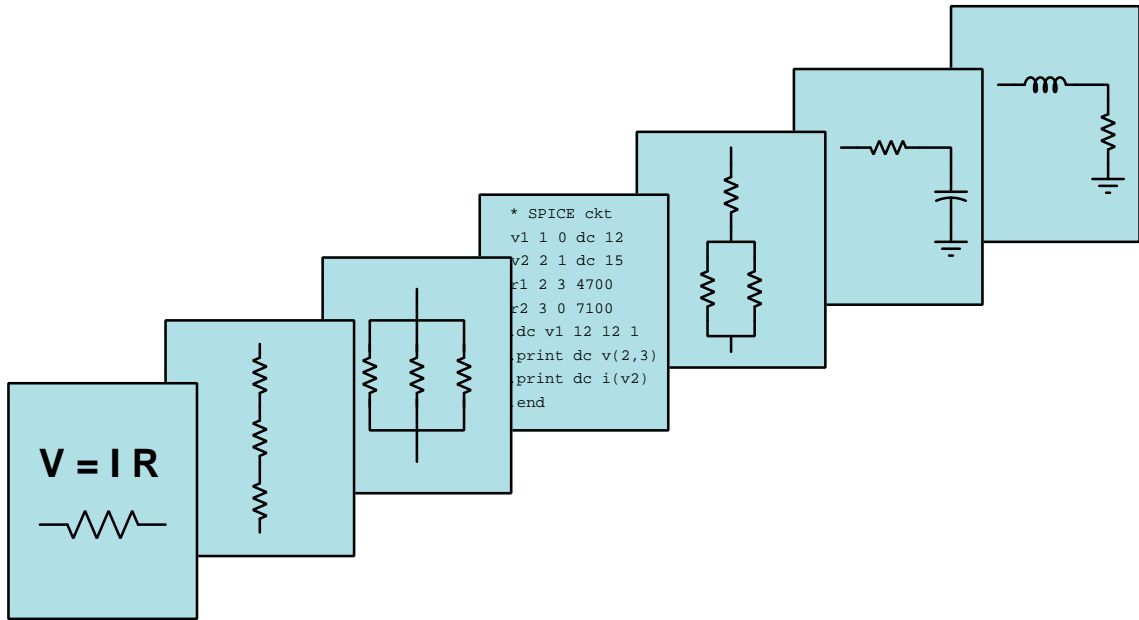


MODULAR ELECTRONICS LEARNING (MODEL) PROJECT



SOLDERING

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Contents

1	Introduction	3
2	Tutorial	5
2.1	Basic concepts of soldering	6
2.2	Soldering metallurgy	11
2.3	Soldering flux	14
2.4	Soldering safety	16
2.5	Hand-soldering	17
2.6	Soldering iron care	24
2.7	Automated soldering	26
2.8	Rework	27
2.9	Typical solder defects	30
3	Animations	35
3.1	Using a soldering iron	36
4	Questions	71
4.1	Conceptual reasoning	75
4.1.1	Reading outline and reflections	76
4.1.2	Foundational concepts	77
4.1.3	Makeshift soldering heat-sink	78
4.2	Quantitative reasoning	79
4.2.1	Miscellaneous physical constants	80
4.2.2	Introduction to spreadsheets	81
4.2.3	Converting between Celsius and Fahrenheit	84
4.3	Diagnostic reasoning	85
4.3.1	Soldering profile temperature rates	86
A	Problem-Solving Strategies	89
B	Instructional philosophy	91
C	Tools used	97
D	Creative Commons License	101

<i>CONTENTS</i>	1
E References	109
F Version history	111
Index	111

Chapter 1

Introduction

Important concepts related to soldering include **melting point**, **intermetallic layer**, **oxidation**, **dwell time**, **heat sink**, **rework**, and **work**.

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

- How might an experiment be designed and conducted to explore the concept of *heat transfer*? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to explore the concept *oxidation*? What hypotheses (i.e. predictions) might you pose for that experiment, and what result(s) would either support or disprove those hypotheses?
- Why is dwell time important in soldering?
- How long should the dwell time be for leaded soldering?
- How long should the dwell time be for lead-free soldering?
- What is the “wetting” process that occurs during soldering?
- How does solder create a bond between metal objects differing in composition from the solder?
- What is a *thermal bridge* and when might you apply one during soldering?
- What are some of the different solder metal alloys available?
- What purpose does *flux* serve in the soldering process?
- How should a soldering iron’s tip be kept in optimal condition?
- What are some different ways solder may be removed from work?
- What are some of the different personal safety hazards associated with soldering?
- Devise your own question based on the text, suitable for posing to someone encountering this subject for the first time

Chapter 2

Tutorial

2.1 Basic concepts of soldering

Solder is a metal alloy¹ 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:



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 may spread over a solid 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.

¹An *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:



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 liquefaction 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.

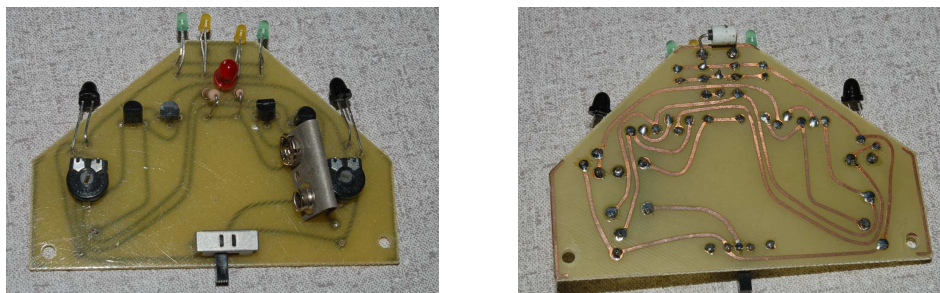
A similar example is this legacy resistor network:



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.

Printed Circuit Boards, or *PCBs*, use solder as the sole form of attachment between conductors and components. The board itself is formed of layered fiberglass², 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 sides³ covered entirely by a sheet⁴ of copper. Traces are formed by selectively etching away all the unwanted copper using a powerful liquid solvent such as hydrochloric acid or ammonium persulfate⁵, 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.

²A 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.

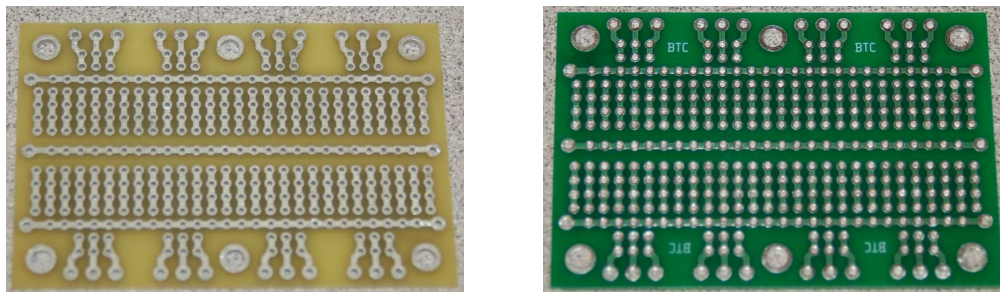
³This is true for single-layer and double-layer boards. PCBs having more than two layers of tracing are comprised of multiple boards individually etched and then layered together to make the final product.

⁴The thickness of this copper layer is typically measured in *ounces of copper per square foot*, with “1 ounce” layering being very common.

⁵This 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 *tinning* on all traces (solder plating designed to minimize corrosion), *soldermask* (a synthetic compound designed to displace molten solder) covering all the areas that should not be soldered, and *silkscreening* (ink used to create text and graphic labels on the board useful for assembly and troubleshooting). A final layer of *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:



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.

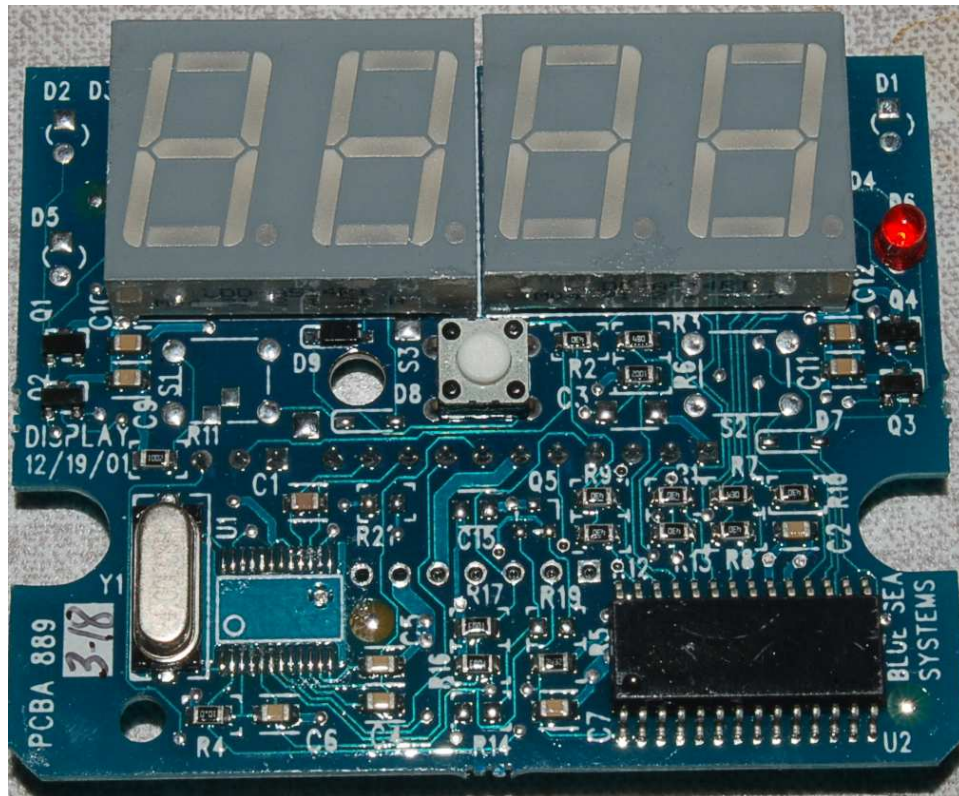
Trace width and trace thickness are additional parameters important to PCB design, together determining the effective cross-sectional area of each trace and therefore the current-carrying ability of each trace (analogous to the gauge of an electrical wire). For standard 1-ounce copper laying, a surface 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

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:



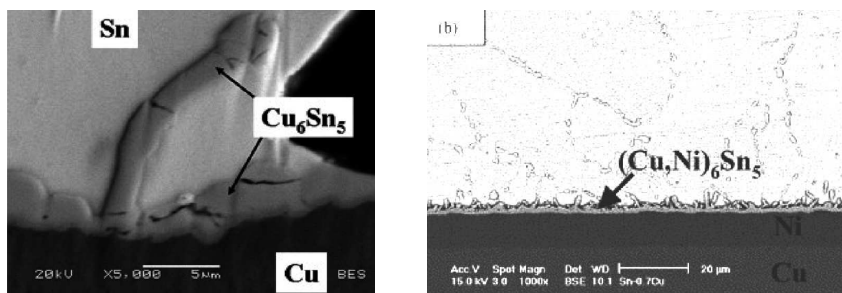
When the components in question are this small and easily to dislodge with one's hand when initially placing them, the task of soldering them to the board becomes challenging. A common technique used for soldering SMDs is to coat each of the component's tabs with a paste consisting of pre-mixed solder 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!

2.2 Soldering metallurgy

Soldering, by definition, is a metallic bonding method by which two or more pieces of *base* metal are bonded together by a different type of metal called a *filler*. Electrical and plumbing soldering is one example, where the metals to be bonded are generally copper and the filler material is an alloy of tin and other metals (confusingly called *solder*). However, other forms of soldering technically exist, including *brazing* where brass is the filler metal used to bond together pieces of steel or other metals with much higher melting temperatures than brass. Soldering differs from *welding* in that only the filler metal becomes molten during soldering, whereas with welding both the filler metal and the base metal must melt in order to fuse together and form a single piece.

All soldering works on the principle that the filler metal, when molten, acts as a solvent to dissolve some of the base metal into it. As portions of the solid base metal dissolve into the molten-hot solder metal, chemical reactions between those metals form an *intermetallic* layer containing compounds of those metals' constituent elements. For example, when using tin (Sn) filler to bond two or more pieces of copper (Cu) together, the chemical compounds Cu_3Sn and Cu_6Sn_5 are formed⁶. The intermetallic layer is what constitutes the mechanical and electrical connection between the pieces of base metal that have been soldered together. Typical intermetallic layers are extremely thin, measured in the unit of microns (*millionths* or a meter).

Electron-microscope photographs showing the cross-sections of metallic bonds between tin-based solder alloy and other metals appear below⁷. On the left we see the bond between tin (Sn) and copper (Cu), and on the right we see the bond between tin and nickel (Ni)-coated copper:



While intermetallic compounds are essential in the formation of an electrically and mechanically sound solder bond, they are problematic in excess primarily because they tend to be crystalline in structure and therefore more brittle than either the base or filler metals. That is to say, *thin* intermetallic layers form strong bonds between the solder (filler) metal and the base metal(s), but *thick* intermetallic layers do not. The primary factor determining intermetallic formation thickness is thermal: *soldering temperature* and *dwelt time*. Both too-cold and too-hot conditions will cause poor solder bonding, the former resulting in insufficient intermetallic formation and the latter too much.

⁶For readers unfamiliar with chemical symbols, Sn is the chemical symbol for the element tin, Cu the chemical symbol for the element copper, and Cu_3Sn the chemical formula for a compound formed of three atoms of copper bonded to one atom of tin by the sharing of some of those atoms' outer-shell electrons.

⁷This photographic image comes from a paper written by Mohd Izrul Izwan Ramli, ; Mohd Arif Anuar Mohd Salleh, Mohd Mustafa Al Bakri Abdullah, Nur Syahirah Mohamad Zaimi, Andrei Victor Sandu, Petrica Vizureanu, Adam Rylski, and Siti Farahnabilah Muhd Amli titled "Formation and Growth of Intermetallic Compounds in Lead-Free Solder Joints: A Review". This publication is licensed under the Creative Commons Attribution license (CC-BY).

Elevated temperatures following the soldering process can cause intermetallic layers to continue to grow, usually on the order of fractions of a micron per day at temperatures above the boiling point of water.

A pre-condition of forming a strong solder bond is a phenomenon known as *wetting*, where the molten solder spreads and flows evenly over the surface of the base metal during the soldering process. This phenomenon is not unique to soldering, but is seen in a great many examples of liquids contacting solids: if you observe a droplet of water placed on a surface and immediately spread out as a thin layer, you have seen “wetting” in action. An aqueous example of non-wetting is when you place a droplet of water on an oiled surface and it remains in the shape of a sphere, refusing to spread.

