**Modular Electronics Learning (ModEL) Project**

```
* SPICE ckt
v1 1 0 dc 12
r2 2 1 dc 15
r2 3 4 4700
r3 3 0 7100
.dc v1 12 12 1
.print dc v(2,3)
.print dc i(v2)
.end
```

**Conductors and Electrical Connections**

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Chapter 1

Introduction

An essential step in constructing any electrical circuit is to make *connections* between component terminals (i.e. the metal tabs on components) and wires (i.e. conductors used to convey electrical charge carriers from one circuit component to another). A variety of methods exist to do this, each with its own set of advantages and disadvantages. This module describes many of these methods and seeks to explain why each method works as it does.

Important concepts related to electrical connections includes the motion of *charge carriers* through conductors, *switch* action, *wire resistance*, *opens* versus *shorts*, wire *gauge* and area, safety *standards*, *Joule’s Law*, solid versus stranded wire, wire *splicing*, *soldering*, *plugs* and *jacks*, and *printed circuit boards*.

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

- What universal properties do all “sound” electrical connections share?
- What factors determine the end-to-end electrical resistance of a wire?
- What determines the current-carrying capacity of a wire?
- What type of wire must be used with compression-style connectors, and why?
- How come there are so many different ways to connect wires together?
- How is wire size measured?
- How do solid and stranded wire types compare with each other?
- Why do metal wires offer resistance to the flow of electric charge carriers?
- Why does air and other gases offer great resistance to the flow of electric charge carriers?
- What are the advantages and disadvantages of various connection methods?
- How do terminal blocks function?
- How does solder work to form an electrical connection between conductors?
CHAPTER 1. INTRODUCTION

• What is a printed circuit board (PCB) and how do they work?
• How are electrical connections made between components using a solderless breadboard?
• What are some of the limitations of a solderless breadboard?
Chapter 2

Simplified Tutorial

Electric circuits are formed by connecting wires and components with each other in specific configurations. Effective electrical connections are reliable and of low resistance to minimize energy dissipation and excessive heating as charge carriers pass through. Electrical connections are made by bringing the surfaces of electrical conductors into tight physical contact with each other. The ideal electrical connection has maximum area of contact with minimum length, for minimum resistance.

Electrically conductive materials are rated for their resistive properties by a quantity called specific resistance. All other factors being equal, a material having less specific resistance will be a better conductor of electricity than a material having more specific resistance.

End-to-end conductor resistance is a function of cross-sectional area, length, and specific resistance. The cross-sectional area of a wire may be expressed by a wire gauge number (with smaller numbers representing larger-area wire) or alternatively by units of area (e.g. circular mils). The ampacity of a wire is the maximum continuous current it may carry without exceeding prescribed temperature limits.

Wire is manufactured in both solid and stranded forms, with stranded having superior flexibility.

Permanent electrical connections may be formed in several different ways:

- Wire splices (twisting wire-ends together)
- Wire nuts (a device used to augment a pigtail splice)
- Wire wrap (thin-gauge wire wrapped around square metal pegs)
- Compression connectors (thin-gauge flat metal wrapped and compressed onto a wire’s end)
- Terminal blocks (screw- or spring-fastened clamp onto a wire’s end)
- Solder (low-temperature welding of two or more wires)

A popular format for the construction of low-power circuits is the printed circuit board (PCB) which uses conductive copper pathways laid onto an insulating fiberglass substrate, components typically attached to those copper traces by soldering.
Several methods also exist to temporarily form electrical connections:

- Alligator clips (spring-loaded clamps)
- Solderless breadboards (plastic boards with tiny spring-clips for insertion of terminals)
- Plugs and sockets
Chapter 3

Full Tutorial

All atoms contain even smaller bits of matter called particles. Some of these particles possess an electrical charge, which means they experience a force when exposed to an electric field. Electrically-charged subatomic particles are found in two fundamental types: some of them negative and others positive.

Electricity is the study of mobile electric charges, and the exchange of energy by those moving charges. Some substances easily permit electric charges to move within them, and we refer to these substances as conductors of electricity. Other substances lack mobile electric charges, and we call these substances insulators of electricity. The degree to which electric charges are impeded from moving within a substance is called electrical resistance.

The amount of energy either gained or lost by a mobile charge between two different locations is called voltage, and is measured in the unit of the Volt (one Volt being equal to one Joule of energy per Coulomb\(^1\) of electric charges). The rate of motion for electric charges through a conductor is called current, and is measured in the unit of the Ampere (one Ampere being equal to one Coulomb of electric charges passing by a point per second of time).

Metals are the most common group of conductors used to construct electric circuits, because the molecular structure of any metal is such that the outer-most electrons of its constituent atoms are free to leave those atoms and drift in the space between adjacent atoms. This makes electrons the predominant form of charge carrier\(^2\) within metals, because these negatively-charged electrons are free to move within the solid volume of the metal. Within some non-metallic conductors, such as liquids, both negatively charged electrons and positively charged atomic nuclei are free to drift through the bulk of the material which means there are two types of charge carriers (drifting in opposite directions when exposed to an electric field).

The particular type(s) of charge carrier(s) within any particular conductor is usually of little importance in the construction of an electric circuit. What matters for the existence of a complete

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1 A “Coulomb” is a rather large number of electric charges: \(6.2415 \times 10^{18}\) to be exact.

2 A charge carrier is any bit of mobile matter possessing a net electrical charge. Electrically charged subatomic particles are charge carriers if they exist in a state where they may move when exposed to an electric field. Much larger pieces of matter may also serve as charge carriers if possessing a net electrical charge and free to move, such as a whole atom or molecule that is either missing electrons or in possession of extra electrons and in a liquid or gaseous state. Even macroscopic objects may serve as charge carriers provided they meet the criteria of possessing a net electrical charge as well as mobility. For example, a latex balloon that is rubbed against a wool shirt to give it an electrical charge is technically a charge carrier if it is then set aloft to float in a direction directed by an electric field!
A circuit is defined as a loop through which charge carriers may travel endlessly.
3.1 Making and breaking connections

The act of joining two or more conductors together so as to form a continuous path for charge carrier motion between them is called making an electrical connection. In essence, this consists of bringing the conductive materials together in direct contact with each other, so that no air gaps exist between. Air, like most gases at room temperature and atmospheric pressure, is an electrical insulator. The electrically charged particles within each molecule of air are opposite in charge and equal in number so that each air molecule has zero net electrical charge. Unlike metals, where the constituent atoms and molecules are packed closely together and electrons may freely drift between, the molecules comprising gases are spaced far apart from each other and their electrons are rather tightly bound to the nuclei. Therefore, any air gap between metallic conductors will serve as an impassable chasm preventing charge carrier motion.

For example, an electrical connection may be made between two metal wires by simply touching the bare metal ends of each wire together. Once direct metal-to-metal contact is made between the two wires, electrons from one wire may cross over into the metal of the other wire. Separating those two metal wires creates an insulating air gap between them once more, thus breaking the connection. This is precisely how an electrical switch functions: a pair of metal “contact points” are brought into direct contact with each other to “close” or “make” or “short” the switch, and then separated from each other to “open” or “break” the switch.

Electrical connections may also be made and broken between conductors of different substances by direct physical contact and separation, respectively, between those substances. For example, an electrical connection may be made between a metal wire and a body of saltwater by immersing the wire’s end in the saltwater. Removing the wire from the water breaks the electrical connection between them.

Likewise, substances other than air may separate two conductors from having direct contact with each other. Some electrical switches, for example, designed for high-power applications use contact points immersed in non-conductive oil which is a more effective electrical insulator than air. Electrical connections between two pieces of metal may become broken by the accumulation of insulating corrosion on the metal surfaces, which is a common way that electrical connections fail.

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4 It should be noted that air may become ionized and therefore electrically conductive, but only by vastly elevating its temperature and/or exposing it to intense electric fields.

5 These electrical oils have a greater breakdown voltage than air, which means a stronger electrical field is required to ionize the oil molecules and thus render it conductive than for air.

6 “Corrosion” is a general term describing any product of chemical reaction between the substrate metal and its environment.
3.2 Connection resistance

The amount of contact area between two connected conductors is an important factor influencing the electrical resistance of that connection. To understand why this is, it is necessary to explore the nature of electrical resistance within a conductor. As stated previously, conductors are substances possessing mobile electric charges within their structure. The plain fact that the charges are mobile, however, does not mean they are free to move without impediment at all. The bulk of an electrical conductor is not a wide-open conduit for charge carriers to flow as one might suspect, but more of an obstacle course in which the charge carriers frequently collide with stationary atoms as they move through the conductor.

When a moving charge carrier collides with a stationary atom within the volume of a conductive substance, the kinetic energy of that charge carrier becomes translated into vibratory motion of the atom (i.e. the temperature of the solid increases). Thus, charge carrier collisions result in energy being dissipated in the form of heat. This is why metal wires become warmer when conducting electric current. After each collision robs a charge carrier of kinetic energy, it begins to pick up velocity again until it collides with another atom within the conductor.

