaction with them. In place of lecture, 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.

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1Technical 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 Reading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

2Lecture 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.
CHAPTER 3. QUESTIONS

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 \text{X}) fails (open/shorted/etc.)?

• What would have to occur to make this system \underline{unsafe}?
3.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking. 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.

---

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.
3.1.1 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, write their own outline and 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 OUTLINE THE TEXT, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do 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.
3.1.2 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
- Conservation of Energy
- Conservation of Electric Charge
- Voltage
- Current
- Resistance
- Electrical source
- Electrical load
- Equipotential points
- Electrically common points
- Ohm’s Law
- Joule’s Law
Properties of series circuits

Properties of parallel circuits

Kirchhoff’s Voltage Law

Kirchhoff’s Current Law

Polarized component

Terminal block

Electrical noise

Rheometric sensing

Bridge network

Electrically common points

Ground

Hot versus Neutral

Arc flash

Noise
3.1.3 Three resistors in series and parallel

Draw connecting wires that will create a *series* circuit with all the components shown, then re-draw to form a *parallel* circuit:

---

**Challenges**

- Supposing the battery has a voltage of 9 Volts, and all resistors are 1 kΩ in resistance value, calculate the voltage dropped by each resistor.

- Supposing the battery has a voltage of 9 Volts, and all resistors are 1 kΩ in resistance value, calculate the current passing through each resistor as well as the current passing through the battery.
3.1.4 Resistors with specified current directions

Draw connecting wires that will create a series circuit, such that current (conventional flow notation) will follow the directions shown by the arrows near each resistor; then redraw as a parallel circuit with the same current directions:

Challenges

- Supposing the battery has a voltage of 12 Volts, and all resistors are 1 kΩ in resistance value, calculate the voltage dropped by each resistor.

- Supposing the battery has a voltage of 12 Volts, and all resistors are 1 kΩ in resistance value, calculate the current passing through each resistor as well as the current passing through the battery.
3.1.5 More resistors with specified current directions

Draw connecting wires that will create a circuit where current (conventional flow notation) will follow the directions shown by the arrows near each resistor, and where each resistor will experience the same amount of voltage; then redraw as a circuit where each resistor experiences the exact same amount of current:

**Challenges**

- Supposing the battery has a voltage of 4 Volts, and all resistors are 10 kΩ in resistance value, calculate the voltage dropped by each resistor.

- Supposing the battery has a voltage of 4 Volts, and all resistors are 10 kΩ in resistance value, calculate the current passing through each resistor as well as the current passing through the battery.
3.1.6 Resistors and terminal blocks with specified voltage polarities

Draw connecting wires to create a circuit where each resistor receives exactly the same amount of voltage regardless of resistance values, then another circuit where each resistor receives exactly the same amount of current. Note the specified voltage drops across each resistor shown by the (+) and (−) symbols:

Challenges

• Supposing the battery has a voltage of 1.5 Volts, and all resistors are 3.3 kΩ in resistance value, calculate the voltage dropped by each resistor.

• Supposing the battery has a voltage of 1.5 Volts, and all resistors are 3.3 kΩ in resistance value, calculate the current passing through each resistor as well as the current passing through the battery.
### Resistors with proportional voltage drops

Draw connecting wires to create a circuit where the voltage dropped across $R_1$ will be twice as much as the voltage dropped across $R_2$ or $R_3$. Assume equal resistor values, and be sure each resistor passes current (conventional flow notation) in the directions as shown by the arrows:

#### Challenges

- Explain why sketching a schematic diagram before attempting to sketch wire connections on the terminal block would be a good strategy to apply for solving this problem.
- Identify two different circuit designs capable of achieving the stated criteria.
- Supposing the battery has a voltage of 10 Volts, and all resistors are 2.2 kΩ in resistance value, calculate the voltage dropped by each resistor.
- Supposing the battery has a voltage of 10 Volts, and all resistors are 2.2 kΩ in resistance value, calculate the current passing through each resistor as well as the current passing through the battery.
3.1.8 Analog voltmeter

Suppose we need to connect a variable resistor in series with a sensitive analog meter movement to range that meter for a certain maximum voltage, and we were going to make all connections using a terminal strip. Draw connecting wires that will create a series circuit between the meter and two terminals of the potentiometer, such that polarity of the applied voltage will be correct for the meter with the red test lead being positive and the black test lead being negative, and also so that turning the potentiometer’s wiper clockwise makes the voltmeter more sensitive:

Challenges
- How would this voltmeter behave if the potentiometer fails open?
3.1.9 Relay-controlled lamp circuit

Sketch connecting wires such that the relay will energize and turn on the lamp when the normally-open (NO) pushbutton switch is pressed. Use the following schematic diagram as a guide:

Note how the relay coil and lamp are separate (parallel) branches in this circuit. The pushbutton switch only carries coil current, while the relay’s switch contact only carries lamp current.