Molten solder filler metal should “wet” the base metal surface when properly heated and applied. If not, there will be little if any opportunity for the solder’s natural solvent action to take effect on the base metal, and therefore little if any intermetallic layer formed to create a solid bond between the different metals. Obstacles to proper solder wetting include insufficient base-metal temperature, insufficient solder (filler) metal temperature, and a base-metal surface that is not bare metal. The presence of oils, metal-oxides, and other coatings will impede proper wetting and therefore will inhibit the proper formation of an intermetallic layer.

In order to facilitate wetting during the soldering process, a chemical compound called *flux* is usually applied to the joint either before or during the application of molten solder. The purpose of this “flux” is to chemically clean the base-metal surfaces in order to enhance wetting and thereby enable intermetallic-layer formation. Flux may come in the form of a liquid or a paste, and may be applied to the base-metal surfaces prior to heating or (more commonly for hand-soldering) is present in the hollow core of the solder wire being used. Heat activates the flux’s cleaning abilities, with a significant portion of the flux turning into vapor as it’s heated. These flux fumes constitute the majority of vaporous emissions from the soldering process, and are never healthy to inhale. One should always use strong ventilation while soldering, ideally using a *fume extractor* machine ideally with a high-efficiency particulate filter to capture the vapor particles.

Solder filler metal used for electrical and electronic bonding is an alloy of tin (Sn) and other metals. Traditionally the “other metals” included lead (Pb) and sometimes silver (Ag). Due to the bio-hazardous nature of lead, though, nearly all production-scale soldering is now performed with *lead-free* solder consisting predominantly of tin.

All solder alloys are *eutectic*, which means the alloy has a lower melting temperature than any of its constituent metal elements. Pure tin melts at 232 degrees Celsius and pure lead melts at 327.5 degrees Celsius, but an optimally-eutectic alloy of 63% tin and 37% lead has a melting point between 183 degrees Celsius. A popular tin-lead soldering alloy for electronics work is 60% tin and 40% lead (often written as Sn60Pb40) melting between 183 and 190 degrees Celsius. A popular lead-free soldering alloy for electronics work is 96.5% tin and 3% silver and 0.5% copper (often written as Sn96.5Ag3.0Cu0.5) melting between 217 and 220 degrees Celsius.

Optimum soldering temperatures always exceed the melting point of the solder alloy being used, in order to ensure rapid heat transfer as well as proper formation of the necessary intermetallic layer. Lead-free solders are more challenging to properly apply, and also require higher temperatures to melt, wet, and bond with the base metals. Their greater concentration of tin compared with tin-lead alloys results in faster copper dissolution rates, creating problems in “wave-soldering” processes where the circuits to be soldered dip into a vat of molten solder, the dissolved copper diffusing

throughout the solder bath and eventually contaminating it.

Just like electronic components, different types of solder are documented by *datasheets* published by the solder-alloy manufacturers.

2.3 Soldering flux

As mentioned previously, the formation of a mechanically strong and electrically conductive bond between the metal terminals of a component, metal wire, and/or the metal traces on a printed circuit board depends on an extremely thin *intermetallic layer* created when atoms from the solder (filler) metal chemically react with and bond to atoms from the component terminal or wire or PCB trace (base metal) to form compounds. In order for this to occur, tin within the molten solder must be allowed to perform its role as a metallic solvent to dissolve some of the base-metal. This solvent action, in turn, requires the solder to effectively “wet” and spread across the base-metal area to be soldered. A clean, bare base-metal surface is absolutely necessary in order for all of this to happen during the soldering process.

Achieving this clean surface state is more challenging than it may at first seem. Certainly, dust and debris are capable of “dirtying” the metal surface, but so is oil and/or layers of metal-oxide formed by the slow chemical reaction between most metals and oxygen molecules in the air.

A very effective method of cleaning the base-metal surface in preparation for soldering is through the use of a chemical compound generally known as *flux*. The purpose of flux is to serve as a solvent to dissolve any and all non-metallic layers of material that would otherwise impede solder wetting. Flux may be applied to a surface prior to the application of heat and solder (filler metal), or it may be applied simultaneously with the solder. In either case, heat from the soldering tool activates the flux to very rapidly clean the metal. Flux also tends to decrease the surface tension of the molten solder to help it spread and “wet” rather than to clump together in beads.

Historically the most common type of flux was (and still is) extracted from the sap of coniferous trees, called *rosin*⁸ or *colophony*. When used for soldering, the acid compounds naturally occurring in rosin are what dissolve the offending surface impurities to prepare the metal surfaces. When heated by thermal energy from a soldering tool such as a soldering iron, rosin flux emits significant quantities of aromatic smoke.

Soldering flux takes several different physical forms, depending on the intended application:

- **Embedded within solder wire** – Solder wire of the type typically used in hand-soldering is actually hollow, with the hollow space inside the solder-alloy wire filled with solid flux. This naturally dispenses the flux in proper measure as the soldering wire is heated and turned molten.
- **Liquid flux** – Flux may also be manufactured to be liquid in form, intended to apply to a pre-soldered area using a small brush.
- **Flux paste** – This is when flux is packaged as a waxy substance to be manually applied to a pre-soldered area.
- **Solder paste** – When soldering surface-mount components to circuit boards using automated soldering processes, solder alloy and flux are applied to component terminals in the form of *soldering paste* which is a mixture of solder-alloy powder and flux in a semi-solid gel form. When heated (usually in a *reflow oven*) the flux immediately liquefies to clean the metal

⁸Incidentally, this is the same substance used by musicians to make horse-hair bows for stringed instruments such as violins and cellos “stickier” so as to produce a louder and better tone against metal strings.

surfaces, and the solder-alloy powder soon melts as well to wet the metal surfaces and form the bonds.

Chemical composition of modern soldering fluxes varies significantly depending on the intended applications. One way to rank soldering flux is according to the aggressiveness of its cleaning action, generally termed *activity*. High-activity fluxes are intentionally corrosive so as to be able to effectively clean and prepare metal surfaces for soldering, though this same “activity” makes it necessary to rinse all flux residue off of the soldered surfaces so the corrosive action does not cause problems.

A class of modern soldering fluxes called *water-soluble* are formulated such that the corrosive residue left after soldering will easily dissolve in water, so that a simple water rinse is all that is necessary to wash this residue off of the soldered components. Water-soluble fluxes are generally very active, making this water-rinse process mandatory. Low-activity fluxes (such as pure rosin) are effective only on metal surfaces that are already reasonably clean, but due to their less-aggressive nature are not as likely to create problems if left on the soldered components. Another class of modern soldering fluxes called *no-clean* are specifically formulated such that there will be no chemically-active residue remaining on the soldered components, which eliminates one step in the soldered-assembly manufacturing process, but in keeping with the no-clean characteristic these fluxes tend to be less active than others.

Just like electronic components and just like soldering filler alloys, different types of flux are documented by *datasheets* published by the solder-alloy manufacturers. Their characteristics and chemical composition are complex, and should be carefully evaluated for any mass-production soldering operation on the basis of environmental emissions, cost, procedures and handling, etc.

2.4 Soldering safety

The act of soldering metal together involves not only molten solder alloy, but also materials potentially hazardous to touch, ingest, and/or breathe. Here are some recommendations for safe soldering:

Safe handling of soldering tools

- Never hold the tool by the bare-metal end – always by the handle!
- Always place the soldering iron in its proper holster when idle, and move all flammable materials away from it
- Never leave a hot tool energized and unattended

Safe handling of solder and flux

- Never hold solder wire in your mouth!
- Avoid breathing flux fumes – use adequate ventilation or a fume extractor if available
- Do not eat food while soldering
- Wash your hands after soldering
- Dispose waste solder as a hazardous metal, to a facility capable of processing such materials

Personal protective equipment (PPE)

- Always wear eye protection (glasses or goggles or a face shield) when soldering and when applying liquid flux
- Wear nitrile gloves if holding solder wire with your hands
- If soldering large wires, wear heat-resistant gloves to help prevent burns
- Use a mechanical ventilation system to extract flux fumes away from your mouth, nose, and skin

Work station clean-up

- Let soldering iron cool to luke-warm before storing it in any enclosed space
- Wrap long lengths of solder wire back on to the spool from which it came
- Always put tools and equipment back where they belong
- Sweep any splattered solder metal into the disposal canister or bin
- Wipe the workstation surface with a damp towel to clean up flux residue

2.5 Hand-soldering

The most popular tool for electronics soldering is the *soldering iron*, a pencil-shaped tool with a tinned-surfaced tip used to apply thermal energy to component leads, wires, and/or copper pads (collectively called the *work*) on printed circuit boards:



This particular soldering station is made by Metcal, and features two soldering irons in their own holders. It is a professional-grade unit with a high power output of approximately 75 Watts which means the iron tip(s) will reach full temperature within just a few seconds of applied power, and also that they will be able to maintain proper soldering temperature even when making thermal contact with large areas of copper on a circuit board that behave like a natural heat sink.

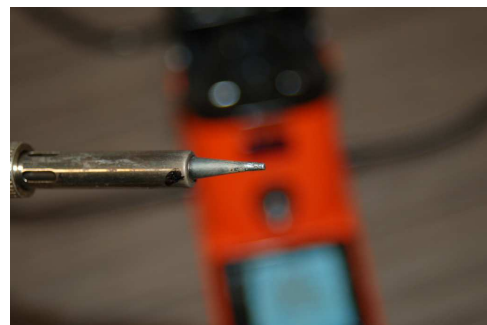
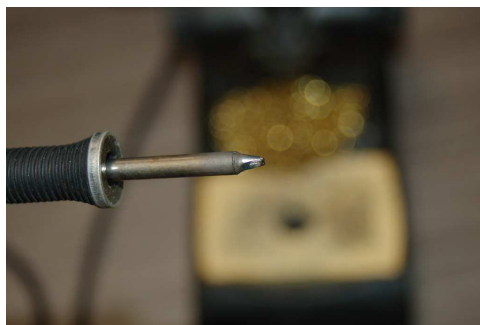
One very convenient feature of this Metal soldering station is that it automatically turns off power to the pencil-style irons whenever they are inserted into the holster. A strong magnet in the holster activates a switching mechanism in the iron's heating element. This automatic powering-down of the heating element reduces the tip's temperature when not in use, thereby slowing down the process of oxidation that occurs between the tip's metal surface and the surrounding air when at full operating temperature.

A hobbyist-grade soldering station appears below, with an adjustable temperature control knob showing the desired tip temperature (this one reading in degrees Fahrenheit):



Optimum soldering tip temperature varies with the solder alloy being used. 600 degrees Fahrenheit (316 degrees Celsius) typically works well with lead-based solders, but with lead-free solders the required tip temperature is significantly hotter: typically 700-800 degrees Fahrenheit (371-427 degrees Celsius). Some professional-quality soldering tools such as the Metcal shown previously, use replaceable soldering tool tips with internal temperature regulation so that the tip's temperature *cannot* be mis-adjusted by the user.

Soldering irons may be equipped with different styles of *tips*. Shown below are the popular “chisel” style (left) and “conical” style (right):



Specialized soldering irons exist, including this “tweezer” style with two heated iron tips that pinch together:



Another type of soldering tool is the *soldering gun*, so named due to its pistol-like shape:

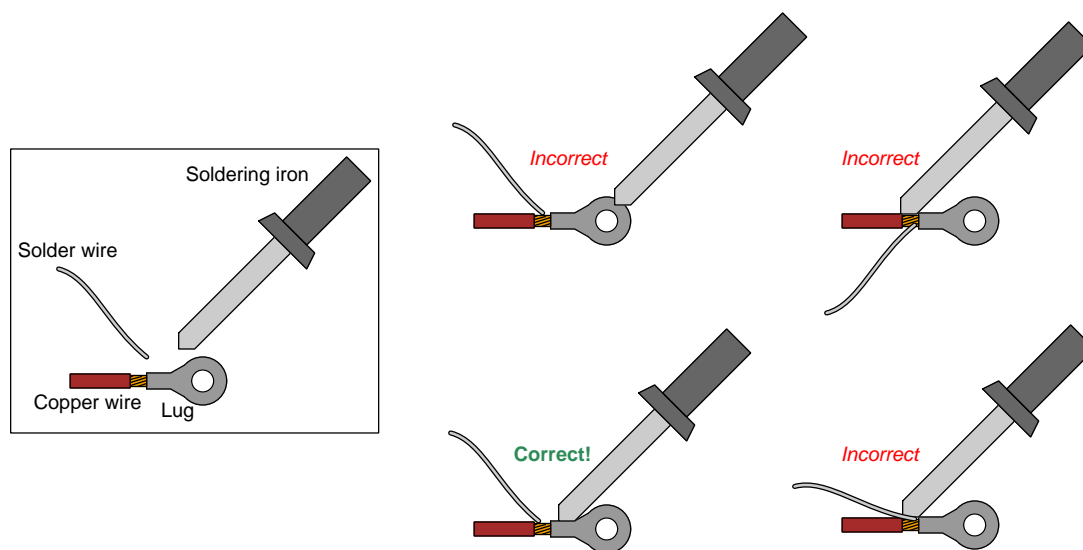


Soldering guns generally have much greater power ratings than soldering irons, in most cases exceeding 100 Watts. They are most useful when soldering large-gauge copper wires. Unlike soldering irons which typically remain powered, soldering guns are trigger-activated which means they de-energize whenever you let go of the trigger with your finger. This is good, as the guns are usually rated for intermittent use only.

Interestingly, the traditional style of soldering gun shown here is actually a *step-down transformer* where the primary winding (not seen in the photo) is energized by AC line power and the secondary winding consists of a single “turn” of thick metal bar terminating at two screw-clamps holding the heating tip. High AC current resistively heats this tip to soldering temperatures.

When hand-soldering two electrical conductors together, it is important to raise the work's temperature to the melting point of solder *before* applying cold solder-wire to that joint. A common “beginner” mistake is to apply heat directly to the solder-wire itself and then try to “drip” molten solder onto the work that is too cold to allow the solder to flow and “wet” the surface. Similarly, if the positioning of the soldering iron tip is such that more heat is applied to the solder-wire than to the conductors, this may also result in a *cold solder joint*.

In all cases, the principle to follow is that the work-object acting as the most effective *heat sink* should be the one in fullest contact with the soldering iron's tip. When that object achieves the correct temperature, all other objects in contact with it will reach the same temperature more easily. The goal is for the work to get hot enough that the applied solder wire melts upon contact with it. The following illustrations show incorrect versus correct methods of applying heat to a terminal lug at the end of a copper wire:



Since the metal lug has far more surface area to dissipate heat to the surrounding environment, it will require the most heat input from the soldering iron's tip to achieve the correct temperature for solder melting and “wetting”. The wire, by contrast, has much less surface area than the lug, and so it does not require direct contact with the soldering iron's tip as the lug does. This is why we should apply the soldering iron to the lug and not the wire.