As charge carriers move at higher velocity, their collisions become more violent, dissipating greater levels of energy per collision. Therefore, the amount of voltage drop (i.e. energy lost per charge carrier) along a conductor’s length increases as a function of current. This phenomenon is codified as Ohm’s Law, where voltage ($V$) is equal to the product of current ($I$) and resistance ($R$): $V = IR$.

Suppose we pass a given amount of current through a conductor that is twice as long as before, but with all other characteristics (e.g. metal type, temperature, cross-sectional area) remaining the same. Those charge carriers will now encounter on average twice as many collisions as before because the “obstacle course” is now twice as long, and therefore each charge carrier will lose twice as much energy as it did traversing the shorter conductor. This means that the voltage drop will be double between the ends of a conductor that is twice as long, all other factors being equal. Stated more simply: resistance is directly proportional to length.

Suppose now we modify the conductor so that it has the same length as before, but twice the cross-sectional area (i.e. a wider conductor). Widening the conductor will have the effect of slowing down the charge carriers’ drift velocity for any given amount of current, just as water in a river slows whenever the river’s dimensions widen or deepen. Slower drift velocity means less violent collisions, which translates into less energy loss per collision. Thus, a conductor with twice the cross-sectional area will generate half the voltage drop from end to end as before. Stated more simply: resistance is inversely proportional to cross-sectional area.

At first it may seem as though length and area are characteristics of the conductors themselves and not the connections between them. However, connections definitely have their own length and area: if an intermediate material is used to join two other conductors together, that intermediate piece’s length contributes to the connection’s resistance. Likewise, the contact area between two conductors represents the aperture through which charge carriers must pass from one conductor to

---

7 Temperature is really just the random motion of atoms and molecules within a substance. The greater a sample’s temperature, the faster its constituent atoms are moving!

8 It is interesting to note that the drift velocity of electrons within a metal conductor is quite slow. To see a mathematical exploration of electron drift velocity, refer to page 42 of the Derivations and Technical References section 4.1.
the other, and so the amount of area shared between two conductors in contact with each other also contributes to the resistance of that connection.

Consider the case of contact points within an electrical switch: two pieces of metal with slightly convex surfaces facing one another. If such a switch is “closed” (i.e. the two metal pads brought into direct contact with each other) there will be a continuous path for electric current from one to the other. The amount of force applied between the two contact points is significant, however, because these metal surfaces slightly deform when pressed together, and the degree of deformation affects the amount of contact area between the two:

Thus, we may conclude that the electrical resistance of a closed switch is not zero, but is a finite quantity inversely dependent on the amount of closing force brought to bear on the contact points.

The relationship of conductor resistance \( R \) to length \( l \) and cross-sectional area \( A \) for any electrically conductive pathway of constant cross-section and material composition may be mathematically expressed as follows:

\[
R = \frac{\rho l}{A}
\]

The Greek letter “rho” \( \rho \) represents the specific resistance of the conductive substance, a factor dependent on the type of substance as well as the temperature of the sample. Specific resistance values for various substances may be found on page 44 of the Derivations and Technical References section 4.2.

When connecting electrical components together, it is usually optimal to have the lowest resistance possible at each connection. Low-resistance connections means less energy loss as charge carriers pass through, allowing those charge carriers to deliver more energy\(^9\) to the intended destination (called a load). In order to minimize resistance at electrical connections according to the formula \( R = \frac{\rho l}{A} \), these connections should be made with minimum length (low \( l \)), maximum contact area (high \( A \)), and minimum specific resistance (low \( \rho \)) as is practical.

\(^9\)The Law of Energy Conservation informs us that energy cannot be created or destroyed, and so any energy extracted from the circuit via heat dissipation as a result of connection resistance is energy that can never reach the load to do useful work.
Bear these factors in mind as we explore the various techniques of making electrical connections. When assessing the integrity of an electrical connection (i.e. minimal electrical resistance $R$), these factors all play significant roles. Choosing the best connection type to use in any circumstance is a matter of assessing how well these factors will be optimized for that application, as well as other factors such as cost and convenience.
3.3 Wire size and type

Metal wires intended for use as electrical conductors are rated according to their cross-sectional area. The common electrical wire sizing system used within the United States is the American Wire Gauge (AWG), which is a number inversely proportional to the wire’s cross-sectional area. For example, a #10 AWG wire has a greater diameter and thus greater cross-sectional area than a #14 AWG wire. Other gauge systems exist for expressing wire size, including the British Standard Wire Gauge (SWG) used for electrical wire in Canada and England and the Steel Music Wire Gauge used to measure steel string sizes for musical instruments.

Very large electrical wires use an altogether different method of sizing called circular mils. A “mil” is \( \frac{1}{1000} \) of an inch, and a circular mil is the area of a wire with a circular cross-section having a diameter of 1 mil (0.001 inch). Since circular mils are fundamentally an expression of two-dimensional area rather than one-dimensional distance, the relationship between wire diameter in mils and wire area in circular mils is quadratic:

\[
A = d^2
\]

Where,
- \( A \) = Wire cross-sectional area in circular mils
- \( d \) = Wire diameter in linear mils

For example, a round wire having a diameter of 0.75 inch could be expressed as having a diameter of 750 mils, and an area of 562,500 circular mils. In order to more conveniently express large number values commonly associated with circular mil area figures, the Roman numeral “M” (representing one thousand) is often used in a manner not unlike the metric prefix “kilo” (k). So, a wire size of 562,500 circular mils would be more commonly expressed as 562.5 MCM, where “MCM” stands for “thousands of circular mils”.

As previously explained, the cross-sectional area of a wire inversely affects its electrical resistance: the more area a conductor has, the less resistance it will exhibit for any given length and material type following the formula \( R = \frac{\rho l}{A} \). Conductors of low resistance are generally desirable because they convey charge carriers with a minimum of energy loss (i.e. voltage drop) which allows for delivery of more energy to the load(s) and less energy dissipated in the form of heat along the conductors. Conductor heating is also a safety concern, as wires may become hot enough to melt their insulation, and/or ignite nearby flammable materials. The ampacity of a wire is the maximum amount of current a wire can handle without exceeding safe temperature limits.

\[\text{“Gauge” scales tend to exhibit this inverse proportionality. The gauge scale used to rate thickness of sheet metal is like this, with larger gauge numbers representing thinner sheet. Shotgun barrel diameter is also expressed by an inverse gauge scale: a 20 gauge shotgun has a smaller barrel diameter than a 12 gauge shotgun.}\]
A wire’s ampacity is fundamentally a function of three factors: (1) the rate of heat dissipated by the electric current passing through that wire based on wire resistance (by Joule’s Law $P = I^2R$), (2) the wire’s ability to shed heat to the surrounding environment, and (3) the high-temperature limit of the wire’s insulation. Heat dissipation, of course, is directly related to the amount of current and the wire’s resistance which is a function of gauge (cross-sectional area) and the type of metal (e.g. copper versus aluminum). Heat shedding is related to the outer surface area of the insulated conductor as well as the material(s) it contacts. For this reason, wires buried in earth or suspended alone in open air have greater ampacity ratings than wires bundled together in an enclosed raceway (e.g. conduit, wire duct). This means wire ampacity varies with the manner in which it is installed as well as its structure and composition.

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

Conductors used for small electrical and electronic projects are typically much smaller (i.e. higher *American Wire Gauge* number) than those specified in Article 310 of the National Electrical Code because the NEC focuses on facility power wiring. NFPA 79, with its focus on the internal wiring of machinery, specifies characteristics of wires over a wider range than the NEC. The following table summarizes some of the NFPA 79 specifications for smaller-gauge single copper conductors, assuming single conductors in free air attaining a temperature of no more than 60 °C:

<table>
<thead>
<tr>
<th>AWG size</th>
<th>Cross-sectional area</th>
<th>Resistance per 1000 ft</th>
<th>Ampacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 gauge</td>
<td>– – – –</td>
<td>– – – –</td>
<td>2 Amperes</td>
</tr>
<tr>
<td>22 gauge</td>
<td>0.324 mm$^2$</td>
<td>17.2 Ω @ 25 °C</td>
<td>3 Amperes</td>
</tr>
<tr>
<td>20 gauge</td>
<td>0.519 mm$^2$</td>
<td>10.7 Ω @ 25 °C</td>
<td>5 Amperes</td>
</tr>
<tr>
<td>18 gauge</td>
<td>0.823 mm$^2$</td>
<td>6.77 Ω @ 25 °C</td>
<td>7 Amperes</td>
</tr>
<tr>
<td>16 gauge</td>
<td>1.31 mm$^2$</td>
<td>4.26 Ω @ 25 °C</td>
<td>10 Amperes</td>
</tr>
<tr>
<td>14 gauge</td>
<td>2.08 mm$^2$</td>
<td>2.68 Ω @ 25 °C</td>
<td>15 Amperes</td>
</tr>
<tr>
<td>12 gauge</td>
<td>3.31 mm$^2$</td>
<td>1.68 Ω @ 25 °C</td>
<td>20 Amperes</td>
</tr>
<tr>
<td>10 gauge</td>
<td>5.261 mm$^2$</td>
<td>1.060 Ω @ 25 °C</td>
<td>30 Amperes</td>
</tr>
</tbody>
</table>
3.4 PERMANENT CONNECTIONS

The resistance of copper wire at room temperature may be approximated based on the gauge of the wire using the following formula:

\[
R_{1000\text{ft}} = e^{0.232G - 2.32}
\]

Where,

- \( R_{1000\text{ft}} \) = Approximate wire resistance in Ohms per 1000 feet of wire length
- \( G \) = American Wire Gauge (AWG) number of the wire

#10 AWG copper wire exhibits approximately 1 Ohm of electrical resistance per 1000 feet of length at room temperature. Increasing the gauge number by 3 approximately doubles a conductor’s resistance.