**Challenges**

- Suppose the battery is rated at 12 Volts, the lamp has a “hot” filament resistance of 3.2 Ohms, and the relay coil has a wire resistance of 240 Ohms. Calculate the amount of current carried by the switch when it is pressed.
3.1.10 Relay-controlled lamp circuit with specified current directions

Sketch connecting wires such that the relay will energize and turn on the lamp when the normally-open (NO) pushbutton switch is pressed. Be sure to wire the relay in such a way that current (conventional flow) follows the directions indicated by the arrows, and that the switch only carries relay coil current (no lamp current in addition to coil current):

Challenges

- Suppose the battery is rated at 18 Volts, the lamp has a “hot” filament resistance of 4.9 Ohms, and the relay coil has a wire resistance of 310 Ohms. Calculate the amount of current carried by the switch when it is pressed.
3.1.11 Relay-switched dual-temperature monitor

Sketch connecting wires such that the relay will select one of two different thermocouples\(^4\) to send millivoltage signals to a temperature indicator. Use the following schematic diagram as a guide:

Challenges

- Explain what useful purpose the relay serves in this circuit; in other words, how is it able to accomplish something that the toggle switch cannot do on its own?

- A good problem-solving strategy is to \textit{simplify the problem} before trying to devise a solution. Identify one way this problem could be simplified, and then devise a solution to that simplified problem.

- When the battery finally dies, which thermocouple will be selected by the relay?

\(^4\)A “thermocouple” is a pair of dissimilar-metal wires joined together which produce a temperature-dependent voltage. They are commonly used as industrial temperature sensors.
• Describe a practical application for this circuit.
3.1.12 MicroLogix PLC analog inputs

Some models of the “MicroLogix” series of programmable logic controller (PLC) manufactured by Allen-Bradley come equipped with analog inputs, designed to receive either voltage or current signals from analog sensors. Examine the internal resistances of the analog inputs (IA/0, IA/1, IA/2, and IA/3) to determine which are designed to input voltage signals and which are designed to input current signals.

Assuming the three sensors shown all have internal power sources (no need for an external DC power supply to make them output their respective signals), draw connecting wires between these sensors and the appropriate inputs on the PLC.

**Challenges**

- Which type of meter has greater input resistance, a voltmeter or an ammeter? Explain the
rationale for this, and also how this principle is helpful in sketching the appropriate wire connections to the PLC’s analog input terminals.

### 3.1.13 DAQ reading solar cell voltage

A Data acquisition module (DAQ) is an analog-to-digital converter circuit designed to accept analog signals (e.g. typically modest voltages) and express them as digital quantities which may be read by a digital computer. You may think of a DAQ unit as being the “front end” of a digital voltmeter, with most DAQs having multiple “channels” capable of simultaneously measuring more than one signal voltage.

Sketch connecting wires to allow this DAQ to sense the voltage produced by the solar cell on input channel #2:

![DAQ Diagram](image)

Your circuit should be wired in such a way that greater light intensity falling on the cell produces a more positive signal measured by the DAQ.

**Challenges**

- Suppose the solar cell produced more than 10 Volts, and would therefore over-power the DAQ channel. How could you re-design the circuit to prevent the DAQ input from being overpowered?
3.1.14 DAQ reading potentiometer position

A Data acquisition module (DAQ) is an analog-to-digital converter circuit designed to accept analog signals (e.g. typically modest voltages) and express them as digital quantities which may be read by a digital computer. You may think of a DAQ unit as being the “front end” of a digital voltmeter, with most DAQs having multiple “channels” capable of simultaneously measuring more than one signal voltage.

Sketch connecting wires so that this DAQ unit will register an increasing positive voltage on channel 2 as the potentiometer shaft is turned clockwise:

![Diagram of DAQ and potentiometer]

**Challenges**

- Suppose the battery output more than 5 Volts, and would therefore over-power the DAQ channel with the potentiometer placed in the maximum-output position. How could you redesign the circuit to prevent the DAQ input from being overpowered?
3.1.15 DAQ reading pot with AC-DC power supply

A Data acquisition module (DAQ) is an analog-to-digital converter circuit designed to accept analog signals (e.g., typically modest voltages) and express them as digital quantities which may be read by a digital computer. You may think of a DAQ unit as being the “front end” of a digital voltmeter, with most DAQs having multiple “channels” capable of simultaneously measuring more than one signal voltage.