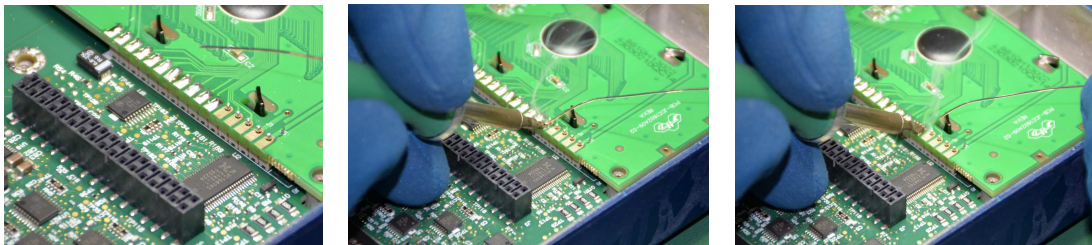
Applying the iron's tip to the lug's barrel is better than applying it to the end-most “ring” portion of the lug, because only the barrel-end of the lug needs to be joined by solder to the copper wire. Although it may be possible to raise the barrel's temperature to the correct amount by heating the far end of the lug, it would be a waste of time and energy.

Similarly, when soldering through-hole component leads to copper pads on a printed circuit board (PCB), it is best to make maximum physical contact between the soldering iron tip and the PCB's copper pad rather than primarily heat up the component lead. Not only does the copper pad usually have more surface area to shed heat, but heating it up first rather than the component lead will spare that component from extra thermal stress.

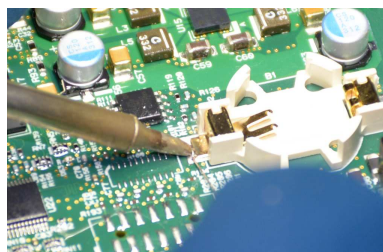
Although it is always best to apply soldering-iron heat to the work and then let the conductor's heat melt the applied solder-wire, this is effective only when heat transfers easily from the iron's tip to the work. In many cases heat-flow is impeded by the presence of oxidation on either surface and/or a lack of adequate contact surface area. A common "trick" to overcome this problem is to first apply a small bead of solder directly to the tip of the soldering iron, and then when that tip is pressed against the conductors to be joined the molten solder will help form a *thermal bridge* between the soldering iron and the work. Flux present in the solder will help clean surfaces of oxidation, and the liquid nature of that solder gives it greater opportunity to make contact with the work than the solid iron tip.

Once the work is hot enough to melt the solder wire, apply solder in short "pulses" rather than continuously. Repeatedly touching and then removing the solder wire to/from the work gives each "pulse" of solder time to melt and flow, and for you to better observe the wetting action. This technique also tends to economize the amount of solder used by helping to avoid over-soldering.

A three-image sequence shows hand-soldering in action, in this case soldering one pin through a hole in a printed circuit board:

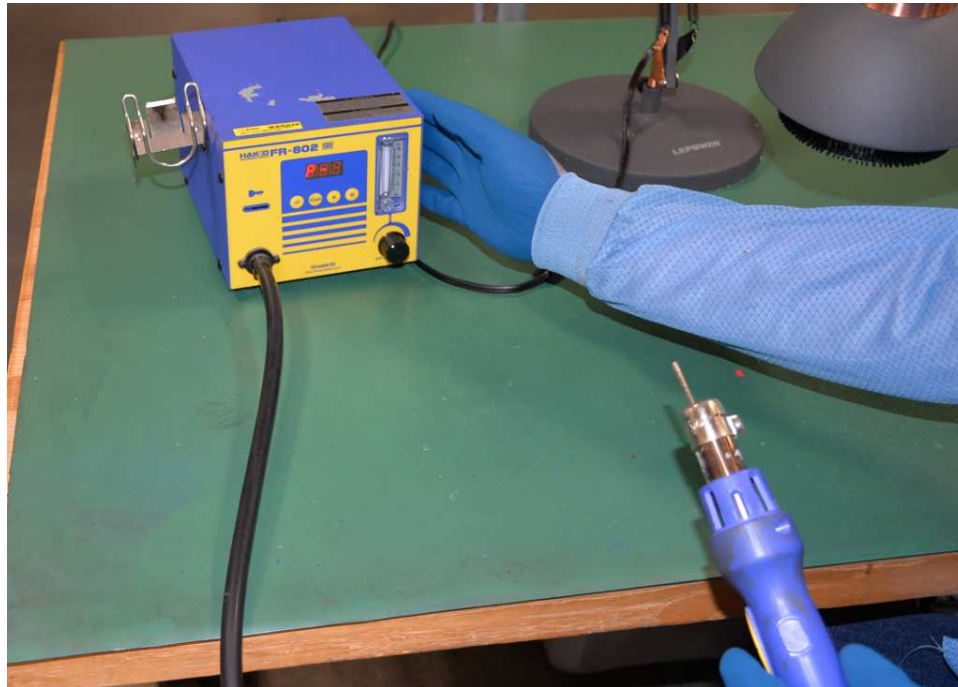


Soldering the terminals of a surface-mount component onto copper pads on a printed circuit board is much the same, in that applying the soldering iron's heat to the copper pad and letting that heat flow into the component lead is generally a good strategy. Here we see one tab of a lithium "button" style battery holder being soldered onto a PCB:



After solder has "wetted" to the work's surface, the soldering iron should remain in contact with the work for a short while longer (called the *dwelt time*) in order to ensure the solder has time to fully flow into all spaces where it should wet. Typical dwell time for lead-based electronic soldering is three to seven seconds (at 600°F/316°C), and typically five to ten seconds (at 700-800°F/371-427°C) when using lead-free solder.

A completely different type of hand-soldering tool is a *hot air pencil* which blows a thin stream of extremely hot air out of a narrow tube, hot enough to melt solder alloy without any need for solid contact with the work. These are intended for surface-mount device (SMD) work. An example of a hot-air station is shown below:



The bench-top portion of this hot air station contains the air blower, air flow monitor and control valve, and power electronics to drive the heating element inside the pencil portion. A cord containing an air tube and wiring connects the pencil to the bench-top portion.

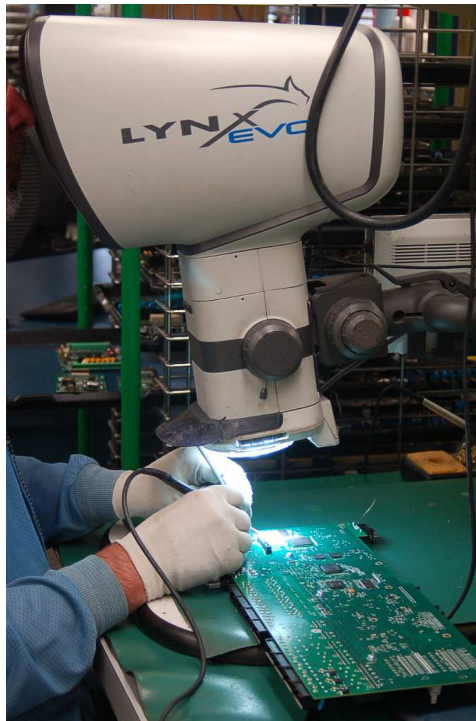
When used to solder new components onto a printed circuit board, hot air pencils rely on solder paste pre-applied to the SMD component terminals and PCB pads rather than solder wire. Hot air pencils actually find their most common use in *removing* components and removing conformal coating⁹ during “rework” processes on previously-soldered PCBs, and are not as versatile as regular pencil-style soldering irons.

The transfer of thermal energy by convection (i.e. a moving fluid such as a stream of air) is not as effective as by conduction (i.e. direct contact), and so hot air pencils struggle to apply sufficient heat to large pads and/or to large components with many pins along each edge. For this reason hot air pencils are often used in conjunction with *preheaters* which are electrically-heated “hot plate” surfaces used to elevate the temperature of an entire printed circuit board assembly to a point just

⁹Conformal coating is a polymer substance applied as a protective layer over the top of a soldered printed circuit board assembly, to help shield the PCB and its components from environmental attack (e.g. high-moisture conditions, conductive dusts, etc.). It is notoriously difficult to remove, which is of course necessary to perform any kind of rework on a conformally-coated PCB. A hot air pencil may be used to heat up the PCB’s surface while a small stick made of orange-tree wood is used to scrape the heat-softened polymer off the board.

below the melting temperature of solder alloy. A hot air pencil may then be used to elevate the temperature just high enough to melt the solder with much greater ease than if used alone.

An essential tool for soldering and de-soldering *fine-pitch* surface-mount devices (SMDs) is a *microscope*. These may be optical or digital, the digital versions using a “macro” lensed digital camera connected to a viewing monitor. The microscope shown in the image below is a *stereo optical* unit, allowing the user to see comfortably through both eyes for accurate depth perception while soldering:



2.6 Soldering iron care

Soldering iron tips suffer much wear in the form of oxidation. Their high operating temperatures accelerate chemical reactions between the metal surface and atmospheric oxygen, creating *oxidation*¹⁰. This oxidation impedes what would otherwise be an easy transfer of thermal energy between the hot soldering iron tip and the cool(er) work, and so it must be periodically cleaned off.

Proper care of a hot soldering iron tip, therefore, includes taking measures to retard this inevitable oxidation process. One way to slow down oxidation is to ensure the hot iron tip is always “tinned” with a thin coating of solder on it and is never left in a bare and hot condition for long periods of time. Occasionally, though, that coating of solder itself will become oxidized and need to be removed. Thrusting the hot soldering iron tip into a ball of brass wool works well to brush off liquid solder and reveal a bare tip, to which you may apply fresh solder. Additionally, one may briefly touch the hot iron tip to a moist sponge or moist paper towel. The thermal shock and steaming action caused by the tip contacting water will work to remove some oxidation from the tip’s surface.

This sponge must be moistened using de-ionized (i.e. distilled or reverse-osmosis filtered) water, or else minerals present in the water will “plate” the soldering iron tip when this sponge is used on it. Here we see someone moistening the sponge using a dispenser bottle filled with de-ionized water. Just above the sponge we can see the brass-wool ball which is never wetted:



A well-maintained soldering iron tip should have a shiny metallic surface. Oxidation usually appears dark in color, and serves as a good visual indicator that cleaning is necessary.

¹⁰This is where atoms of metal chemically bond to atoms of oxygen to form *metal oxide* which is far less conductive of heat than pure metal.

Another useful tool for soldering iron tip care is a chemical compound known as *tip tinner*. This is a mixture of metallic tin and ammonium phosphate useful for cleaning and coating with solder alloy (“tinning”) a worn soldering iron tip. In this photograph we see a small container of tip tinner compound resting atop a rotary brush tool used to clean heavily oxidized iron tips:



Generally speaking, good tip-maintenance habits such as regularly tinning the tip with solder to guard against oxidation should make tip tinner and brush tools unnecessary. However, for low-quality and/or mis-treated soldering iron tips they may be useful.

The act of cleaning oxidation off of any metal object’s surface paradoxically wears down that metal surface. If metal atoms join with oxygen to form the metal-oxide layer¹¹, and then that oxide layer is removed, it means not only has the object lost some of its solid mass but it is once more fully susceptible to further oxidation. At some point this wear will degrade a soldering iron tip to the point where it becomes unusable and must be discarded. For this reason, all soldering irons have replaceable tips so that the rest of the iron is not rendered useless by a worn tip. The lesson to be learned here is that prevention of oxidation is a better strategy than its frequent removal.

It should be noted that lead-free solder, with its higher required soldering temperature and its higher tin concentration, degrades soldering iron tips at a significantly faster rate than leaded (Pb) solder. This, among other disadvantages of lead-free solder, is an unfortunate price we must pay for not introducing metallic lead into the environment when electronic circuit assemblies inevitably reach their end of life.

¹¹Chemical engineers refer to this naturally-formed layer of oxide on otherwise bare metal as a *passivation layer*, because its presence tends to impede the migration of more oxygen atoms to un-oxidized metal lying beneath, thereby helping to protect the metal from further oxidation.

2.7 Automated soldering

Modern printed circuit boards containing dozens or even hundreds of tiny components are impractical to hand-solder as a method of production. Not only would hand-soldering require vast amounts of time due to its slow nature, but the number of mistakes a person is likely to commit trying to solder dozens or hundreds of components to that PCB would be unacceptable. Therefore, mass-production soldering operations are *automated* by machinery that place components onto PCBs and then solder those components on in rapid fashion.

A machine that picks components from tubes or reels and then places them on a PCB is naturally called a *pick-and-place machine*. These machines take components from tubes or reels as needed and robotically place those components in the correct locations and in the correct orientations, at a rate much faster than any human being could muster, and with an error rate far less than any human being could hope to achieve.

From there, the PCBs populated with components from the pick-and-place machines pass through one of two different automated soldering processes: *reflow ovens* or *wave-solder machines*, based on those components either being surface-mount devices (SMDs) or through-hole (TH) devices.

Reflow ovens simply bathe the populated circuit board with intense but carefully-controlled heat for precise amounts of time, and rely on *solder paste* having already been applied to the PCB's exposed copper pads that will melt under that heat and solder the component's terminals to their respective pads. This solder paste (containing bits of solder alloy mixed with paste-textured soldering flux) activates under the heat to chemically clean the copper pads, then with rising temperature the solder metal within that paste melts and wets the surfaces to be joined. Surface tension of the molten solder tends to attract each pin toward the geometric center of its respective copper pad, actually aligning the component's footprint to its intended position.

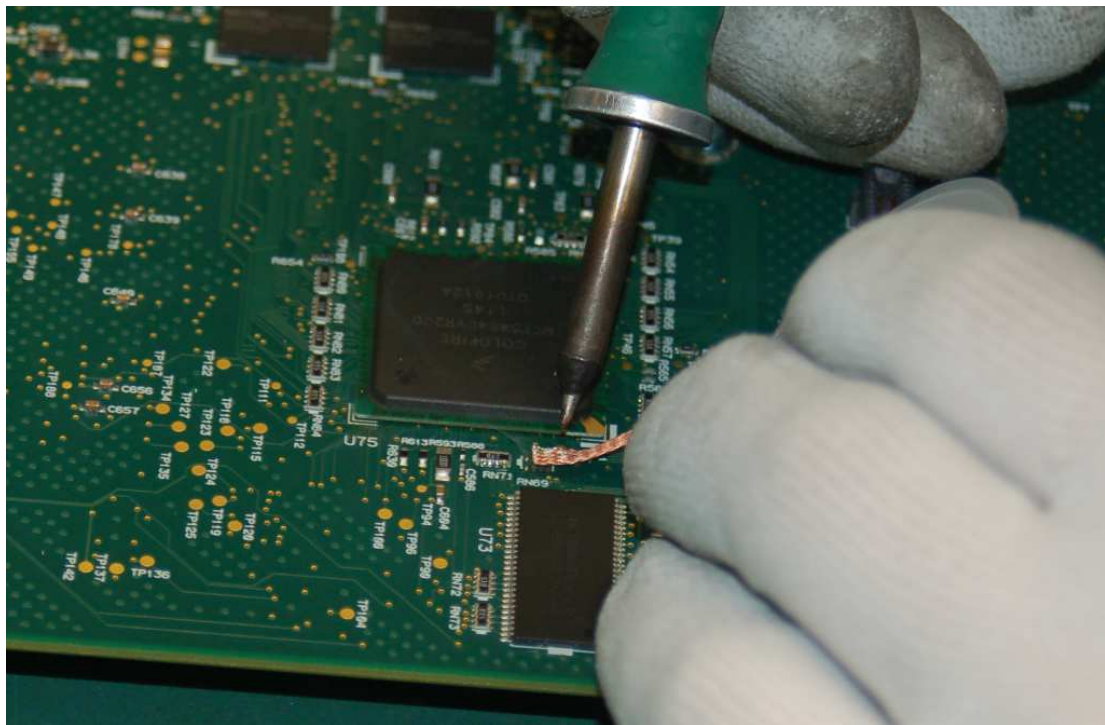
Wave-solder machines maintain a liquid bath of solder alloy just below a metal-linked conveyor belt, that belt transporting populated circuit boards across the top of the solder bath where the molten solder wicks up the component leads, through the holes in the PCB, thoroughly wetting the surfaces to be joined.