Wires may be constructed of solid wire, or alternatively as bundles of smaller solid strands. Solid wire is less expensive to manufacture, but is rather stiff and will break if repeatedly bent. Stranded wire costs more to manufacture, but is much more flexible. Comparative end-views of each wire type are shown in the following illustration:

![Solid wire vs Stranded wire](image)

The degree of flexibility for any given gauge of wire depends on the size of the individual strands: the smaller (finer) the strands, the more flexible the wire. Gauge and circular mil sizing of stranded electrical wire is based on total cross-sectional area. Thus, a #10 AWG stranded wire will have the exact same cross-sectional area, and therefore the same electrical resistance per unit length, as a #10 AWG solid wire made of the same metal even though the #10 AWG stranded wire will be slightly larger in diameter than a #10 AWG solid wire.

The choice of solid versus stranded electrical wire is an important factor when selecting an appropriate connection type. Some connections only work well with solid wire, and others only with stranded. Some connection types work equally well with either solid or stranded wire.

3.4 Permanent connections

Electrical connections are formed by bringing conductive materials in direct physical contact with each other. Tight solid-to-solid contact is essential in order that there be no air between the conductive surfaces, since air is electrically insulating under most conditions. The ideal electrical connection has maximum contact area.

Some electrical connections are intended to be permanent, or at least potentially permanent even if it is possible to intentionally break the connection. The following subsections describe various ways to permanently connect electrical conductors to each other.
3.4.1 Mechanical splicing

Solid wire is stiff enough that two or more pieces may be twisted together to form a permanent electrical connection. The twisted form provides both a large contact area between the conductors to ensure low resistance as well as mechanical strength to resist disconnection by stress or vibration.

A splice may be thought of as a knot, except for electrical wire instead of rope or string. Splices generally do not work well for stranded wire, as the wire is too flexible to maintain its twisted shape when subjected to mechanical stress.

A type of wire splice developed during the era of the telegraph, intended to provide both robust mechanical and electrical connectivity is the Western Union splice. This splice is illustrated here in three steps:

The design of this particular splice is such that any external tension applied to it brings the two mutually-coiled conductors in closer contact with each other.

A much less robust splice is the so-called pigtail which consists simply of two or more wire ends twisted together:

Pigtail splices are easy to make but are quite inferior to the Western Union splice. First, the pigtail splice creates a protrusion from what otherwise would be a straight length of wire, occupying unnecessary space. Second, any external tension applied to a pigtail splice will act to unwrap the two conductors from each other, potentially breaking the splice. This type of splice is rarely used apart from secondary splicing techniques, such as wire nuts and compression connectors (both described later in this tutorial).
3.4. PERMANENT CONNECTIONS

On occasions where a cable with multiple conductors must be spliced, each conductor splice should be staggered from the next in order that no two splices will lie adjacent to each other. This helps prevent accidental contact between the different conductors as well as minimize the overall diameter of the cable splice:

![Diagram of staggered splices](image)

Spliced wires should be covered with a layer of electrical insulation to prevent accidental contact with other conductors. Ideally, flexible tape or heat-shrink tubing is tightly wrapped over the splice to seal it from air and moisture in order to protect against corrosion. In the case of multi-conductor cable splices, each individual conductor should have its own layer of insulation, with a final layer placed over all the individual splices to serve as an extension of the cable’s outer jacket.
3.4.2 Wire nuts

Intended for use with solid wire, and commonly used for residential electrical connections in the United States, wire nuts are plastic thimbles with internal threads which grip onto the wire ends when twisted over two or more wires. High-quality wire nuts use coil springs as the thread structure, which provides an additional measure of tension to maintain firm contact between the wires over time. Looking into this wire nut, you can see the metal spring at the bottom of the blind hole:

Applying a wire nut is a simple task: after stripping away the insulation from two or more wires and laying them parallel to each other, the wire nut is screwed onto the wire ends in such a way that the wires are forcibly twisted together within the nut. Turn the wire nut clockwise over the wire ends until the nut will no longer turn on the wires but the wires themselves simply twist together.

In essence, the twisting action used to apply the wire nut creates a pigtail splice between the connected wire ends, with the wire nut serving to secure that pigtail splice. Connections made in this manner are still susceptible to external tension, but they are more secure than plain pigtail splices.

A recommended technique for minimizing corrosion within the wire nut connection is to seal it off with a layer of tightly-wound electrical tape, much in the same way that a splice is sealed with a layer of tape. This helps protect against oxidation and corrosion by sealing the connection from air and moisture.

It is important to emphasize that stranded wires do not work well with wire nuts because the strands tend to fray and flatten when twisted by the nut. This results in a less-secure grasp of the wires by the wire nut, and therefore a weaker connection both mechanically and electrically. The double-helix formed by two solid wire ends twisted together provides a better surface for the wire nut’s threads to engage. Stranded wires tend to form a smooth circular shape when twisted together, providing a less irregular surface for the wire nut’s threads to engage.
3.4.3 Solder

*Solder* is a metal alloy\(^\text{11}\) with a relatively low melting temperature, used as a medium to weld metal conductors together, either solid or stranded. A small spool of solder intended for fine electrical work is shown here:

![Solder spool](image)

The process of soldering involves heating the conductors to the melting temperature of the solder metal, applying the solder to the connection so that it melts and “wets” the conductor surfaces (similar to how water flows into a porous surface), allowing the liquid solder to penetrate and fill all the spaces between the conductors, and then letting everything cool until the solder freezes into solid form. There are many different types of solder and soldering technique, but all rely on the following conditions to create a reliable connection:

- The conductors must be free of corrosion, debris, moisture, and any other surface impurities so as to facilitate a strong bond between the conductor and solder metals. A chemical compound called *flux* is applied to the surfaces prior to soldering, which chemically cleans the surfaces during the pre-heat phase of the soldering process.

- The conductors and solder must all be heated to the proper temperature. Too low of temperature may not sufficiently liquefy the solder, and/or may not enable good bonding between the solder and conductor metals. Too high of temperature may cause unnecessary oxidation of the conductor surfaces during the soldering process.

- The assembly must not be moved or otherwise stressed during the cooling phase, or else the solder will fracture and weaken.

Solder may be used to augment another style of connection, such as splicing. Wires that are twisted together and then soldered enjoy a superior electrical connection over wires that are only twisted together. The presence of solder filling all the spaces between the twisted wires greatly increases the contact area between those conductors, as well as completely displacing all air and moisture that might otherwise cause those wire surfaces to develop an external layer of corrosion. Connection styles based on spring or screw tension, however, should never be soldered.

\(^{11}\)An *alloy* is a mixture of two or more metallic elements. Traditionally a mixture of *tin* and *lead* was used to formulate electrical solder. Lead, however, is a toxic metal and has mostly been replaced in solder alloys by other metals.
A photograph showing a pigtail splice augmented with solder appears here:

![Image of a pigtail splice with solder](image)

It should be clear from this photograph how the solder has filled the spaces between the two twisted wire ends, thereby greatly increasing the amount of surface area connecting the two wires together. The metallic bonding between the copper wire and the solder alloy also greatly strengthens the splice and prevents corrosion by positively displacing all air and moisture from reaching the copper wire surfaces.

Soldering does not produce as strong a bond as welding (where the substrate metals are heated to the point of liquification and subsequent fusion), and so care should be taken to not stress the soldered connection any more than necessary. Ideally, a mechanical connection between conductors is formed prior to the application of solder, so that the solder need not bear all mechanical stress placed upon the connection. The example of the pigtail splice shown previously fulfills this criterion: the twisting of the two copper wires provides substantial mechanical integrity even without the solder in place.