Sketch connecting wires so that this DAQ unit will register an increasing positive voltage on channel 5 as the potentiometer wiper moves to the left:

![DAQ diagram](image)

**Challenges**

- Suppose the AC power supply output more than 10 Volts, and would therefore over-power the DAQ channel with the potentiometer placed in the maximum-output position. How could you re-design the circuit to prevent the DAQ input from being overpowered?

- Explain how this power supply could still overpower the DAQ input even if its AC output was limited to 10 Volts RMS.
3.2 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” for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely on an answer key!

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5In 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.

6This 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.
3.2.1 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, Avogadro’s number given as $6.02214179(30) \times 10^{23}$ means the center value ($6.02214179 \times 10^{23}$) plus or minus $0.00000030 \times 10^{23}$.

Avogadro’s number ($N_A$) = $6.02214179(30) \times 10^{23}$ per mole (mol$^{-1}$)

Boltzmann’s constant ($k$) = $1.3806504(24) \times 10^{-23}$ Joules per Kelvin (J/K)

Electronic charge ($e$) = $1.602176487(40) \times 10^{-19}$ Coulomb (C)

Faraday constant ($F$) = $9.64853399(24) \times 10^{4}$ Coulombs per mole (C/mol)

Magnetic permeability of free space ($\mu_0$) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space ($\epsilon_0$) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

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

Gravitational constant ($G$) = $6.67428(67) \times 10^{-11}$ cubic meters per kilogram-seconds squared (m$^3$/kg-s$^2$)

Molar gas constant ($R$) = $8.314472(15)$ Joules per mole-Kelvin (J/mol-K) = $0.08205746(14)$ liters-atmospheres per mole-Kelvin

Planck constant ($h$) = $6.62606896(33) \times 10^{-34}$ joule-seconds (J-s)

Stefan-Boltzmann constant ($\sigma$) = $5.670400(40) \times 10^{-8}$ Watts per square meter-Kelvin$^4$ (W/m$^2$-K$^4$)

Speed of light in a vacuum ($c$) = **299792458 meters per second** (m/s) = $186282.4$ miles per second (mi/s)

Note: All constants taken from NIST data “Fundamental Physical Constants – Extensive Listing”, from [http://physics.nist.gov/constants](http://physics.nist.gov/constants), National Institute of Standards and Technology (NIST), 2006; with the exception of the permeability of free space which was taken from NIST’s 2018 CODATA recommended values database.
3.2. QUANTITATIVE REASONING

3.2.2 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:

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Distance traveled</td>
<td>46.9</td>
<td>Kilometers</td>
</tr>
<tr>
<td>2</td>
<td>Time elapsed</td>
<td>1.18</td>
<td>Hours</td>
</tr>
<tr>
<td>3</td>
<td>Average speed</td>
<td>= B1 / B2</td>
<td>km/h</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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\(^7\) 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.

\(^7\)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 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 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 $ax^2 + bx + c$:

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

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$x_{-1}$</td>
<td>$(-B4 + \text{sqrt}((B4^2) - (4<em>B3</em>B5))) / (2*B3)$</td>
</tr>
<tr>
<td>2</td>
<td>$x_{+2}$</td>
<td>$(-B4 - \text{sqrt}((B4^2) - (4<em>B3</em>B5))) / (2*B3)$</td>
</tr>
<tr>
<td>3</td>
<td>a =</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>b =</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>c =</td>
<td>-2</td>
</tr>
</tbody>
</table>

This example is configured to compute roots 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.

---

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.

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.

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:

\[ y = \sqrt{b^2 - 4ac} \quad \quad z = 2a \]

\[ x = \frac{-b \pm y}{z} \]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x_1</td>
<td>((-B4 + C1)) / C2 = sqrt((B4^2) - (4<em>B3</em>B5))</td>
<td>= sqrt((B4^2) - (4<em>B3</em>B5))</td>
</tr>
<tr>
<td>2 x_2</td>
<td>((-B4 - C1)) / C2 = 2*B3</td>
<td>= 2*B3</td>
</tr>
<tr>
<td>3 a</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>4 b</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>5 c</td>
<td>-2</td>
<td></td>
</tr>
</tbody>
</table>

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\(^{11}\) – 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.

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\(^{11}\)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.
3.2.3 Extending the range of a voltmeter

Suppose you need to measure voltage in a circuit where the expected voltage ranges between 1000 and 2000 Volts, but the only voltmeter you have is a DMM (Digital MultiMeter) with a maximum rating of 600 Volts. Design a circuit that would allow the voltmeter to safely and easily measure these higher voltage values, using only “mental math” to solve for component values.