2.8 Rework

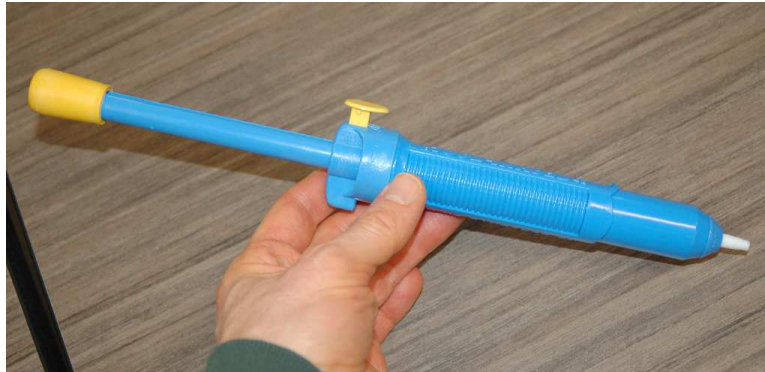
Sometimes the best of intentions and effort still result in poor solder connections, or the wrong component got soldered into place, or perhaps was soldered in an incorrect orientation. The act of de-soldering and correcting the soldered connection(s) is commonly known as *rework* in mass-production electronics manufacturing, and this requires special tools and skill distinct from that of normal hand-soldering.

One such tool/technique is called *solder wick*, consisting of a narrow braid of woven copper wire stands which is placed on solder that needs to be removed. Heat from a soldering iron is then used to raise the temperature of both the wick and the underlying solder. Once the solder melts, it naturally “wets” the wick and in doing so is removed from the original connection area.

Here we see a photograph of solder wick being used to remove solder from a surface-mount device (SMD) soldered on to a printed circuit board, in preparation for removing that component entirely:



Another manual de-soldering tool is the spring-loaded *pump*. This has a plunger handle on one end which you depress to charge the spring. Subsequently pressing the yellow-colored button on the side will release this spring and cause the internal plunger to quickly retract. This causes a vacuum to form at the white-plastic nozzle of the tool, which when pressed up against molten solder will suck the solder into the plunger's cylinder. Depressing the plunger handle again forces a metal pin to shove all collected solder pieces out through that same nozzle hole.



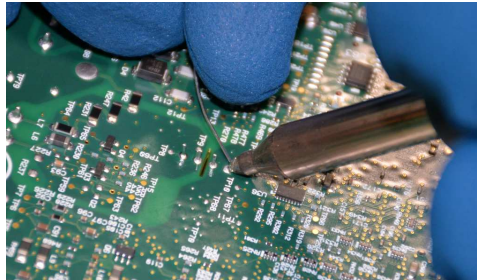
These tools work well to clear out through-hole pads in printed circuit boards, by applying suction to the hole on one side of the PCB and soldering-iron heat to the other side.

A more sophisticated version of this tool is a *de-soldering station* containing its own electrically-powered vacuum pump, and both gun-style and pencil-style heating tools with hollow metal tips designed to both liquefy the solder and suck it away into chambers where it may be manually cleaned out from time to time:

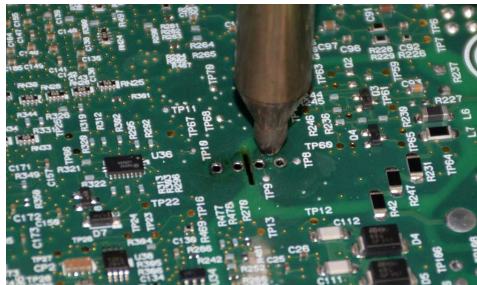


Vacuum desoldering irons are extremely useful tools for rework, but paradoxically one must usually apply extra solder to the tip of one during use in order to maximize its effectiveness. This extra applied solder forms a thermal bridge to ensure the work becomes sufficiently heated to enable the tool's vacuum pump to draw the solder away from the work.

A photograph of a vacuum desoldering iron at work appears below:

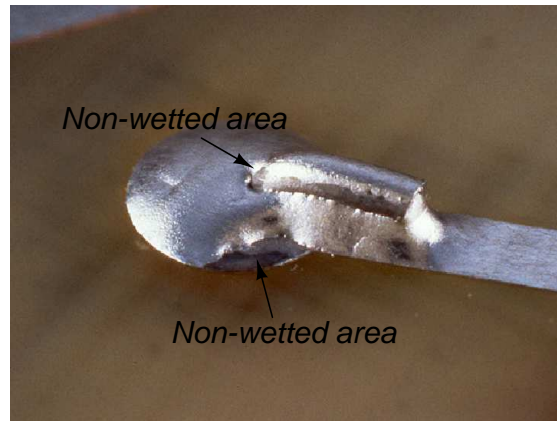


Here you can see the solder wire plainly being added while heating the work to be de-soldered. That added solder simply gets sucked up into the desoldering tool along with the rest of the solder that came from the work. The degree to which this tool is able to draw solder away from a PCB and out of its through-holes is impressive, as shown in the next photograph after a four-terminal through-hole component has been removed from a PCB:

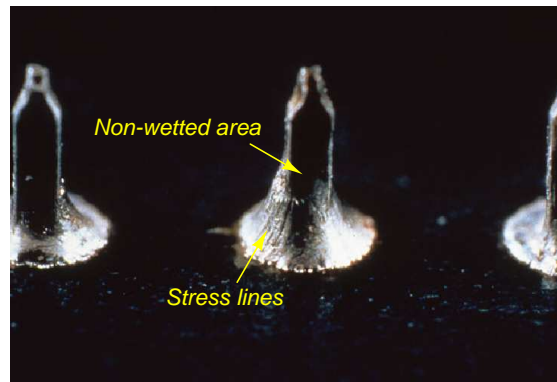


2.9 Typical solder defects

In this photograph¹² we see a solder joint between a copper PCB pad and a through-hole component lead with *non-wetted* areas, caused by insufficient soldering temperature:



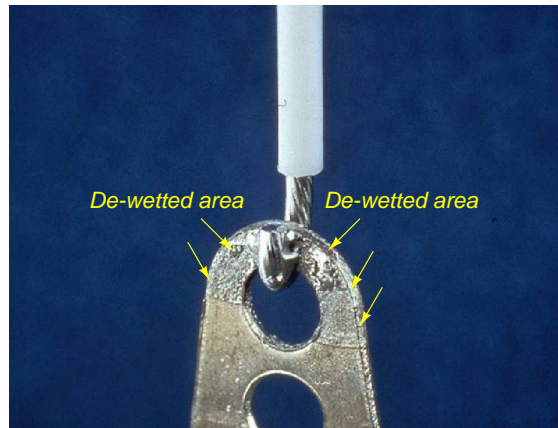
Below we see another photograph¹³ of a solder joint having non-wetted areas, as well as visible stress lines on the surface of the solder:



¹²Public-domain image courtesy of NASA.

¹³Public-domain image courtesy of NASA.

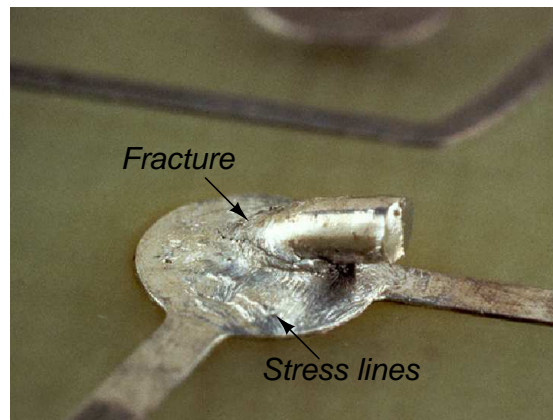
In this photograph¹⁴ we see a *de-wetted* solder connection between a wire and a pierced metal terminal. There is *some* solder wetted to the terminal and the wire, but clearly not enough to make a sturdy connection. Also, we can see where during the soldering process some of the solder did indeed “wet” a fairly large area of the terminal’s surface but for some reason got removed from the terminal leaving a rough surface:



The fact that solder *was* wetted to the terminal surface but then pulled away leads us to classify this as a *de-wetted* connection rather than a *non-wetted* connection.

¹⁴Public-domain image courtesy of NASA.

Another common soldering defect occurs when the molten solder is physically disturbed during the cooling process as it transitions from liquid to solid states. This usually happens when the wire(s) or component(s) are allowed to shift position as the solder solidifies. An example of this appears in this next photograph¹⁵:



Ripples evident in the solder surface indicate how the solder shifted during the cooling process, and in this example we can even see a fracture in the solder adjacent to the component lead where the solder mass actually separated in its weakened (partly-molten) state.

¹⁵Public-domain image courtesy of NASA.

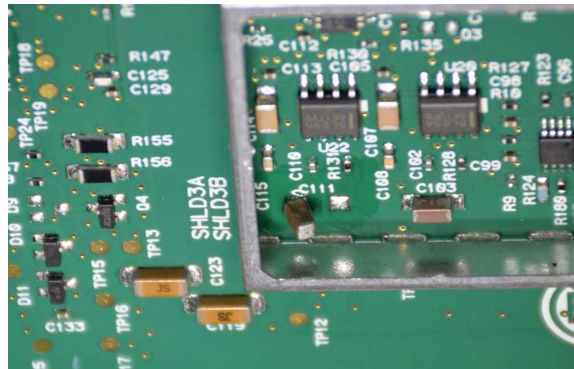
Pinholes and *blowholes* may form in solder if there are gases or vapor escaping from beneath the molten mass during the cooling process. This typically occurs during automated soldering processes such as *wave soldering* (where PCBs populated with components are briefly dipped into a pool of molten solder) if the PCB in question contains excessive moisture. The following photograph¹⁶ shows a particularly obvious blowhole:



Another potential source of blowholes is excessive flux applied to a joint prior to the application of molten solder. Since flux vaporizes with the application of soldering heat, this vapor needs a route to escape, and if there is too much flux applied prior to soldering (either in liquid or paste form), some of that flux vapor will escape as bubbles through the molten solder, potentially leaving voids or holes in its wake.

¹⁶Public-domain image courtesy of NASA.

of a tombstoned SMD capacitor labeled C₁₁₁:



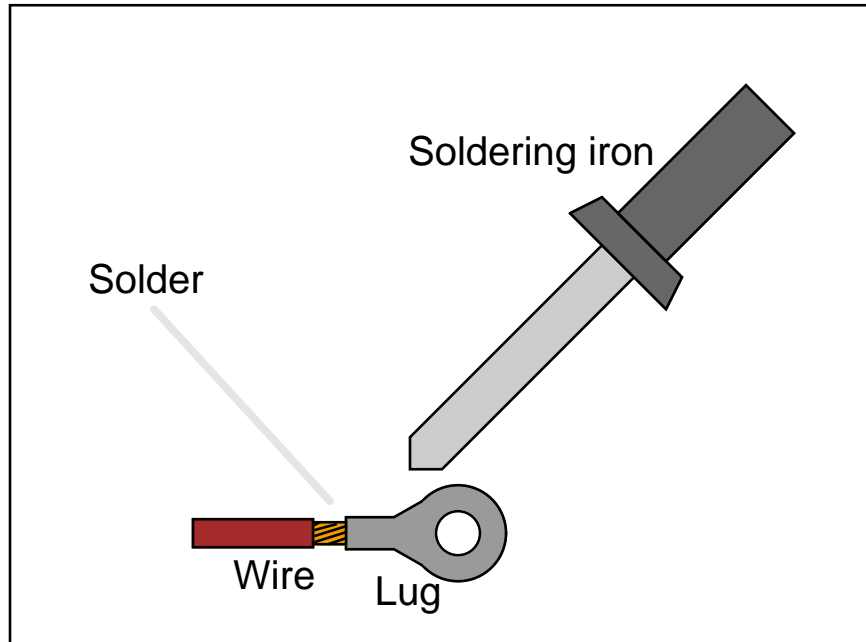
Chapter 3

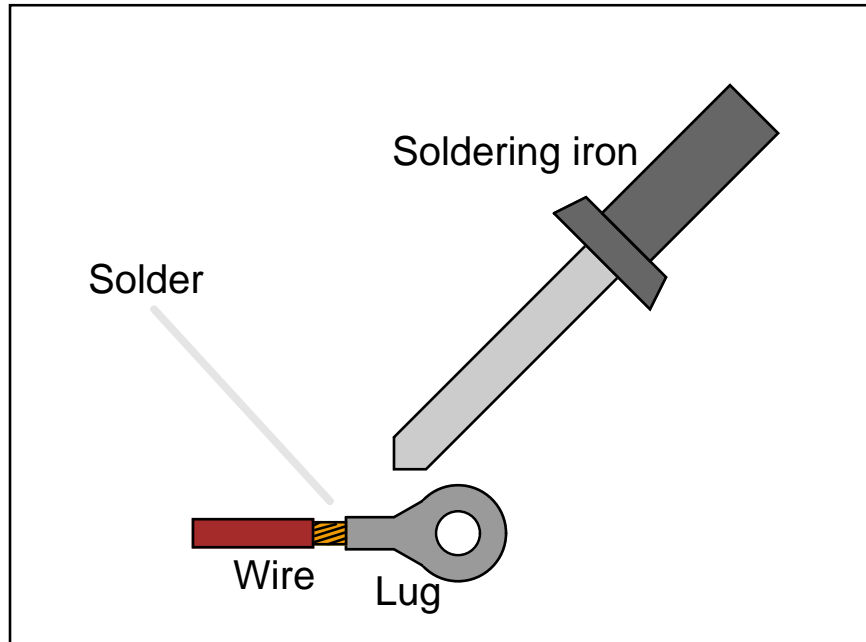
Animations

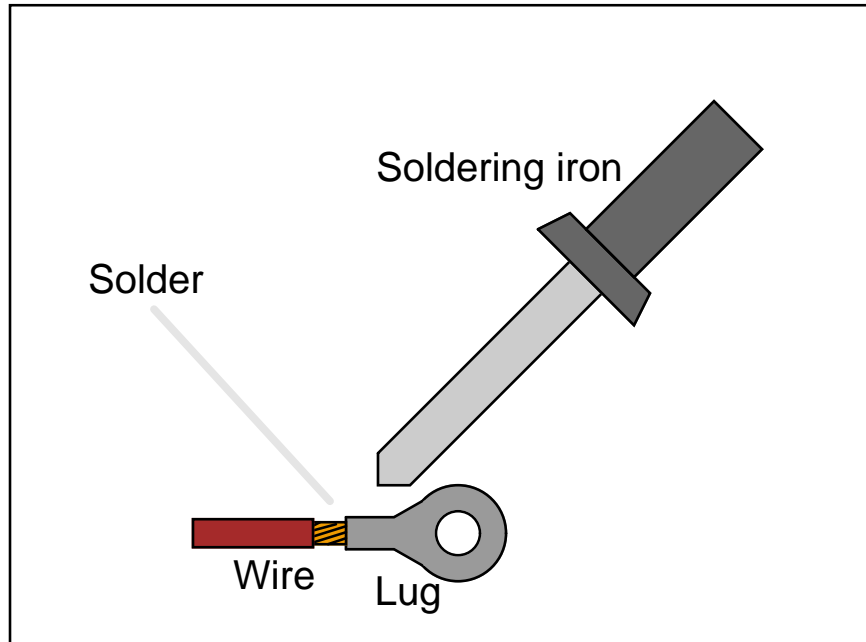
Some concepts are much easier to grasp when seen in *action*. A simple yet effective form of animation suitable to an electronic document such as this is a “flip-book” animation where a set of pages in the document show successive frames of a simple animation. Such “flip-book” animations are designed 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.