A similar example is this legacy resistor network:

![Image of a legacy resistor network](image)

Note how the shape of each of the resistors’ leads may be seen beneath the layer of solder, showing each wire partially wrapped around a notched metal tab for mechanical integrity. The metal tabs are anchored to a fiberglass board (similar to printed circuit board material) which is electrically non-conductive.
3.4. PERMANENT CONNECTIONS

Printed Circuit Boards, or PCBs, use solder as the sole form of attachment between conductors and components. The board itself is formed of layered fiberglass\textsuperscript{12}, with conductive copper metal traces laid down on the fiberglass surface in lieu of wires. Components connect to these traces by the strength of solder joints between the component terminals and traces.

A front and back view of a simple PCB is shown here, using through-hole components where the component wire leads are pushed through pre-drilled holes aligned with the copper traces. Solder applied to each of these protruding leads bonds it to the respective copper trace, providing both an electrical connection to the trace and a mechanical connection to the board:

PCBs begin as a fiberglass board with either one or both sides\textsuperscript{13} covered entirely by a sheet\textsuperscript{14} of copper. Traces are formed by selectively etching away all the unwanted copper using a powerful liquid solvent such as hydrochloric acid or ammonium persulfate\textsuperscript{15}, the placement of each desired trace marked by a substance which displaces acid and leaves the underlying copper untouched. The layout of traces on a PCB design is a process which may be done manually as in the case of the PCB shown above (as evidenced by the hand-drawn traces), or done using computer drafting software. Computer-based PCB design is highly recommended over “hand” layout, and is not complicated for anyone already accustomed to two-dimensional drafting (CAD) software such as AutoCAD.

\textsuperscript{12}A very common fiberglass-based material for PCB construction is called FR4. It has a very high dielectric breakdown strength of approximately 39 kilovolts per millimeter, with good mechanical properties as well.

\textsuperscript{13}This is true for single-layer and double-layer boards. PCBs having more than two layers of tracing are comprised of multiple boards individually etched and then layered together to make the final product.

\textsuperscript{14}The thickness of this copper layer is typically measured in ounces of copper per square foot, with “1 ounce” layering being very common.

\textsuperscript{15}This process obviously produces hazardous waste consisting of spent solvent and dissolved copper metal. In the interest of minimizing the environmental impact of your PCB designs, I recommend laying out your PCBs so as to eliminate as little copper as possible. Unless constrained by other design criteria, make your traces wide to keep as much copper on the board as possible.
The simple hand-laid PCB shown previously consists of nothing but bare copper traces laid on fiberglass substrate. Most professional-quality PCBs come complete with additional layers of \textit{tinning} on all traces (solder plating designed to minimize corrosion), \textit{soldermask} (a synthetic compound designed to displace molten solder) covering all the areas that should not be soldered, and \textit{silkscreening} (ink used to create text and graphic labels on the board useful for assembly and troubleshooting). A final layer of \textit{conformal coating} may be applied to a PCB after all components and connecting wires are soldered in place, the purpose of which is to seal everything from exposure to air or moisture for superior resistance to corrosion.

A comparison of two PCBs is shown here, the one on the left consisting of just FR4 fiberglass with tinned copper traces, and the one on the right also having a green layer of soldermask and lighter-colored silkscreened text:

![PCB comparison](image1.png)

The use of different-diameter holes and different-width traces is clearly evident on this PCB. Hole diameter is important for a good fit with through-hole component leads and external connecting wires. The size of the copper “pad” surrounding a PCB hole determines the bonding strength of that pad to the fiberglass substrate, which is important for resisting stress from the wire soldered to that hole. For maximum pad strength, double-layer PCBs may be used with pads on both sides of the board for each hole. PCBs manufactured in a professional “board shop” may have the interior circumference of the holes plated as well to form a continuous metal structure from one side of the board to the other at each hole.

Note the six large holes on each of the PCBs previously shown: these are placed for the purpose of screws used to anchor the PCB to some other framework.

Trace width and trace thickness are additional parameters important to PCB design, together determining the effective cross-sectional area of each trace and therefore the current-carrying ability of each trace (analogous to the gauge of an electrical wire). For standard 1-ounce copper laying, a surface trace 0.010 inch in width (10 “mils” or 10 “thou”) will have a resistivity of 0.052 Ohms per linear inch, and should be sufficient to carry 1 Ampere of continuous current with a 10 degrees Celsius rise in temperature over ambient air. Traces between layers of fiberglass on a multi-layer PCB will have less ampacity than their surface counterparts because their ability to shed heat is more limited.

Resistance decreases proportionately to trace width and trace thickness. For example, a trace 20 mils in width for 1 ounce copper thickness will have half the resistivity of a 10-mil trace: 0.026 Ohms per linear inch instead of 0.052 Ohms per inch. A trace with the same width (10 mils) but twice the thickness (2 ounce copper) will also have 0.026 Ohms per linear inch. Ampacity (current-carrying
3.4. PERMANENT CONNECTIONS

capacity) also scales with trace thickness, but not linearly because power dissipation is proportional to the square of current in accordance with Joule’s Law \( P = I^2 R \). This means a trace four times as thick is necessary to double ampacity for any given width. The relationship between trace width and ampacity is even more complicated because a wider trace has less resistance and greater surface area to dissipate heat.

The need for more compact circuitry and smaller components led to the development of surface-mount devices (SMDs) where no holes are drilled in the PCB, but instead each component is equipped with conductive tabs which are soldered directly to copper “pads” provided on the same side of the PCB.

This next photograph shows a PCB populated mostly with surface-mount devices, and only a few through-hole devices. The size of this square PCB is approximately 5 centimeters on each edge:

When the components in question are this small and easily to dislodge with one’s hand when initially placing them, the task of soldering them to the board becomes challenging. A common technique used for soldering SMDs is to coat each of the component’s tabs with a paste consisting of pre-mixed solder and flux, place each component in the correct position, then heat the entire assembly in an oven until the solder paste melts and fuses with the PCB’s pads. Interestingly, the surface tension of the molten solder actually works to align each component squarely with its PCB pads, so that when finished the components are typically better-placed than before heating!
### 3.4.4 Wire wrap

A legacy technique for connecting small electronic component terminals together on a fiberglass breadboard\(^\text{16}\) is to provide the components with square cross-section leads and then wrap small-gauge solid wire tightly around these square “posts” using a special tool. These wire-wrapped connections are quite durable, as the solid wire “bites” into the corners of the square posts to form multiple points of electrical contact with good mechanical strength.

The following photograph shows the underside of a breadboard with wire-wrapped connections between component posts:

![Wire-wrapped connections on a breadboard](image)

Special small-gauge solid wire is made just for this purpose, along with tools designed to easily wrap (and unwrap!) this wire around the square posts.

\(^{16}\)The term “breadboard” refers to a time when electrical hobbyists would assemble radios and other circuits by attaching the components to a wooden board originally intended as a bread-cutting surface. Modern breadboards are made of thin layers of plastic, fiberglass, or some other insulating material with many holes drilled through them for component lead and wire insertion.
3.4. PERMANENT CONNECTIONS

3.4.5 Compression connectors

A hollow metal barrel designed to be crushed around the ends of one or more wires is called a compression connector. These devices are intended to be used with stranded wire only! Stranded wire easily deforms to fit the exact shape of the compressed barrel, but solid wire does not. The result of trying to use solid wire with a compression connector is relatively low contact surface area between the wire and the connector barrel. This offers greater electrical resistance and reduced mechanical integrity over time as the connector experiences stress; over time the solid wire will become loose within the connector barrel, and may detach completely.

Similarly, compression-style connectors should never be applied to the end of a tinned wire (i.e. a stranded wire that has been bonded with solder), because the soft-metal solder alloy will “cold-flow” over time with the force of the terminal’s compression and eventually loosen. Generally speaking, solder-tinned stranded wire should never be connected to any terminal of any type using physical compression.

Special crimping tools exist to compress these connectors around stranded wire ends. General-purpose pliers should never be used to crimp these connectors, as they do not provide the correct crimping shape and will therefore result in a poor connection.

Compression connectors designed to terminate a single wire at a screw-head connection point of an electrical device are called lugs or terminals. Two common styles, called fork and ring, are shown here:

![Fork terminal](image1.png) ![Ring terminal](image2.png)

The “fork” and “ring” ends of these terminals are obviously designed to fit underneath the head of a screw. Fork terminals are the easier of the two to remove and attach: just loosen the screw. Ring terminals require complete removal of the screw, making them less convenient to use. This loss of convenience is countered by a gain in reliability, as the terminal will not become completely detached even if the screw becomes loose from vibration or incorrect assembly.