Challenges

- Explain how you could make this range-extending circuit \textit{adjustable} so that it could be calibrated from time to time.

- Identify some of the criteria necessary for properly choosing component values in this circuit.
3.3 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.
3.3.1 Parallel resistors?

Someone connects these three resistors as shown and declares “Resistors $R_1$ and $R_2$ are in parallel”. Identify the misconception at work here. How do we know $R_1$ and $R_2$ are not in parallel with each other?

Challenges

- Incidentally, this happens to be a very common misconception among new students. Explain why you think this is. What, do you suppose, prompts so many people to falsely declare the existence of parallel connections where none exists?
3.3.2 Nonfunctioning relay-controlled lamp

A student connects a battery, switch, and lamp to a relay as shown, but the lamp refuses to energize when the switch is actuated:

Identify the problem with this circuit, and propose a modification to it which will make it function as it should.

**Challenges**

- Incidentally, this happens to be a *very* common wiring mistake for new students. Explain why you think this is. What, do you suppose, prompts so many people to build a circuit such as this and expect it to work?

- Suppose someone wired this circuit and came to you asking for help in making it function. Devise a diagnostic test you could recommend to the builder to identify the nature and location of the problem.
3.3.3 Miswired DAQ

A student connects a battery, potentiometer, and data acquisition unit (DAQ) together, but the DAQ’s registered voltage signal does not vary as the potentiometer knob is turned:

Identify the problem with this circuit, and propose a modification to it which will make it function as it should.

**Challenges**

- Incidentally, this happens to be a *very* common wiring mistake for new students. Explain why you think this is. What, do you suppose, prompts so many people to build a circuit such as this and expect it to work?

- Suppose someone wired this circuit and came to you asking for help in making it function. Devise a diagnostic test you could recommend to the builder to identify the nature and location of the problem.

- How much voltage do you suspect the DAQ will register for the circuit as shown?
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

“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.

The following principles inform the instructional and assessment philosophies embodied in these learning modules:

- 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 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 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 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

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1In 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.

2Socrates 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.

3This 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 characteristic of these learning modules is a lack of step-by-step instructions in the
Project and Experiment chapters. Unlike many modern workbooks and laboratory guides where
step-by-step instructions are prescribed for each experiment, these modules take the approach that
students must learn to closely read the tutorials and apply their own reasoning to identify the
appropriate experimental steps. Sometimes these steps are plainly declared in the text, just not as
a set of enumerated points. At other times certain steps are implied, an example being assumed
competence in test equipment use where the student should not need to be told again how to use
their multimeter because that was thoroughly explained in previous lessons. In some circumstances
no steps are given at all, leaving the entire procedure up to the student.

This lack of prescription is not a flaw, but rather a feature. Close reading and clear thinking are
foundational principles of this learning series, and in keeping with this philosophy all activities are
designed to require those behaviors. Some students may find the lack of prescription frustrating,
because it demands more from them than what their previous educational experiences required. This
frustration should be interpreted as an unfamiliarity with autonomous thinking, a problem which
must be corrected if the student is ever to become a self-directed learner and effective problem-solver.
Ultimately, the need for students to read closely and think clearly is more important both in the
near-term and far-term than any specific facet of the subject matter at hand. If a student takes
longer than expected to complete a module because they are forced to outline, digest, and reason
on their own, so be it. The future gains enjoyed by developing this mental discipline will be well
worth the additional effort and delay.

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.

This methodology of assigning text-based modules to students for digestion and then using
Socratic dialogue to assess progress and hone students’ thinking was developed over a period of
several years by the author with his Electronics and Instrumentation students at the two-year college
level. While decidedly unconventional and sometimes even unsettling for students accustomed to
a more passive lecture environment, this instructional philosophy has proven its ability to convey
conceptual mastery, foster careful analysis, and enhance employability so much better than lecture
that the author refuses to ever teach by lecture again.

Problems which often go undiagnosed in a lecture environment are laid bare in this “inverted”
format where students must articulate and logically defend their reasoning. This, too, may be
unsettling for students accustomed to lecture sessions where the instructor cannot tell for sure who
comprehends and who does not, and this vulnerability necessitates sensitivity on the part of the
“inverted” session instructor in order that students never feel discouraged by having their errors
exposed. Everyone makes mistakes from time to time, and learning is a lifelong process! Part of
the instructor’s job is to build a culture of learning among the students where errors are not seen as
shameful, but rather as opportunities for progress.
To this end, instructors managing courses based on these modules should adhere to the following principles:

- Student questions are always welcome and demand thorough, honest answers. The only type of question an instructor should refuse to answer is one the student should be able to easily answer on their own. Remember, *the fundamental goal of education is for each student to learn to think clearly and independently.* This requires hard work on the part of the student, which no instructor should ever circumvent. Anything done to bypass the student’s responsibility to do that hard work ultimately limits that student’s potential and thereby does real harm.