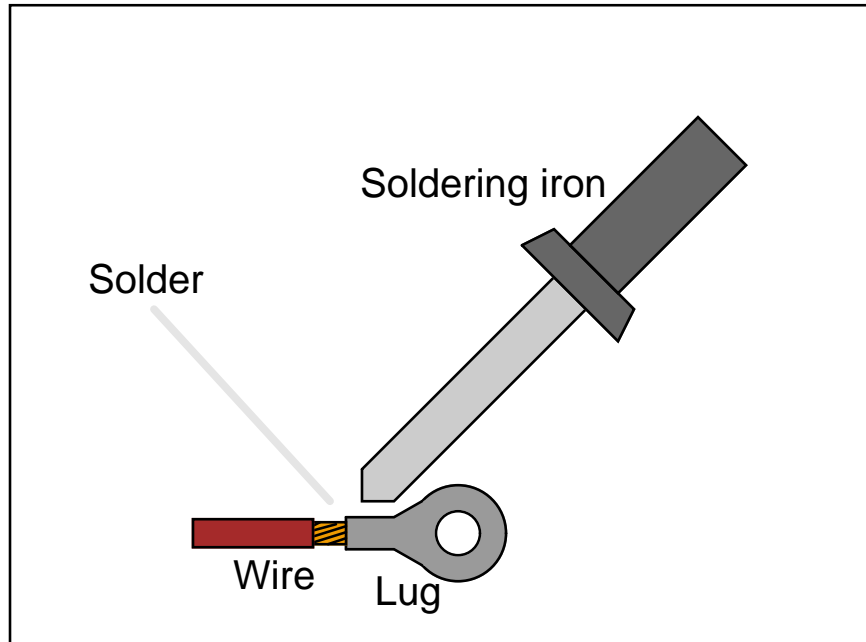
3.1 Using a soldering iron

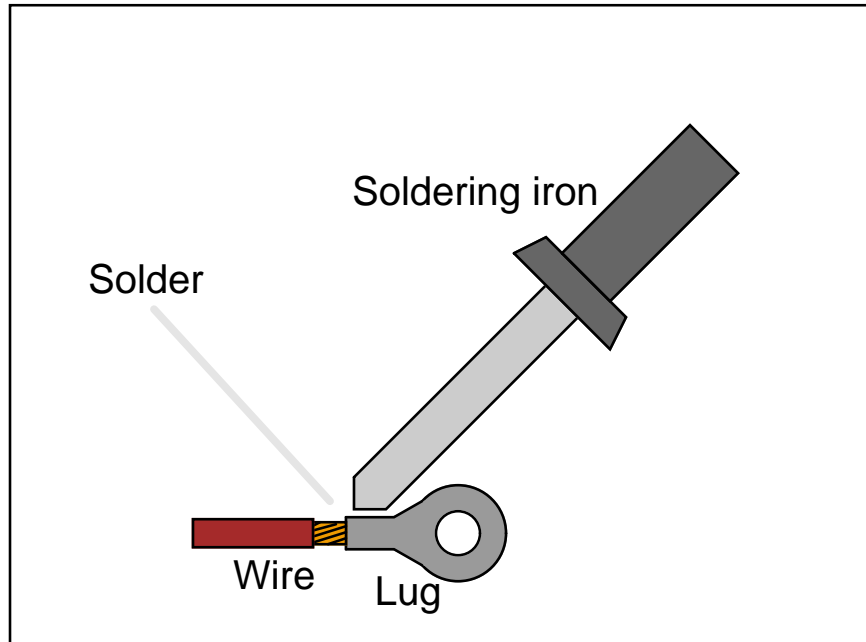
This animation shows the proper usage of a soldering iron to solder a wire to a lug-style connector. Note how heat from the soldering iron tip is applied to the connector (lug) itself, and not to the solder. This ensures the connector's metal will be at full temperature necessary for good bonding between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