These photographs show the steps involved with attaching a ring terminal to the end of a stranded copper wire:

![Attachment steps](image3.png)

Note the three different jaw positions on this crimping tool, designed to compress three different sizes of connector barrel. Each jaw position has a color-coding dot which matches the standard colors of three different sizes of connector barrel (typically color-coded yellow, blue, and red in order of decreasing diameter).
Compression terminals designed to provide a “solid” end to a length of stranded wire are called ferrules. A photograph of one appears here:

A jaw different from the one used to compress fork or ring terminals must be used in the compression tool to properly “crimp” a ferrule to the end of a stranded wire. Typically these tools have interchangeable jaws, allowing one tool to be used on a wide variety of compression connectors.

A compression connector designed to splice two wires together end-to-end is called a butt splice. An example of one shown before and after compression is shown here:
Another popular form of compression connector is the *spade terminal*, manufactured in male and female forms. Photographs of a male/female spade connector pair appear here (without wires), disconnected on the left and connected on the right:

The male spade connector terminates as a flat piece of metal, which fits alongside the female spade connector and is held in place by the tension of the female spade’s curled edges. Spade connectors facilitate temporary connections between wires, even though the spade connectors themselves remain permanently compressed on the ends of their respective wires. Many electrical components are terminated by male spade ends, allowing female-terminated wires to be easily connected and disconnected.

Aside from butt splices and ring, fork, spade, and ferrule compression terminals, a wide array of compression-style connectors are available for terminating multi-conductor cables. *Coaxial* cables – consisting of a center conductor surrounded by insulation, which in turn is surrounded by a braided or foil-type outer conductor – may be terminated using special compression-style connectors suited for the specific cable size. Flat *communication* cable such as Category-5 and Category-6 (used for Ethernet computer networks) also have special connectors which attach to the cable’s end by means of compression. Most professional-grade crimping tools provide special jaws for crimping all of these connector types.
3.4.6 Terminal blocks

A very common connection style for industrial electrical circuits is the terminal block, comprised of a “block” of insulating material (usually plastic) containing short metal strips with screws or spring clips at each end for attaching wires.

Some terminal blocks are monolithic, meaning they exist as a single component. More commonly used in industrial applications are modular terminal blocks with stackable sections to create terminal block assemblies of custom size. Monolithic terminal blocks typically provide screw-holes for mounting the block to a flat surface, while modular terminal block sections are molded to snap on to a special metal rail\(^\text{17}\) which itself is mounted to a flat surface.

An example of a 12-position monolithic terminal block is shown in this photograph:

![Monolithic terminal block](image1.png)

An example of a modular terminal block section is shown here, with a ferrule-tipped wire inserted into the right-hand side:

![Modular terminal block section](image2.png)

Note the vise-like clamping system engaged by the screw which holds the ferrule tip in close contact with the metal bar. The screws run vertically in this photograph, their heads recessed within the plastic body of the terminal block section but accessible through two holes on top. Connecting two wires together with this style of terminal block is as simple as loosening both screws, inserting the wire ends into their respective sides of the block, and tightening both screws. The screw-actuated clamps are able to accept either solid or stranded wire ends with ease.

\(^{17}\)The most common rail at the time of this writing (2017) is called DIN rail because its physical dimensions conform to a European DIN standard.
Some terminal blocks use a more primitive metal “leaf” pressed against the wire or ferrule by the screw, as seen in this photograph of a modular terminal block section. Like the “vise” style of clamping system seen in the previous terminal block, the “leaf” style still applies a flat metal surface to the conductor, making it suitable for solid, stranded, and ferrule-tipped stranded wires alike:

Some terminal block designs are even more primitive than this, using the end of the screw itself as the clamp for the wire end or ferrule. In designs where the rotating screw end directly contacts the conductor, stranded wire is unacceptable. The rotation of the screw end as it is tightened on the wire would fray the strands and cause some of them to break. Only solid wire, or a stranded wire tipped with a ferrule, are usable on this style of terminal block. An example of this design is seen here:

An important caveat when using any screw-style terminal block is to never “tin” the end of a stranded wire with solder in an attempt to make it suitable for a block where the screw tip directly contacts the wire. The logic behind this is that “tinning” a stranded wire should make it resemble a solid wire, and therefore be acceptable for use with one of these terminal blocks which would otherwise fray the strands of a stranded wire. Unfortunately, though, this will lead to another problem: the soft metal alloy that makes up solder will “cold-flow” under the compression of the terminal block, eventually becoming loose unless someone periodically tightens the screw.
Some terminal block designs use the flat head of the screw as the clamping mechanism. With this style of terminal block, only a solid wire bent into a “hook” shape, or a stranded wire tipped with a fork- or ring-style compression connector is suitable:

As with all direct-screw clamping designs, this one is unsuited for stranded wire. Exposing the end of a stranded wire to the shear forces of the rotating screw head will cause the strands to fray and likely break. As usual, tinned stranded wire is also unsuitable for this type of terminal block, and for the same “cold-flow” reason.
A more modern design of modular terminal block uses internal *spring clips* rather than screws to make firm connections with wire ends. An example is shown in this photograph, where two ferrule-tipped wires have been inserted into vertical sockets in the terminal block section and are held in contact with the metal bar by the tension of the spring clips:

These *screwless* terminal blocks maintain firm contact with the inserted wires even in conditions of high vibration, which tends to loosen screws. They even work with tinned stranded wire, because the continuous spring tension compensates for cold-flow of the soft solder alloy. Their assembly is also easier, as the spring clip may be released by the straight insertion of a special tool into a hole adjacent to the wire’s hole, rather than by the repeated twisting\(^{18}\) of a screwdriver.

Some screwless terminal block designs include a plastic button mechanism to release the spring clip’s tension, allowing actuation of the spring clip with *any* suitably-sized tool rather than some special-purpose tool. The following photograph shows a set of such terminal blocks, with small orange-colored buttons next to each of the wire sockets (four per block):

---

\(^{18}\)Frequent use of screwdrivers is an occupational hazard for electricians and other craftspeople charged with turning screws. Excessive twisting of the wrist, especially when applying forceful torque, can lead to *carpal tunnel syndrome* which is a form of repetitive stress injury.
A feature of some modular terminal blocks is the ability to accept pre-manufactured jumpers forcing a set of adjacent terminals to be electrically common to each other. The following photograph shows a modular terminal block with two yellow-colored jumpers installed. The left-hand jumper connects nine terminal block sections together, while the right-hand jumper connects three together:

All terminal blocks, regardless of style, are rated according to the size of wire (or compression terminal) they may accept, as well as by maximum current (through any terminal) and maximum voltage (between adjacent terminals). If the maximum current rating is exceeded for too long of a time period, the terminal block will overheat due to the energy dissipated by the high rate of charge carrier motion through the small resistance of the terminal block metal and the connection resistance between the terminal block and the wire ends. If the maximum voltage rating is exceeded, the plastic (or other insulating material separating adjacent blocks) may break down and begin to conduct current.
3.5 Temporary connections

Electrical connections exist where conductive materials come into direct physical contact with each other. Tight solid-to-solid contact is essential for a sound electrical connection in order to eliminate air between the conductive surfaces, since air is electrically insulating under most conditions. The ideal electrical connection has maximum contact area.

Some electrical connections are intended to be temporary, either for the purpose of convenient connection and disconnection of permanent fixtures, or for the construction of a prototype circuit which will be dismantled later. A common design technique for maintaining firm physical contact in a temporary electrical connection is to use a mechanical spring to hold the conductors together. The following subsections describe various spring-based means of temporarily connecting electrical conductors to each other.
3.5.1 Alligator clips

An alligator clip is a spring-actuated metal jaw used to grab and hold on to a conductive object, attached to the end of a connecting wire. A photograph of a single alligator clip (with no connecting wire) is shown here, its spring-loaded jaw being held open by the squeezing force of my fingers:

Lengths of wire with an alligator clip on either end are often referred to as jumper wires.

The following photograph shows a yellow-colored jumper wire temporarily “jumping” two screw terminals together on an industrial relay. The alligator clip jaws are shrouded under yellow rubber guards, to help avoid unwanted electrical contact with nearby conductors:

Alligator-clip style jumper wires are perhaps the easiest method of connection for constructing very simple circuits, and are often used by beginning students of electricity and electronics.
3.5.2 Solderless breadboards

The term *breadboard* refers to wooden bread cutting boards which were often used by electrical hobbyists many years ago as temporary structures for attaching components and wires. Modern breadboards are thin insulating structures with many holes drilled in them, ready to accept component leads, wires, and other thin conductive objects. A *solderless* breadboard is a special device made of plastic with rows and columns of small holes designed to accept metal pins and wire ends. Underneath each hole is a spring clip designed to automatically engage with any inserted object, sets of holes joining in common to a short row of spring clips formed from a single piece of metal. Wires inserted into any “common” holes become connected to each other by virtue of the common spring clips.