- It is not only permissible, but encouraged, to answer a student’s question by asking questions in return, these follow-up questions designed to guide the student to reach a correct answer through their own reasoning.

- All student answers demand to be challenged by the instructor and/or by other students. This includes both correct and incorrect answers – the goal is to practice the articulation and defense of one’s own reasoning.

- No reading assignment is deemed complete unless and until the student demonstrates their ability to accurately summarize the major points in their own terms. Recitation of the original text is unacceptable. This is why every module contains an “Outline and reflections” question as well as a “Foundational concepts” question in the Conceptual reasoning section, to prompt reflective reading.

- No assigned question is deemed answered unless and until the student demonstrates their ability to consistently and correctly apply the concepts to *variations* of that question. This is why module questions typically contain multiple “Challenges” suggesting different applications of the concept(s) as well as variations on the same theme(s). Instructors are encouraged to devise as many of their own “Challenges” as they are able, in order to have a multitude of ways ready to probe students’ understanding.

- No assigned experiment or project is deemed complete unless and until the student demonstrates the task in action. If this cannot be done “live” before the instructor, video-recordings showing the demonstration are acceptable. All relevant safety precautions must be followed, all test equipment must be used correctly, and the student must be able to properly explain all results. The student must also successfully answer all Challenges presented by the instructor for that experiment or project.
Students learning from these modules would do well to abide by the following principles:

- No text should be considered fully and adequately read unless and until you can express every idea *in your own words, using your own examples*.

- You should always articulate your thoughts as you read the text, noting points of agreement, confusion, and epiphanies. Feel free to print the text on paper and then write your notes in the margins. Alternatively, keep a journal for your own reflections as you read. This is truly a helpful tool when digesting complicated concepts.

- Never take the easy path of highlighting or underlining important text. Instead, summarize and/or comment on the text using your own words. This actively engages your mind, allowing you to more clearly perceive points of confusion or misunderstanding on your own.

- A very helpful strategy when learning new concepts is to place yourself in the role of a teacher, if only as a mental exercise. Either explain what you have recently learned to someone else, or at least imagine yourself explaining what you have learned to someone else. The simple act of having to articulate new knowledge and skill forces you to take on a different perspective, and will help reveal weaknesses in your understanding.

- Perform each and every mathematical calculation and thought experiment shown in the text on your own, referring back to the text to see that your results agree. This may seem trivial and unnecessary, but it is critically important to ensuring you actually understand what is presented, especially when the concepts at hand are complicated and easy to misunderstand. Apply this same strategy to become proficient in the use of *circuit simulation software*, checking to see if your simulated results agree with the results shown in the text.

- 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 effort, and never give up!

Students interested in using these modules for self-study will also find them beneficial, although the onus of responsibility for thoroughly reading and answering questions will of course lie with that individual alone. If a qualified instructor is not available to challenge students, a workable alternative is for students to form study groups where they challenge one another.

To high standards of education,

Tony R. Kuphaldt

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4 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.

5 Avoid the temptation to simply share answers with study partners, as this is really counter-productive to learning. Always bear in mind that the answer to any question is far less important in the long run than the method(s) used to obtain that answer. The goal of education is to empower one’s life through the improvement of clear and independent thought, literacy, expression, and various practical skills.
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.
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

References
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.

24 February 2022 – added more questions to the Introduction chapter, and added some more Challenge questions.

7 February 2022 – added a qualification to the “Extending the range of a voltmeter” Quantitative Reasoning problem challenging students to solve it using mental math.

8 May 2021 – commented out or deleted empty chapters.

18 March 2021 – corrected multiple instances of “volts” that should have been capitalized “Volts”.

11 February 2021 – corrected instances where “Ohms” was uncapsitalized.

2 September 2020 – minor edits to Tutorial, emphasizing how current sources differ from voltage sources.

29 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.


29 January 2020 – added more Foundational Concepts to the list in the Conceptual Reasoning section.

2 November 2019 – added more questions.

13 September 2019 – added more questions.

29 May 2019 – added index reference to KVL in the Tutorial, as well as added questions.
26 May 2019 – added discussion of differential versus ground-referenced voltages to the Tutorial.

22 May 2019 – elaborated more on noise voltage between different ground points.

19 May 2019 – added content to the Tutorial chapter.

17 May 2019 – document first created.
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