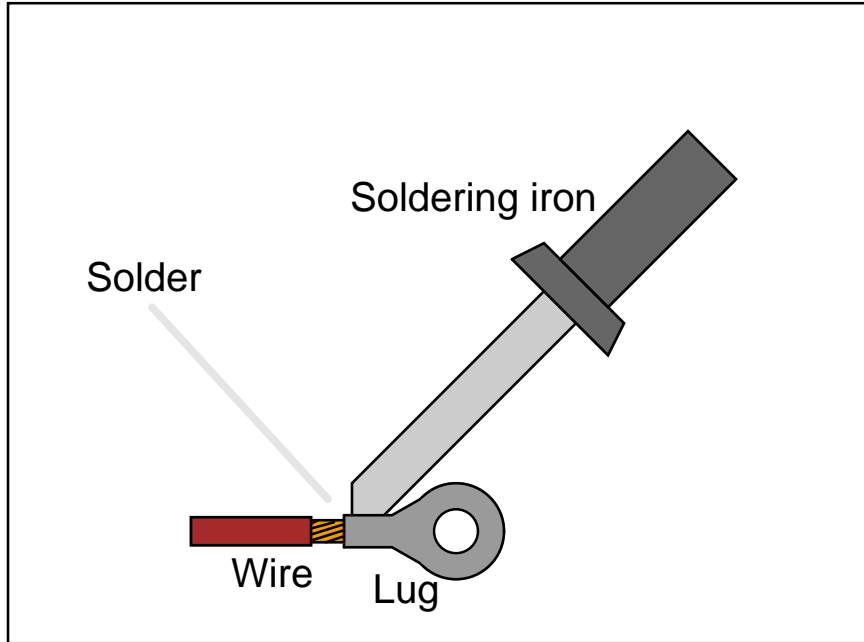


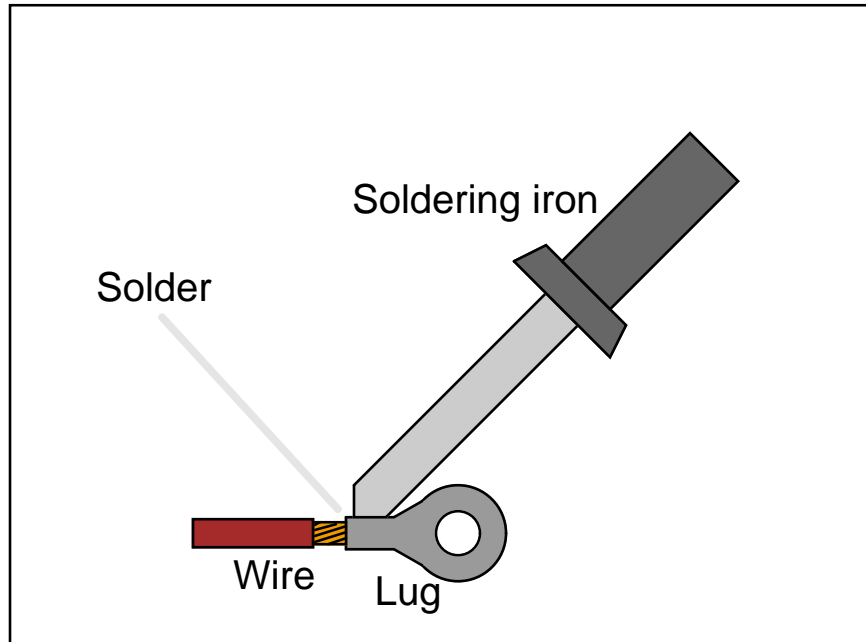


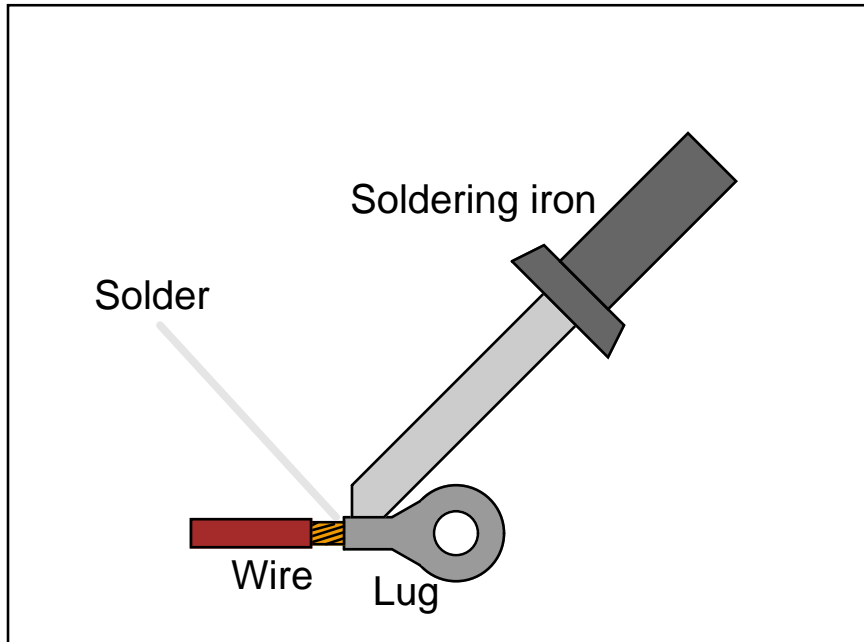


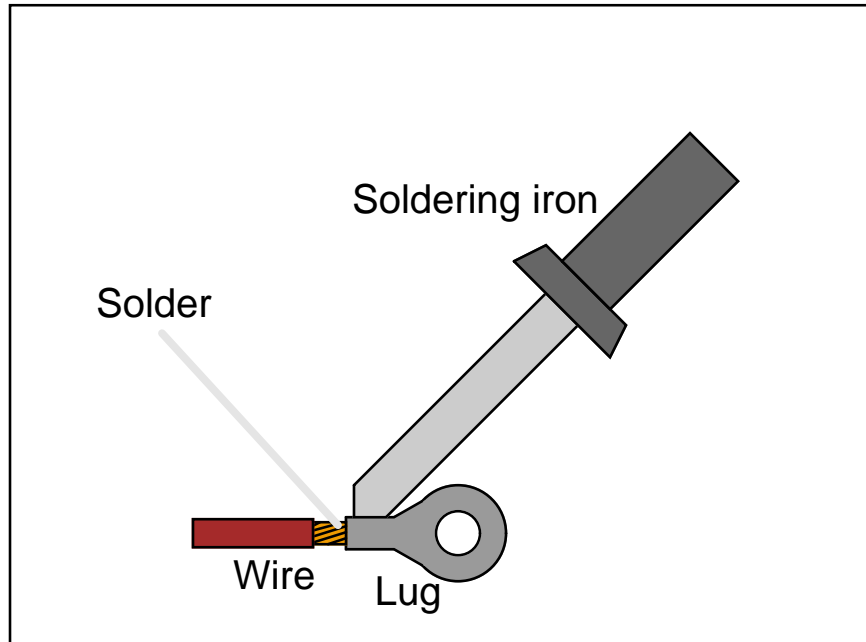


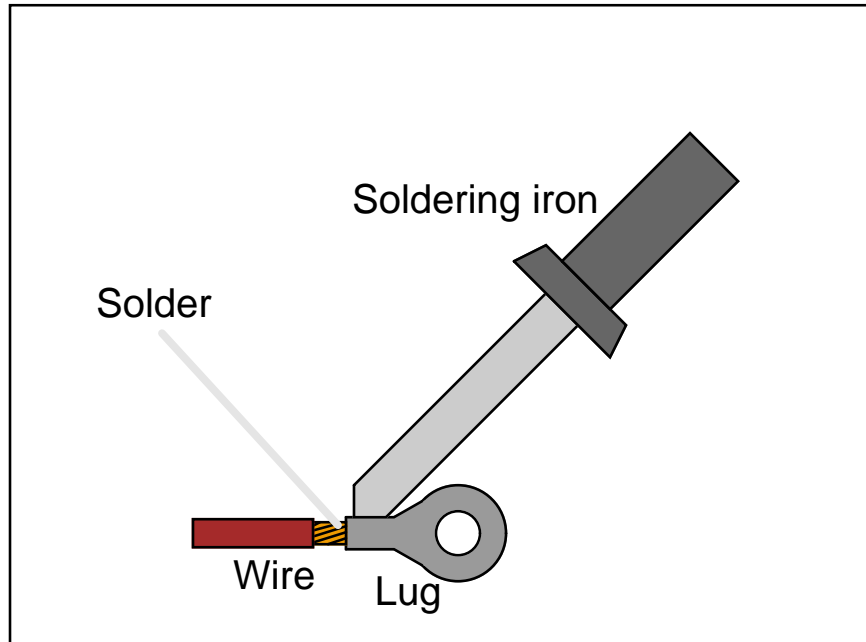


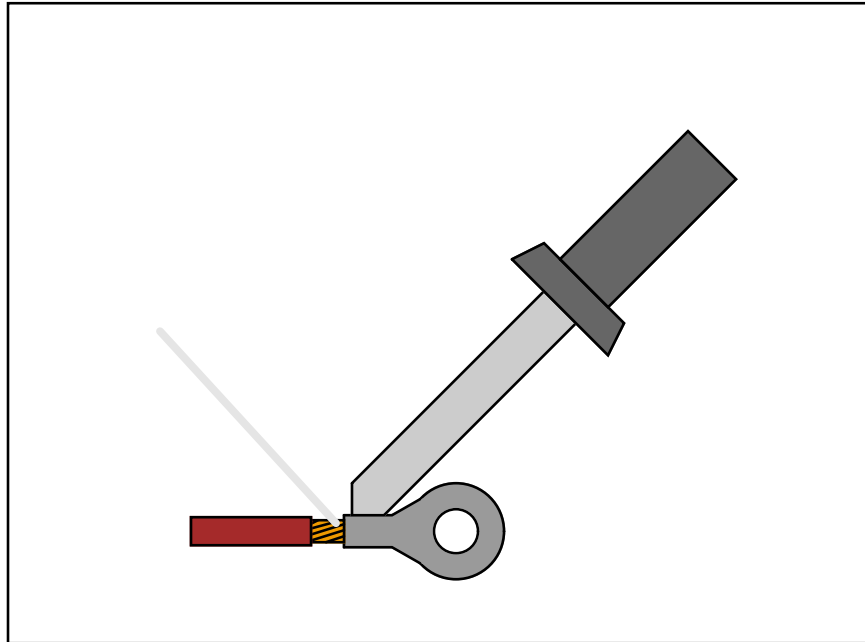


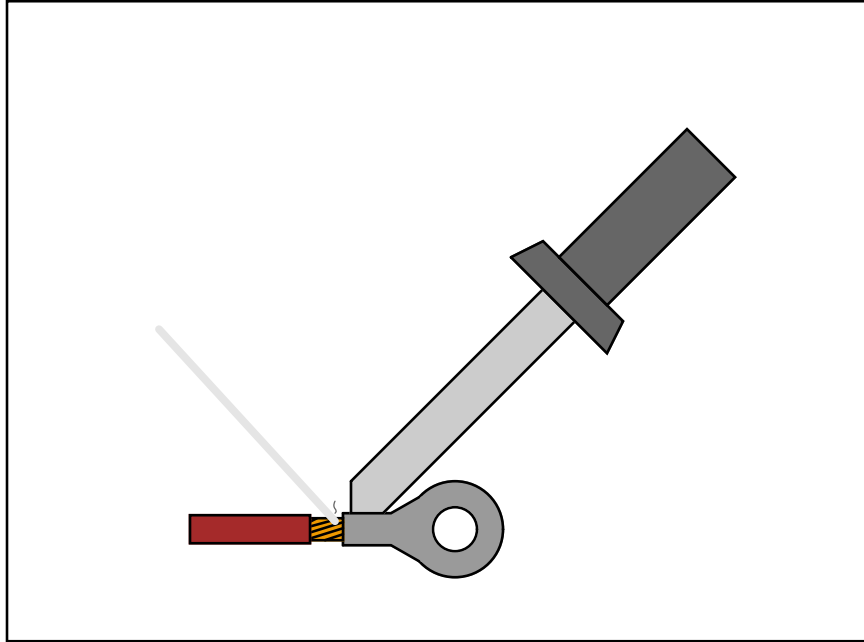


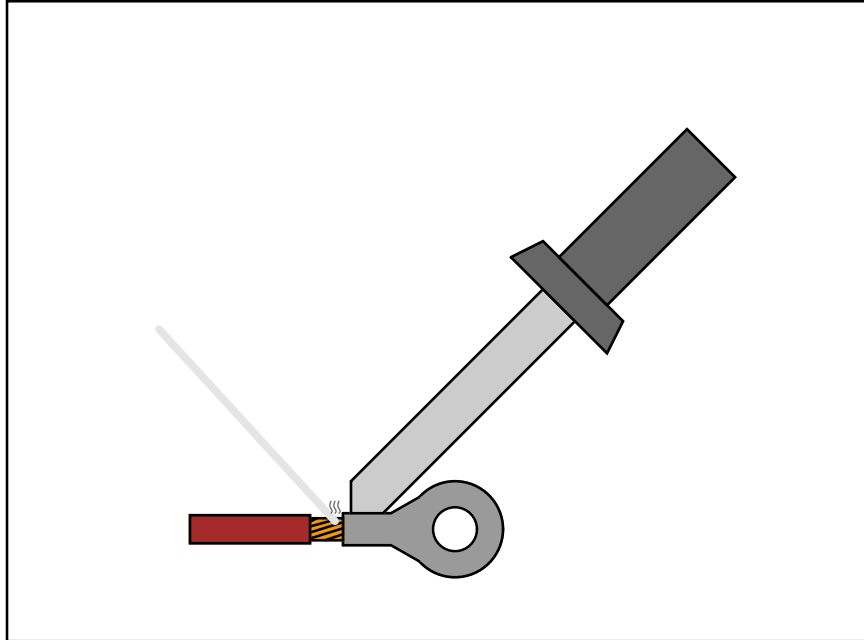


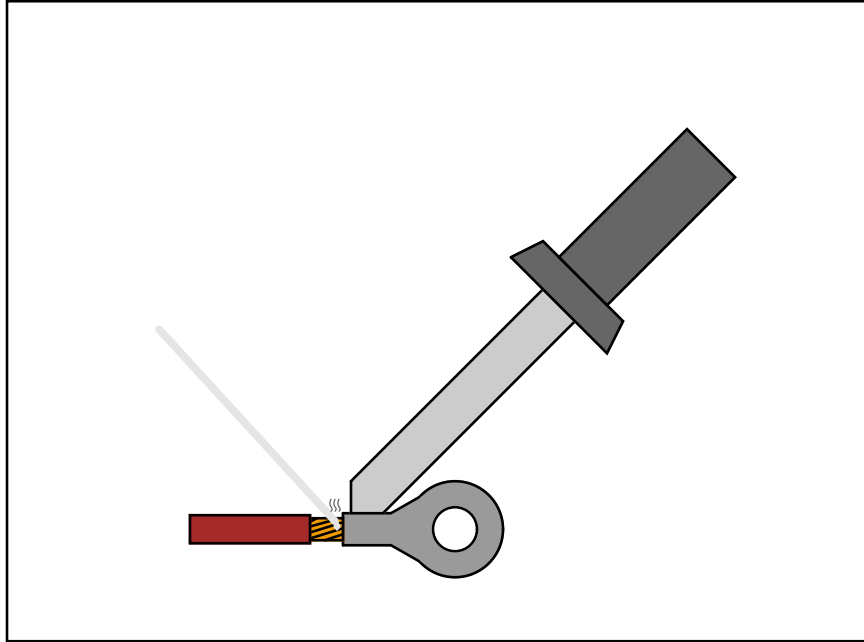


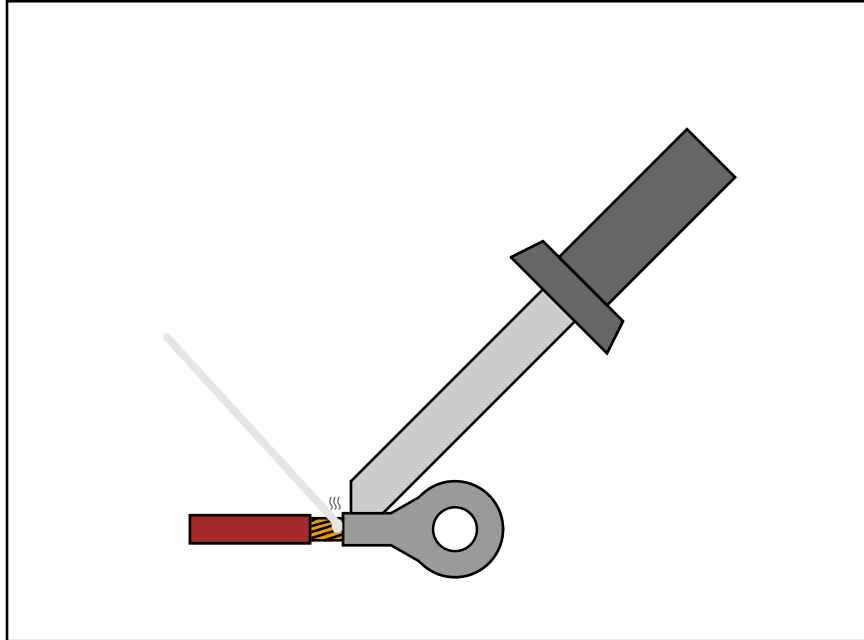


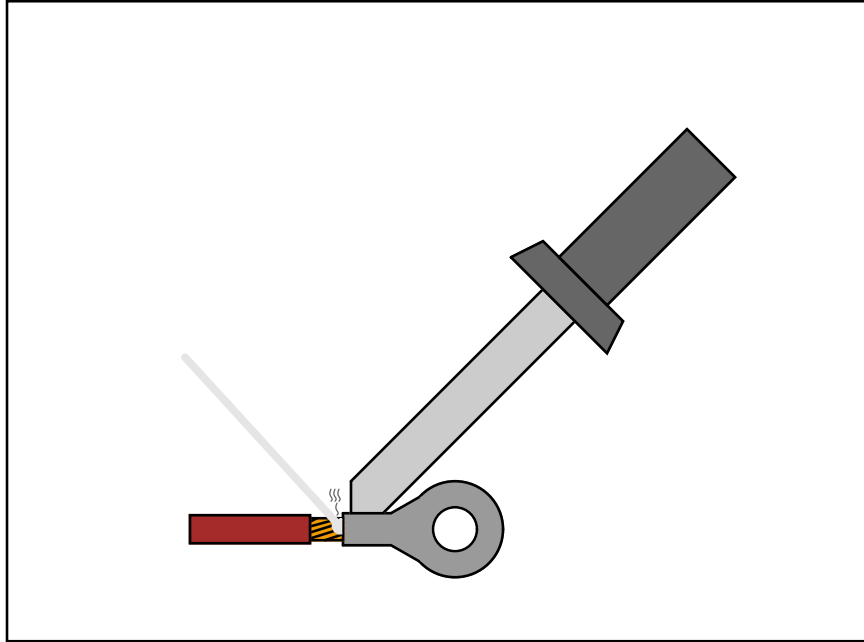


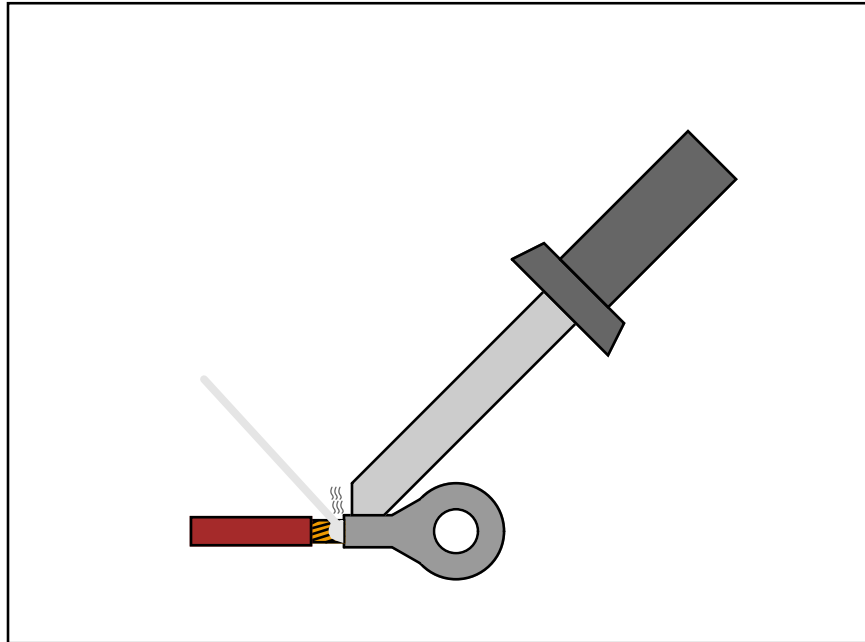


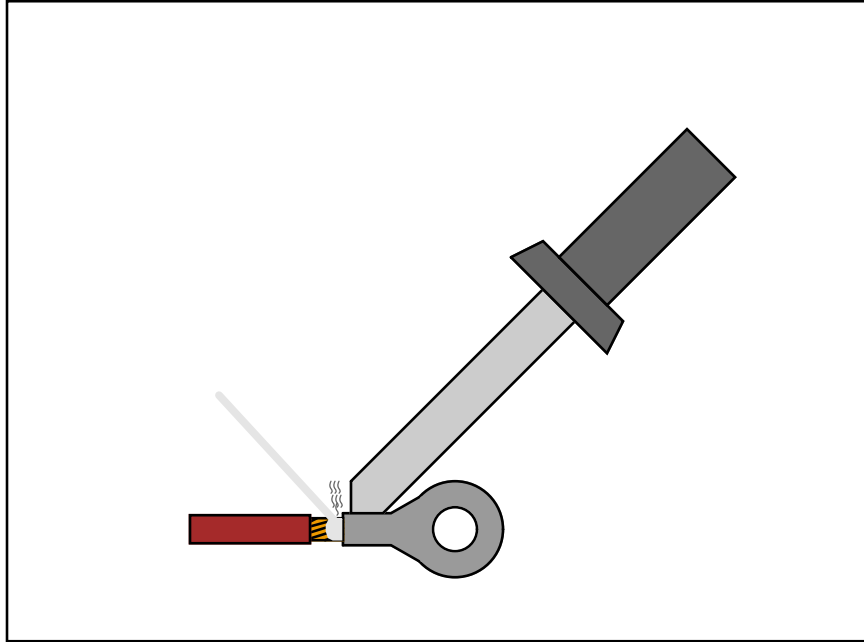


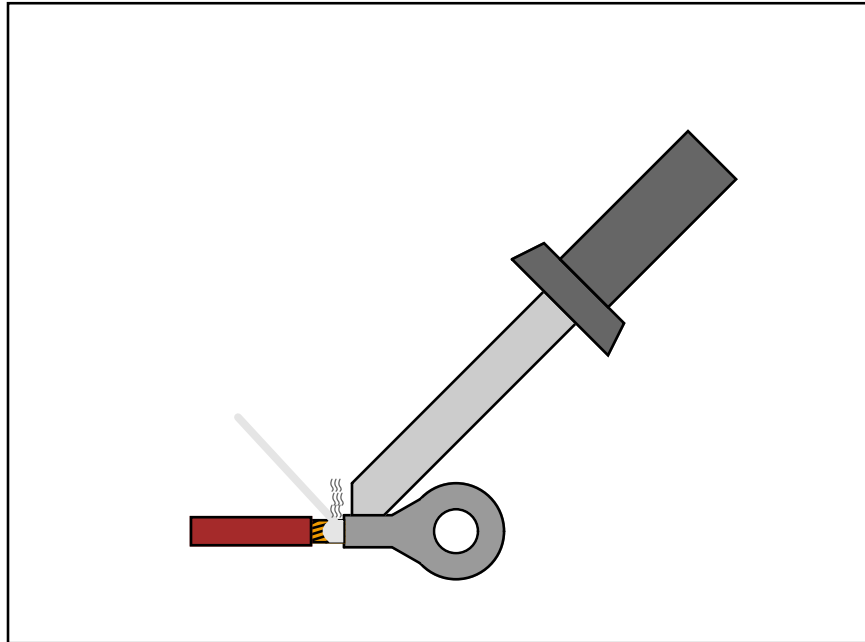


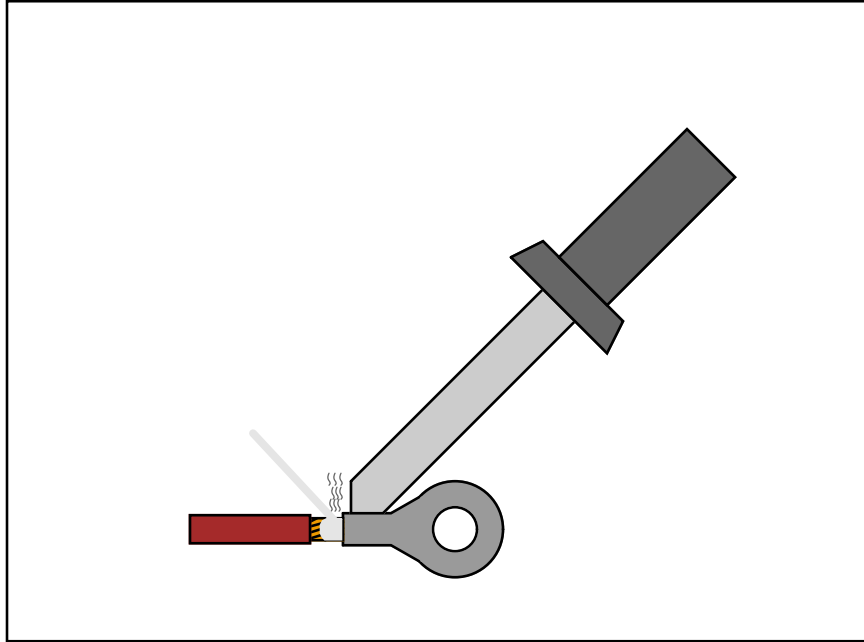


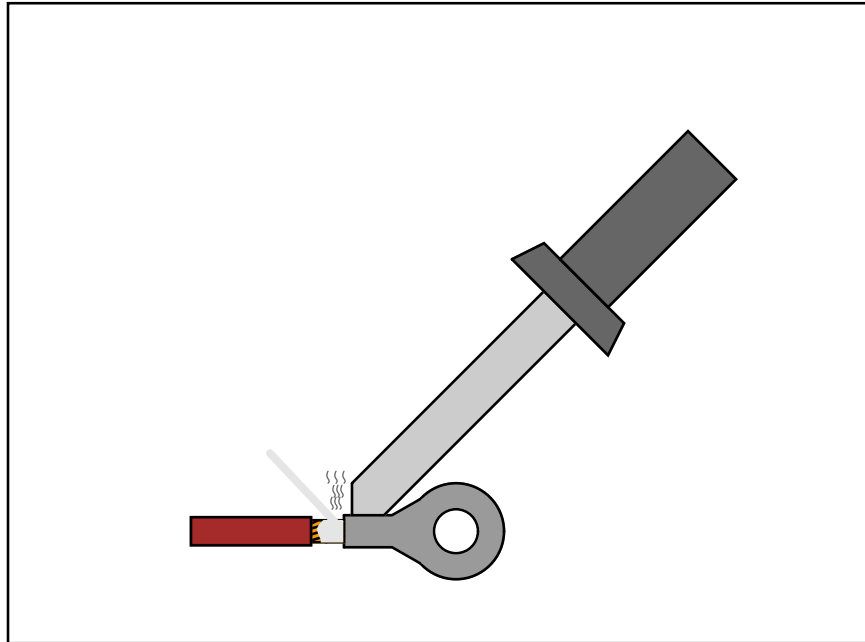


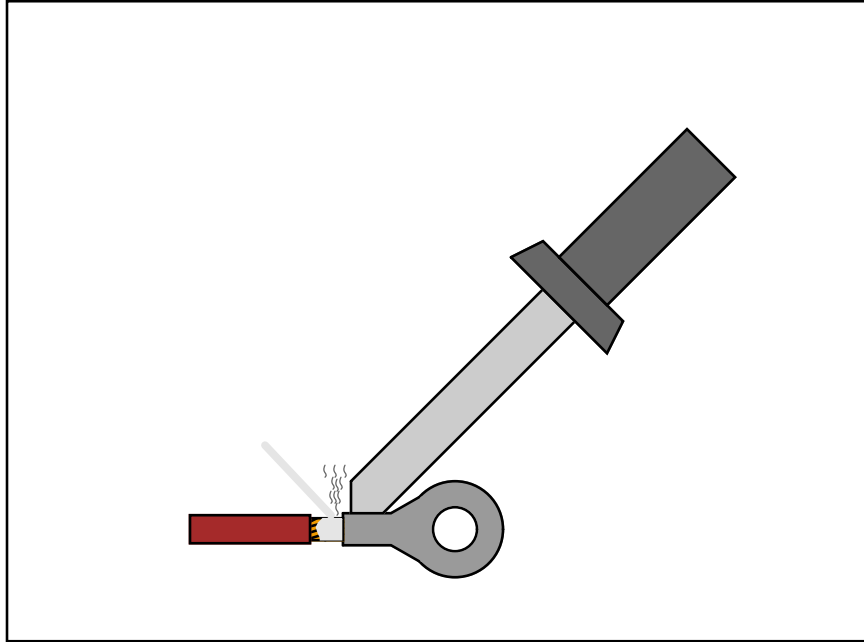


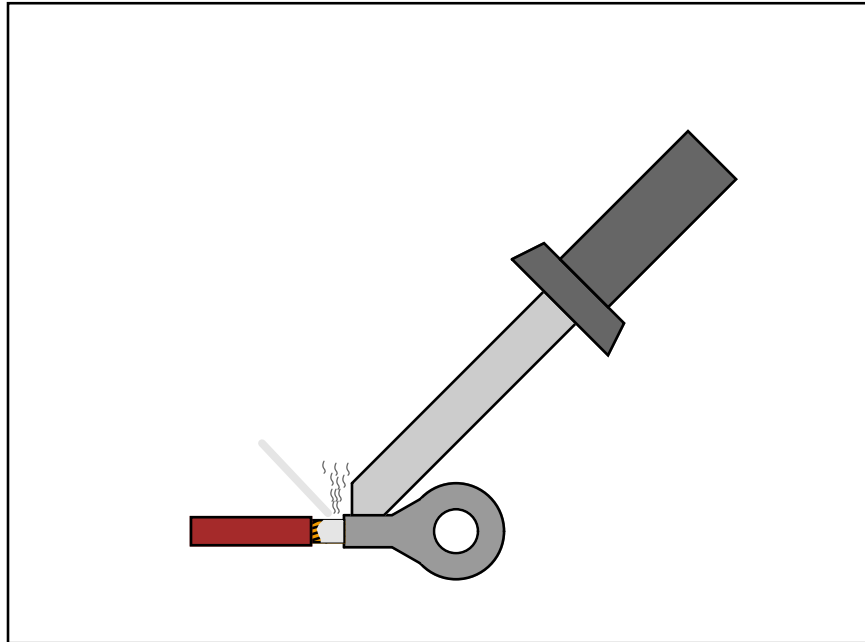


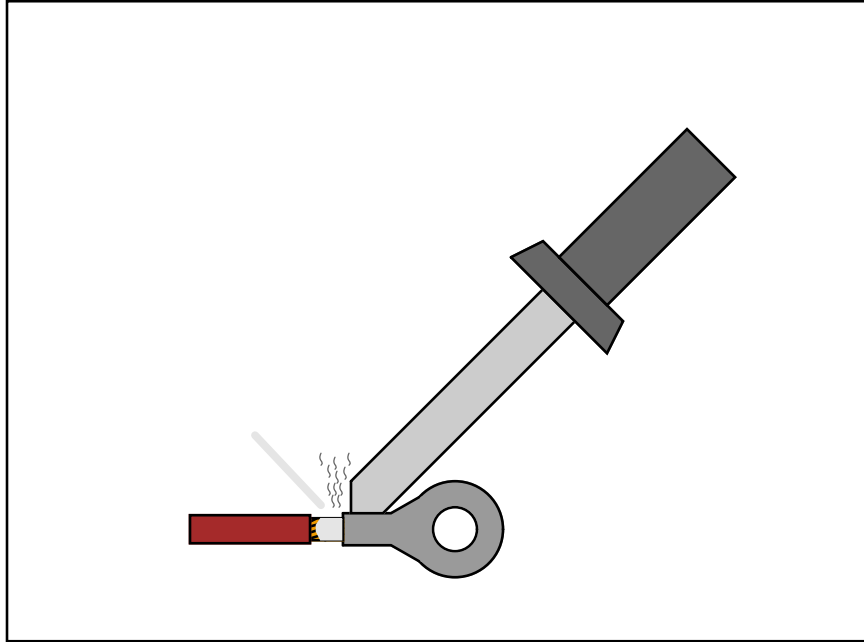


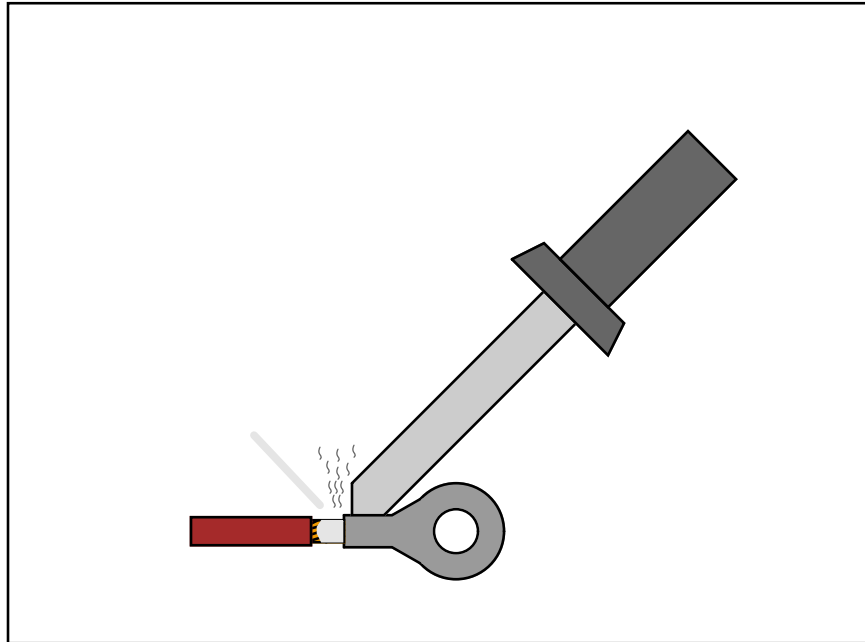


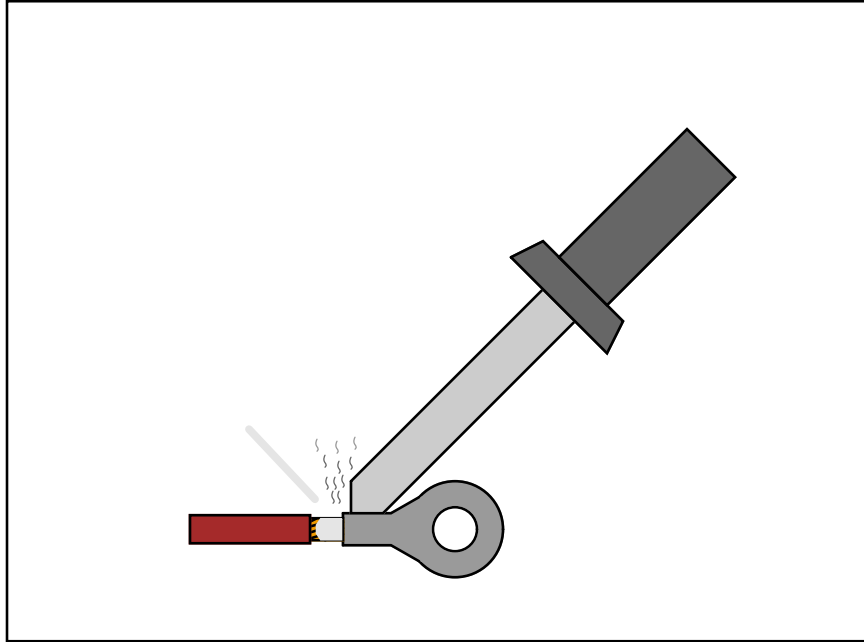


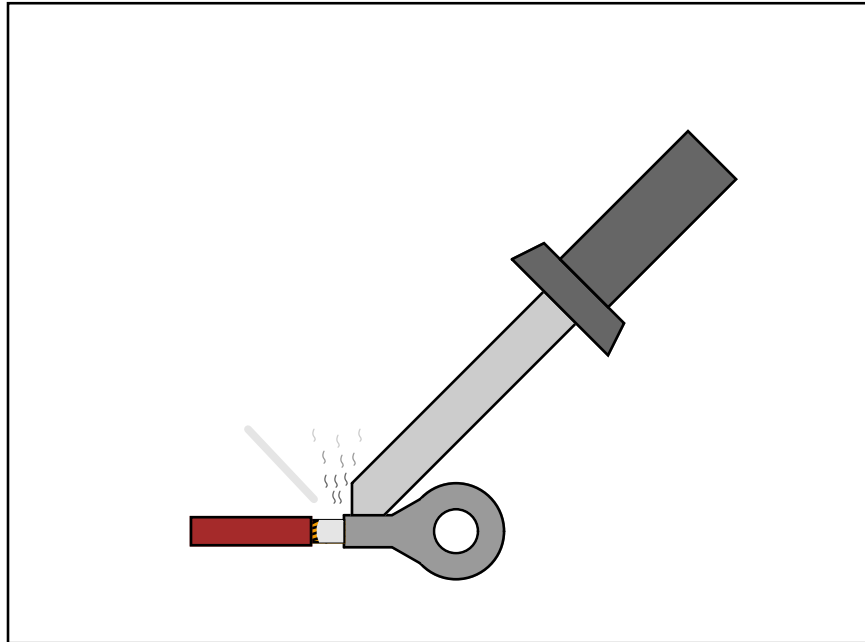


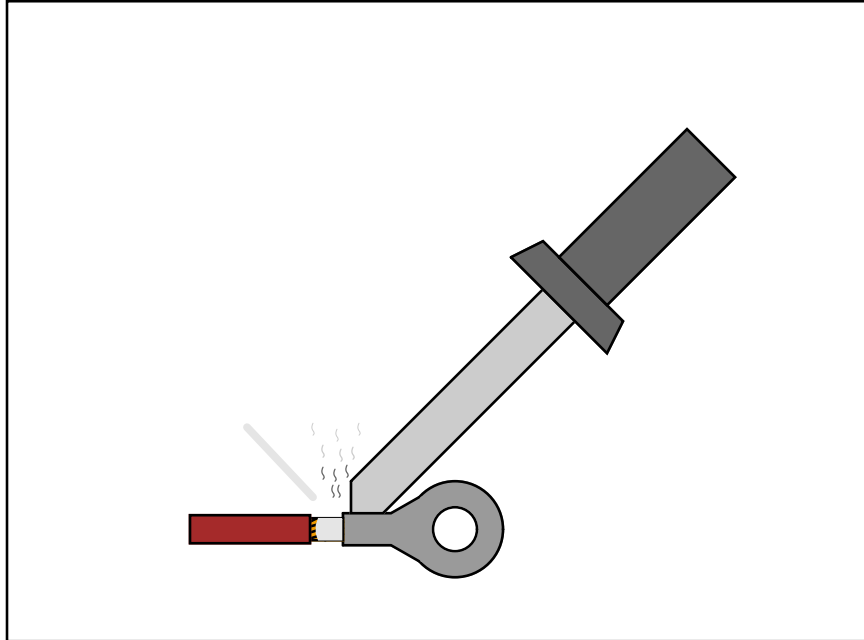


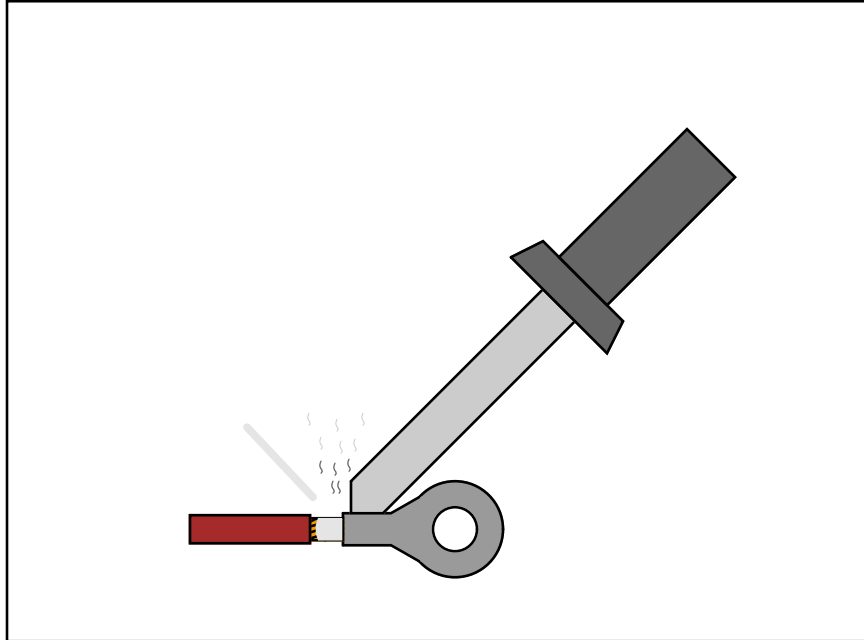


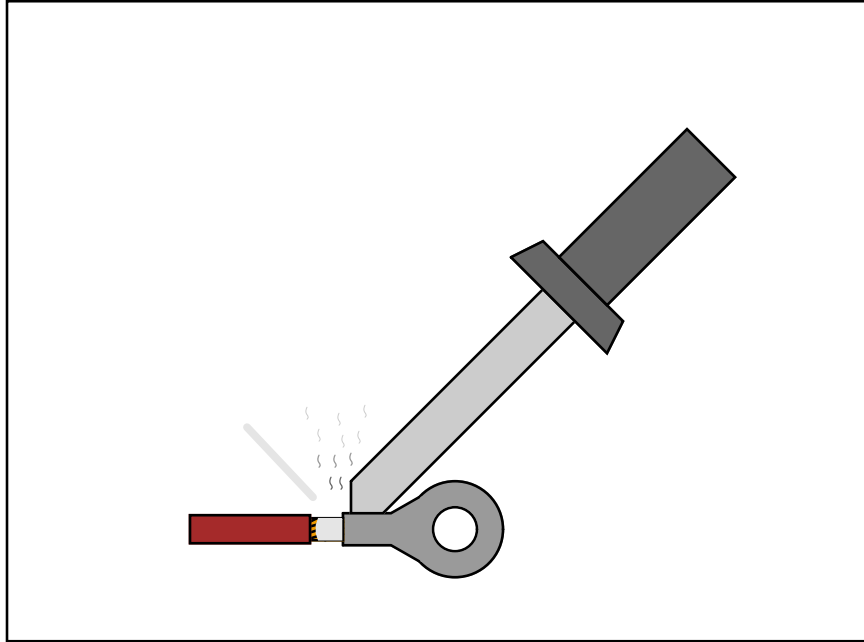


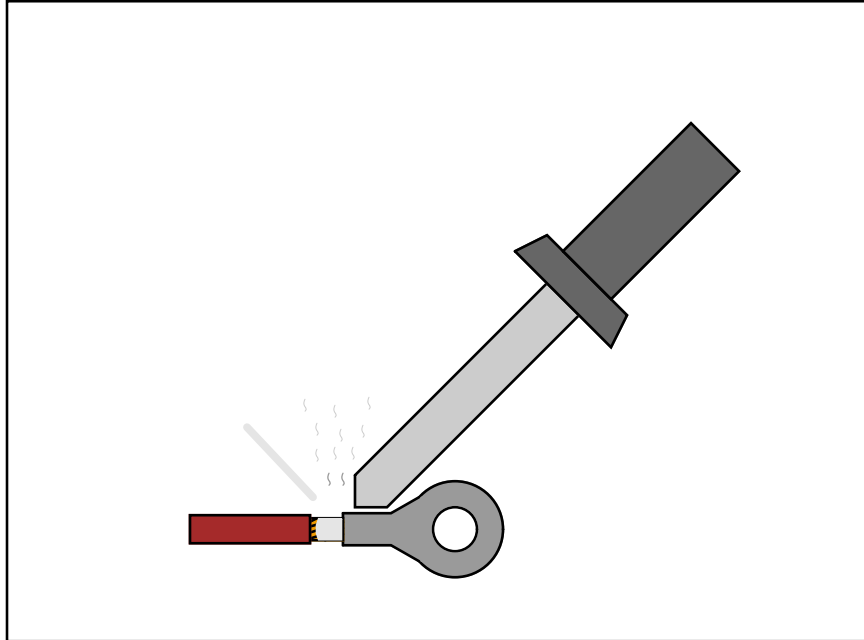


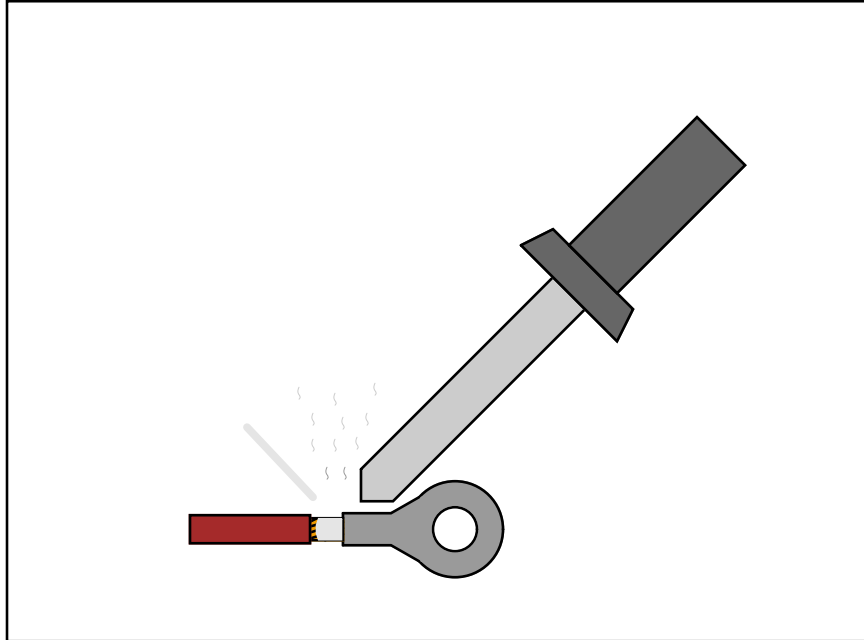


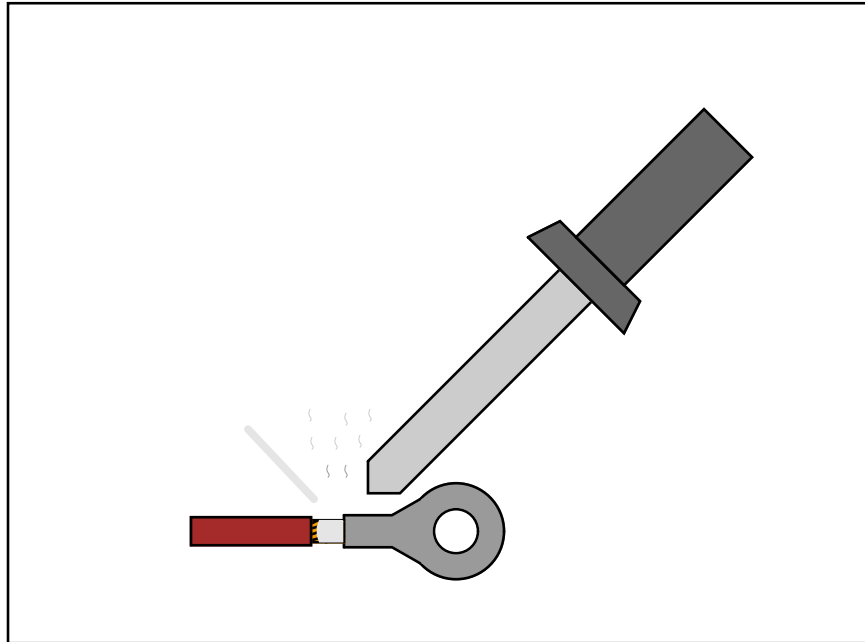


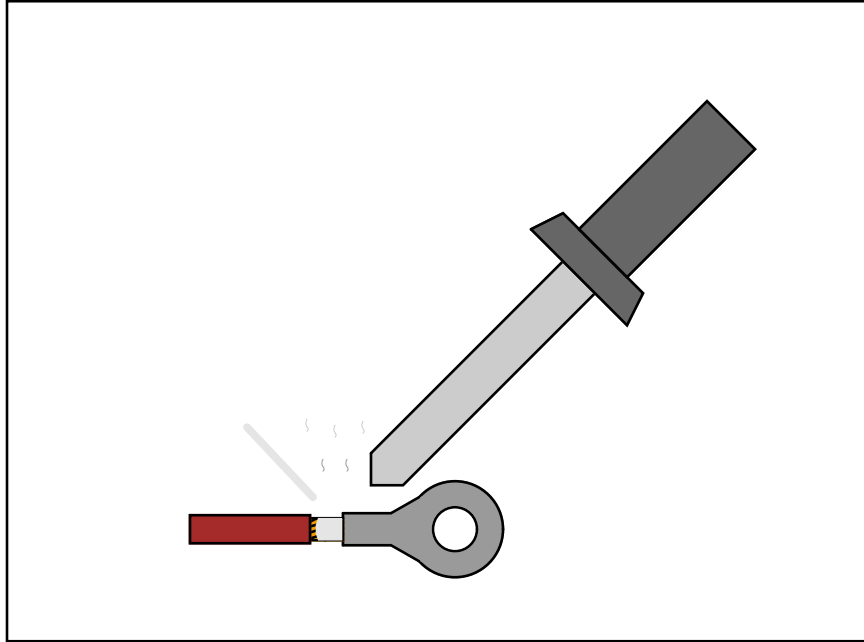












Chapter 4

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 read¹ the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture², 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.

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

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

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?

4.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking³. 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.

4.1.1 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.

4.1.2 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

Simplification as a problem-solving strategy

Thought experiments as a problem-solving strategy

Limiting cases as a problem-solving strategy

Annotating diagrams as a problem-solving strategy