![Solderless breadboard](image)

In addition to these rows and columns of holes, most solderless breadboards also include rows of electrically common *bus* holes at the upper and lower edges of the breadboard, useful for power supply + and − terminals and for circuit “ground” points. The following photograph shows a solderless breadboard with four bus rows, two along the top edge and two along the bottom edge:

![Solderless breadboard](image)

Solderless breadboards are especially useful for building circuits comprised of *integrated circuit* (IC) “chips” which are small rectangular packages containing specialized subcircuits, having one or more rows of metal pins protruding along the side. The spacing between adjacent holes in a solderless breadboard match the standard pin spacing (typically 0.1 inch) of SIP (single inline package) and DIP (dual inline package) IC chips. Solderless breadboards are designed for DIP integrated circuits to be plugged in along the board’s centerline (straddling the lengthwise groove along the board’s center), with each row of inline pins engaging with columns of holes on either side of the chip.
CHAPTER 3. FULL TUTORIAL

While extremely useful for prototyping and educational purposes, a solderless breadboard should never be used for permanent circuit construction. The spring clips are quite weak, and provide no security against vibration. Furthermore, the weakness of the spring clips results in relatively high and inconsistent connection resistance. A few Ohms of connection resistance may not pose a problem for a typical IC-based circuit with extremely low current values\(^{19}\), but higher current levels will cause overheating of the board. Any circuit relying on low connection resistance for purposes of precision (e.g. resistance-based sensors) may experience trouble for the same reason if constructed on a solderless breadboard. Breadboards are also very limited in their voltage and current capacities.

3.5.3 Plugs and sockets

A bewildering array of plug and socket styles exist to facilitate easy connection and disconnection between conductors. No attempt will be made in this tutorial to categorize all plugs and sockets. All of them share common features, though:

- The male plug has conductive “pins” or “prongs” or “stabs” protruding outward
- The female socket or cap has holes into which the male plug’s pins insert, each containing a conductive receptacle
- Spring tension holds the male and female parts in close contact with each other

Photographs of the common plug and cap\(^{20}\) style used in North America for temporary household electrical power connections appear here:

\(^{19}\)It should be noted that a few Ohms of connection resistance can be problematic for precision resistance circuits such as RTD (Resistive Thermal Detector) bridge circuits where mere fractions of an Ohm of resistance may represent significant differences in temperature.

\(^{20}\)A “cap” is the female counterpart to a male electrical plug, designed to fit on the end of a cable. A female counterpart to a male electrical plug designed for mounting to a wall board or panel is called a socket or receptacle or jack.
A popular style of plug-and-socket connector for electronic equipment is the so-called molex connector, a four-terminal male and female pair shown in the following photograph:

![Molex Connector](image)

Note the asymmetrical shape of the plastic frames, to ensure they may only be connected together in one orientation. This is a simple example of connector keying: the use of a geometric shape to ensure only one orientation is possible.

While many plug-and-socket designs rely on internal spring tension between the male pins and female receptacles to hold those pieces firmly in contact with each other, other designs use threaded bodies which screw together to achieve mechanical security. These threaded connectors are more expensive, and more tedious to connect and disconnect than their non-threaded counterparts, but are far more robust than connectors relying on spring tension alone. Connections between cables aboard aircraft and other vehicles subject to vibration often use some form of external threads or clamping mechanism to hold the male and female elements together. A photograph of a military-grade female connector with a threaded barrel appears in this photograph:

![Military-Grade Connector](image)

Note also the keying tabs around the circumference of this connector which make it impossible to accidentally connect to the male plug in the incorrect orientation.
Circular connectors with simpler securing and keying mechanisms are commonplace on industrial proximity switches, an example of which is shown here:
3.5. TEMPORARY CONNECTIONS

3.5.4 Banana plugs and jacks

A special type of electrical plug connection is called the banana plug, so-called because the metal barrel of the male plug is wider in its center than at the ends so as to form a spring-tight fit with the female banana jack it inserts into. The following photograph shows a set of three banana jacks installed on the surface of a metal panel, ready to receive banana plugs attached to wires. On the other side of the metal panel these banana jacks have soldered attachment points for wires allowing connections to components inside the panel:

Banana plugs and jacks are deserving of their own section in this tutorial due to their nearly universal use for test lead connections on multimeters and other electrical test instruments. The instrument’s front panel will have multiple banana jacks, while the test leads are terminated with banana plugs for insertion into the proper jacks on the instrument. In the following photograph you can see four banana plugs (two red, two black) inserted into four banana jacks on the front panel of a test instrument:
Some banana plugs are *stackable*, which means each plug has both a male end (for inserting into a banana jack) and a female jack into which another banana plug may be inserted. Stackable plugs are exceptionally useful for complex test instrument connections.

The following photograph shows stackable banana plugs inserted into jacks on the front panel of a Manta model 5000 protective relay test set, used to generate precise AC voltages and currents for the purpose of testing protective relays in electric power systems. Although none of the banana jacks happen to be stacked upon each other in this particular test setup, it should be clear to see that this is possible because each banana plug clearly exhibits a jack (i.e. a female socket) on the camera-facing side. Banana jacks are particularly well-suited for this application because of their relatively high voltage and current ratings, easily handling the hundreds of Volts and dozens of Amperes necessary to thoroughly test protective relay devices:
Chapter 4

Derivations and Technical References

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

Electrons typically drift at a very slow velocity through an electrical conductor, even when the current value is rather large. To illustrate, we will analyze a case where 200 Amperes of current passes through a solid copper bar with a cross-sectional area of 1 square centimeter. We must imagine this copper bar as being part of a larger circuit complete with a source, because an open-ended metal bar obviously does not comprise a circuit for a continuous current to pass nor does it provide any energy to motivate a current:

Our analysis will proceed as follows:

1. Calculate the number of charge carriers within one cubic centimeter of this bar (i.e. 1 centimeter of the bar’s length, given a 1 cm$^2$ cross-sectional area)
2. Calculate the drift rate of the current (200 Amperes) in charge carriers per second
3. Divide the carrier drift rate (carriers/second) by the carrier density (carriers/cm$^3$) to find the volumetric drift rate in cubic centimeters per second
4. Divide the volumetric drift rate in (cm$^3$/sec) by the cross-sectional area (1 cm$^3$) to find the drift velocity in linear centimeters per second

Note that most values will be shown rounded to two significant figures for the sake of brevity, but the actual calculations will be performed with many more significant figures in order to avoid unnecessary rounding errors.

First, calculating the number of charge carriers within 1 cm$^3$ of solid copper. The density of solid copper metal is 8900 kg per cubic meter, or 8,900,000 grams per cubic meter. Converting this into grams per cubic centimeter by using the “unity fraction” method of unit cancellation:

$$\left( \frac{8900000 \text{ g}}{\text{m}^3} \right) \left( \frac{1 \text{ m}}{100 \text{ cm}} \right)^3 = \frac{8.9 \text{ g}}{\text{cm}^3}$$

The atomic weight of copper (found in a Periodic Table of the Elements) is 63.546 amu, or 63.546 grams per mole. We will use this figure to determine the number of moles of copper atoms within our 1 cm$^3$ volume of solid copper:

$$\left( \frac{8.9 \text{ g}}{\text{cm}^3} \right) \left( \frac{1 \text{ mol}}{63.546 \text{ g}} \right) = \frac{0.14 \text{ mol}}{\text{cm}^3}$$
1 mole of anything is $6.022 \times 10^{23}$ units, so we may calculate the number of individual copper atoms in our 1 cm$^3$ sample by multiplying 0.14 moles by this number:

$$\left(\frac{0.14 \text{ mol}}{\text{cm}^3}\right) \left(\frac{6.022 \times 10^{23} \text{ atoms}}{\text{mol}}\right) = 8.4 \times 10^{22} \text{ atoms cm}^3$$

Each copper atom possesses one “free” electron in its valence shell, which means our 1 cm$^3$ sample of the copper bar contains $8.4 \times 10^{22}$ free charges (electrons).

One Ampere of electric current is equal to $6.2 \times 10^{18}$ individual charges passing by per second of time. 200 Amperes of current is therefore equal to:

$$\left(\frac{200 \text{ A}}{1}\right) \left(\frac{6.2 \times 10^{18} \text{ electrons / sec}}{1 \text{ A}}\right) = 1.2 \times 10^{21} \text{ electrons / sec}$$

Dividing this electron flow rate by the volumetric density of electrons within copper will yield a volumetric flow rate in cubic centimeters’ worth of electrons per second:

$$\frac{1.2 \times 10^{21} \text{ electrons / sec}}{8.4 \times 10^{22} \text{ electrons / cm}^3} = 0.015 \text{ cm}^3 / \text{sec}$$

Dividing this volumetric charge flow rate by the bar’s cross-sectional area yields the linear drift velocity in centimeters per second:

$$\frac{0.015 \text{ cm}^3 / \text{sec}}{1 \text{ cm}^2} = 0.015 \text{ cm / sec}$$

Converting into centimeters per minute:

$$\left(\frac{0.015 \text{ cm}}{\text{sec}}\right) \left(\frac{60 \text{ sec}}{1 \text{ min}}\right) = 0.88 \text{ cm / min}$$

As you can see, the average drift velocity of electrons through this copper bar is quite slow, even for a relatively high\(^1\) amount of current. At this velocity, the electrons will take over a minute’s worth of time to move just 1 centimeter along the bar’s length!

\(^1\)For reference, 200 Amperes is the maximum amount of current most North American households are rated to consume in total.
4.2 Table of specific resistance values

Note: this table\(^2\) assumes a substance temperature of 20 degrees Celsius. Order is from least resistive (top) to most resistive (bottom).

<table>
<thead>
<tr>
<th>Substance</th>
<th>Element or Alloy</th>
<th>Ohm-cmil/ft</th>
<th>microOhm-cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>Element</td>
<td>9.540</td>
<td>1.586</td>
</tr>
<tr>
<td>Copper</td>
<td>Element</td>
<td>10.09</td>
<td>1.678</td>
</tr>
<tr>
<td>Gold</td>
<td>Element</td>
<td>13.5</td>
<td>2.24</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Element</td>
<td>15.97</td>
<td>2.655</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Element</td>
<td>31</td>
<td>5.2</td>
</tr>
<tr>
<td>Tungsten</td>
<td>Element</td>
<td>34.0</td>
<td>5.65</td>
</tr>
<tr>
<td>Zinc</td>
<td>Element</td>
<td>35.59</td>
<td>5.916</td>
</tr>
<tr>
<td>Nickel</td>
<td>Element</td>
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<td>6.84</td>
</tr>
<tr>
<td>Iron</td>
<td>Element</td>
<td>58.4</td>
<td>9.71</td>
</tr>
<tr>
<td>Platinum</td>
<td>Element</td>
<td>63.8</td>
<td>10.6</td>
</tr>
<tr>
<td>Tin</td>
<td>Element</td>
<td>66.2</td>
<td>11.0</td>
</tr>
<tr>
<td>Lead</td>
<td>Element</td>
<td>124.20</td>
<td>20.648</td>
</tr>
<tr>
<td>Steel (99.5% iron, 0.5% carbon)</td>
<td>Alloy</td>
<td>100</td>
<td>16.62</td>
</tr>
<tr>
<td>Antimony</td>
<td>Element</td>
<td>235</td>
<td>39.0</td>
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<tr>
<td>Titanium</td>
<td>Element</td>
<td>253</td>
<td>42.0</td>
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<tr>
<td>Constantan</td>
<td>Alloy</td>
<td>272.97</td>
<td>45.38</td>
</tr>
<tr>
<td>Manganin</td>
<td>Alloy</td>
<td>290</td>
<td>48.21</td>
</tr>
<tr>
<td>Nichrome V</td>
<td>Alloy</td>
<td>650</td>
<td>108.1</td>
</tr>
<tr>
<td>Nichrome</td>
<td>Alloy</td>
<td>675</td>
<td>112.2</td>
</tr>
</tbody>
</table>

\(^2\)Values of microOhm-centimeters for elements taken from the *CRC Handbook of Chemistry and Physics, 64th edition* (page F-125, “Electrical Resistivity and Temperature Coefficients of Elements”) and then converted into Ohm-cmil/ft using exact conversion factors (e.g. 2.54 centimeters per inch, 12 inches per foot, 1000 mil per inch, \(\frac{4}{\pi}\) circular units per square unit).
Chapter 5

Animations

Some concepts are much easier to grasp when seen in action. A simple yet effective form of animation suitable to an electronic document such as this is a “flip-book” animation where a set of pages in the document show successive frames of a simple animation. Such “flip-book” animations are designed to be viewed by paging forward (and/or back) with the document-reading software application, watching it frame-by-frame. Unlike video which may be difficult to pause at certain moments, “flip-book” animations lend themselves very well to individual frame viewing.
5.1 Using a soldering iron

This animation shows the proper usage of a soldering iron to solder a wire to a lug-style connector. Note how heat from the soldering iron tip is applied to the connector (lug) itself, and not to the solder. This ensures the connector’s metal will be at full temperature necessary for good bonding between the metal and the solder.
5.1. USING A SOLDERING IRON
5.1. USING A SOLDERING IRON

![Diagram of a soldering iron, solder, wire, and lug]

- Soldering iron
- Solder
- Wire
- Lug
5.1. USING A SOLDERING IRON

Soldering iron

Solder

Wire

Lug
5.1. USING A SOLDERING IRON

![Diagram of a soldering iron with solder, wire, and lug.]

- Soldering iron
- Solder
- Wire
- Lug
5.1. USING A SOLDERING IRON
CHAPTER 5. ANIMATIONS

Soldering iron
Solder
Wire
Lug
5.1. USING A SOLDERING IRON
5.1. USING A SOLDERING IRON
5.1. USING A SOLDERING IRON
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CHAPTER 5. ANIMATIONS
5.1. USING A SOLDERING IRON
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5.1. USING A SOLDERING IRON
Chapter 6

Questions

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

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

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

---

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

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

- **Summarize** as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.

- **Simplify** a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.

- Where did the text make the most sense to you? What was it about the text’s presentation that made it clear?

- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.

- Identify any new concept(s) presented in the text, and explain in your own words.

- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.

- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.

- Devise an experiment to disprove a plausible misconception.

- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.

- Describe any useful problem-solving strategies applied in the text.

- **Devise a question** of your own to challenge a reader’s comprehension of the text.
General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.

- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.

- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?

- Is there more than one way to solve this problem? Which method seems best to you?

- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.

- What would you say was the most challenging part of this problem, and why was it so?

- Was any important information missing from the problem which you had to research or recall?

- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?

- Examine someone else’s solution to identify where they applied fundamental laws or principles.

- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).

- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.

- For quantitative problems, try approaching it qualitatively instead, thinking in terms of “increase” and “decrease” rather than definite values.

- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.

- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?

- Identify where it would be easy for someone to go astray in attempting to solve this problem.

- Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?

- Identify some of the challenges you faced in completing this experiment or project.
• Show how thorough documentation assisted in the completion of this experiment or project.

• Which fundamental laws or principles are key to this system’s function?

• Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.

• What will happen if (component X) fails (open/shorted/etc.)?

• What would have to occur to make this system unsafe?
6.1 Conceptual reasoning

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

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

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

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

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

---

\(^3\)Analytical thinking involves the “disassembly” of an idea into its constituent parts, analogous to dissection. Synthetic thinking involves the “assembly” of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.
6.1.1 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.
6.1.2 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
- Conductors versus Insulators
- Voltage
- Resistance
- Current
- Open
- Short
- Switch
- Ohm’s Law
- Specific resistance
- Electrical load
6.1.3 Switch contact size

Electrical switches use pairs of metal contact points to open and close an electrical connection. In the “open” position the points are separated from each other, usually by an air gap. In the “closed” position the points are pressed together in firm contact with one another.

Does the maximum current rating of an electrical switch matter in its open or closed state?

Does the maximum voltage rating of an electrical switch matter in its open or closed state?

All other factors being equal, do you suppose a switch rated for a high amount of electrical current would have larger or smaller or the same size contact points as a switch rated for a low amount of current? Explain your answer in detail.

Challenges

- What design factors other than contact point size might be optimized for a switch intended for high-current applications?
- Suppose we needed a switch for a high voltage application rather than high current. What design factors might be altered to achieve this goal?
6.1.4 Why use gold plating?

High-quality electrical connectors are often plated with a thin layer of gold metal, which is obviously expensive. Consulting a table of specific resistance values, we see that gold is actually a less effective conductor than copper, so why would anyone bother plating a copper wire or connector with gold?

Note: a table of specific resistance values for common metal types is found on page 44 of section 4.2 for your reference.

Challenges

- Contact points for heavy-duty electrical switches are often plated with silver rather than gold. Why do you suppose silver is the better metal for this application?
6.1.5 Diagnostic thermal imaging

A modern diagnostic tool for electrical power connections is the thermal imaging camera, which provides a color-coded graphic display of surface temperature. The following thermal image shows a 24 Volt DC circuit breaker within an active solar electric power circuit. Higher surface temperature is represented by red, lower surface temperature by blue:

Connections between current-carrying wires and the threaded posts of the circuit breaker (in the upper-right and lower-left corners of the rectangular breaker body) are made using compression-style ring terminals.

First, explain the concept behind analyzing electrical connections using a thermal imaging camera. What does temperature tell us about an electrical connection?

Next, determine whether or not any poor-quality connections exist with the particular circuit breaker shown in the image.

Thermal images are best used to compare a set of identical electrical connections positioned near each other, carrying the same amount of current each. Explain why a thermal image of such an arrangement might be easier to interpret than a thermal image of a single connection.

**Challenges**

- One of the challenges of thermal imaging is that shiny objects such as bright metal compression terminals act as mirrors, reflecting the infra-red light from surrounding objects. Explain how this phenomenon might lead to erroneous temperature measurements.
6.1.6 Soldering iron usage

When soldering a wire into a metal lug, which of these positions would be considered best for soldering iron and solder?

Explain your answer in detail.

**Challenges**

- For each of the other positions, explain what is wrong.
6.1.7 Battery-lamp-switch circuit on a solderless breadboard

Show how to build a simple circuit consisting of a battery, a lamp, and a switch, mounting the lamp and switch on a solderless breadboard (also known as a proto-board):

- As versatile as solderless breadboards are, they definitely have limitations. Identify a few.
6.2 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!

---

4In 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.

5This 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.
6.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation ($\sigma$) 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 ($\varepsilon_0$) = $8.8541878128(13) \times 10^{-12}$ 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.
6.2.2 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></th>
<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>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Time elapsed</td>
<td>1.18</td>
<td>Hours</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Average speed</td>
<td>= B1 / B2</td>
<td>km/h</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\(^6\) would in an algebraic formula.

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

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

\(^6\)Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels “names”), but for simple spreadsheets such as those shown here it’s usually easier just to use the standard coordinate naming for each cell.
Common 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}) = ((-B4 + \sqrt{B4^2 - (4<em>B3</em>B5)}) / (2*B3))</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>(x_{-2}) = ((-B4 - \sqrt{B4^2 - (4<em>B3</em>B5)}) / (2*B3))</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>a = (9)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>b = (5)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>c = (-2)</td>
<td></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.

---

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

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

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

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

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

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

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x_1</td>
<td>(-B4 + C1) / C2</td>
<td>sqrt((B4^2) - (4<em>B3</em>B5))</td>
</tr>
<tr>
<td>2</td>
<td>x_2</td>
<td>(-B4 - C1) / C2</td>
<td>2*B3</td>
</tr>
<tr>
<td>3</td>
<td>a</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>b</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>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\(^{10}\) – all that matters is that they properly reference each other in the formulae.

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

---

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

Suppose a power system delivers power to a resistive load drawing 150 Amperes:

\[ V_{\text{load}} = \frac{P_{\text{load}}}{I} \]
\[ P_{\text{load}} = I^2 R_{\text{wire}} \]
\[ P_{\text{wires}} = I^2 R_{\text{wire}} \]
\[ \eta = \frac{P_{\text{load}}}{P_{\text{source}}} \]

Now, explain what each of these quantities means, in terms understandable to someone unfamiliar with voltage, current, power, and efficiency:

- Voltage
- Current
- Power
- Efficiency
Now, suppose we were to re-design both the generator and the load to operate at 2400 Volts instead of 240 Volts. This ten-fold increase in voltage allows just one-tenth the current to convey the same amount of power. Rather than replace all the wire with different wire, we decide to use the exact same wire as before, having the exact same resistance (0.1 Ω per length) as before. Re-calculate load voltage, load power, wasted power, and overall efficiency of this (higher voltage) system:

\[ V_{\text{load}} = \]  
\[ P_{\text{load}} = \]  
\[ P_{\text{wires}} = \]  
\[ \eta = \]

**Challenges**

- Show how to estimate answers for these calculated results without using a calculator.
- Explain why electric power transmission and distribution systems use such high voltage levels (typically many thousands of Volts).
6.2.4 Siemens model 3AP1/2 high-voltage circuit breaker

According to a technical brochure for the model 3AP1/2 high-voltage circuit breaker manufactured by Siemens, for use as a switch in electrical power substations, the 550 kilo-Volt (550 kV) model has the following current ratings:

- Rated normal current = 5,000 Amperes
- Rated peak withstand current = 170,000 Amperes
- Rated maximum breaking current = 63,000 Amperes
- Rated maximum making current = 170,000 Amperes

The “normal” and “peak withstand” ratings refer to a condition when the unit is in its closed state. However, the other two ratings refer to the circuit breaker transitioning between states, “breaking” referring to the transition from closed to open, and “making” referring to the transition from open to closed.

Calculate how much greater the “making” current rating is than the “breaking” current rating, and then hypothesize why the “making” rating is greater than the “breaking” rating.

Challenges

- As you can see, the values of current a power-system circuit breaker must manage are quite large. If the normal amount of current for a circuit breaker such as this is 5,000 Amperes, what sort of abnormal condition do you suppose would create a current over ten times larger than this, which the circuit breaker would have to be able to reliably interrupt by opening?

- High-voltage circuit breakers such as this model often are filled with a special gas called SF$_6$ (sulfur hexafluoride). Why do you suppose a special gas-fill is needed, rather than have the electrical contacts operate in plain air?
6.2.5 Resistance of copper busbar

The cross-sectional dimensions of a copper “busbar” measure 8 cm by 2.5 centimeters. How much resistance would this busbar have, measured end-to-end, if its length is 10 meters? Assume a temperature of 20° Celsius, and a specific resistance for pure copper of $1.678 \times 10^{-8} \, \Omega \cdot \text{meters}$.

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**Challenges**

- What might be a good method of establishing a solid electrical connection between two of these busbars?
6.3 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.
6.3.1 Testing for a broken connection

Suppose the lamp in this circuit refuses to energize. The person who built this circuit decides to perform some tests with a multimeter to determine the nature and location of the fault:

The first test is a measurement of voltage between the battery terminals, where the voltmeter registers 6.3 Volts. This is as expected, since both the battery and the lamp are known to be rated for 6 Volts.

The next test is between two screw-heads on the terminal block, as shown:

Explain what we may determine about the condition of the circuit from the result of this test.
The next test is another voltage measurement taken directly at the lamp’s terminals, as shown:

Explain what we may determine about the condition of the circuit from the result of this test.
6.3. **DIAGNOSTIC REASONING**

The last test is a measurement of voltage between two screw terminals on the same terminal block section, as shown. The person’s stated rationale for performing this test is to check for a bad connection where one of the wires meets the terminal block section:

Explain why this test does not, in fact, tell us anything about the condition of the connections between either wire and the terminal block section.

Devise a better test, which *will* reveal a broken connection between a wire and the terminal block section.

**Challenges**

- Identify a fault which *would* result in voltage being measured between the two screw-heads of one terminal block section.

- Explain why such a fault is in fact highly unlikely to occur.
6.3.2 Improper breadboard use

Solderless breadboards provide convenient means for electronics hobbyists, students, technicians, and engineers to build circuits in a non-permanent form. The following illustration shows a three-resistor series circuit built on a breadboard:

The interconnections between the metal spring clips within the holes of the breadboard allow continuity between adjacent leads of the resistors, without the resistor leads having to be jammed into the same hole.

However, new students often get themselves into trouble when first learning how to use solderless breadboards. One common mistake is shown here, where a student has attempted to create a simple single-resistor circuit:

Re-draw this circuit in schematic form, and explain why this circuit is faulty.

Challenges
• Explain what might happen if a large battery or high-current power supply were powering this short circuit.

• Show how the single-resistor circuit should have been built on the breadboard so as to avoid a problem.
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\(^4\) 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\(^5\) 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 \textit{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 \textit{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 \textit{Word} suggests nothing to the reader about \textit{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

“High-Voltage Circuit-Breakers 3AP1/2 72.5 kV up to 550 kV”, Order number E50001-U113-A165-V3-7600, Siemens, Berlin.

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.

15 March 2022 – added comments about solder-tinned wire ends “cold-flowing” under mechanical compression. Also, relocated the “Solder” subsection to an earlier part of the Tutorial, so that it precedes the subsection on terminal blocks where these new comments are found.

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

18 July 2021 – added foundational concept review to the “Power losses over wires” Quantitative Reasoning question.

1 June 2021 – minor additions to the beginning of the “Permanent Connections” and “Temporary Connections” sections of the Tutorial.

8 May 2021 – commented out or deleted empty chapters.

2 February 2021 – minor edits.

14 September 2020 – added “soldering” to the list of Foundational concepts.

8 September 2020 – minor edits to the Introduction chapter.

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.

14 April 2020 – added some questions.

14 February 2020 – added ampacity figures from NFPA 79 standard.
2 February 2020 – minor typographical error correction.

20 October 2019 – added an animation showing the proper use of a soldering iron to attach a wire to a lug.

August 2018 – added more photographs to the tutorial, especially of plug and socket connectors, and of terminal blocks. Also, made minor edits to Introduction chapter.

May 2018 – minor edit to “parallel” illustration, annotating connected points as electrically common to each other, not just equipotential to each other. Minor edit to open vs. shorted switch illustration, relating open with electrical isolation (no current) and relating shorted with electrical commonality (no voltage).

2017 – document first created.
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