Interpreting intermediate results as a problem-solving strategy

Graphing as a problem-solving strategy

Converting a qualitative problem into a quantitative problem

Converting a quantitative problem into a qualitative problem

Working “backwards” to validate calculated results

Reductio ad absurdum

Re-drawing schematics as a problem-solving strategy

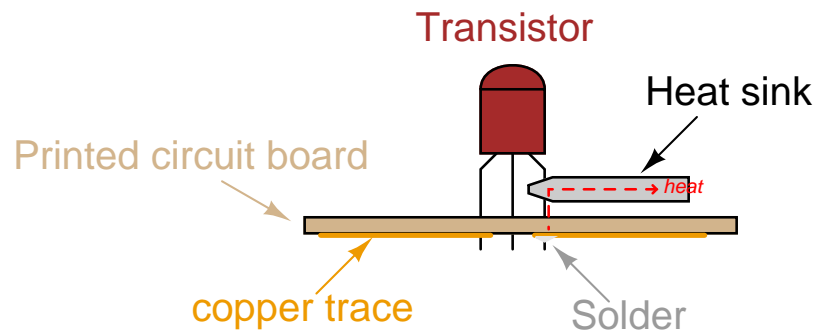
Cut-and-try problem-solving strategy

Algebraic substitution

???

4.1.3 Makeshift soldering heat-sink

Semiconductor components such as diodes and transistors are easily damaged by the high temperatures of soldering, so care must be taken to protect these components during the soldering process. One way to do this is to use a *heat sink* to draw heat away from the component without cooling the connection point too much. Heat sinks made out of sheet metal, or hemostats, may be temporarily clipped to the component leads, one at a time, to prevent the solder's high temperature from thermally conducting all the way to the component body:



In the absence of a formal heat sink, can you think of any ways to fashion your own “makeshift” heat sinks out of commonly available tools and/or objects?

Challenges

- What components other than semiconductors may be damaged by excessive soldering heat?

4.2 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 cases⁴” for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely⁵ 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.

4.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared (m³/kg-s²)

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

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

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**⁴ (W/m²·K⁴)

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

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

4.2.2 Introduction to spreadsheets

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

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

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

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

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

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

⁶Spreadsheets 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.

Common⁷ 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 ensure⁸ proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

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

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

This example is configured to compute roots⁹ 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.

⁷Modern 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.

⁸Spreadsheet 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.

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

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

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

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

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

Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary¹⁰ – 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.

¹⁰My 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.*

4.2.3 Converting between Celsius and Fahrenheit

The equation for converting degrees Celsius ($^{\circ}C$) to degrees Fahrenheit ($^{\circ}F$) is as follows:

$$T_F = \frac{9}{5}T_C + 32$$

Use this equation to convert the following temperatures from Celsius to Fahrenheit:

- $0^{\circ}C =$
- $100^{\circ}C =$
- $-40^{\circ}C =$
- $250^{\circ}C =$
- $310^{\circ}C =$

Now, algebraically manipulate the equation so that you may solve for degrees Celsius from a given figure in degrees Fahrenheit. Show all your work, then check your results by working backward through the five calculations above to arrive at the original figures in degrees Celsius.

Challenges

- Why is working backward through the five calculations a better way to check for errors than simply repeating the original calculation?

4.3 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.

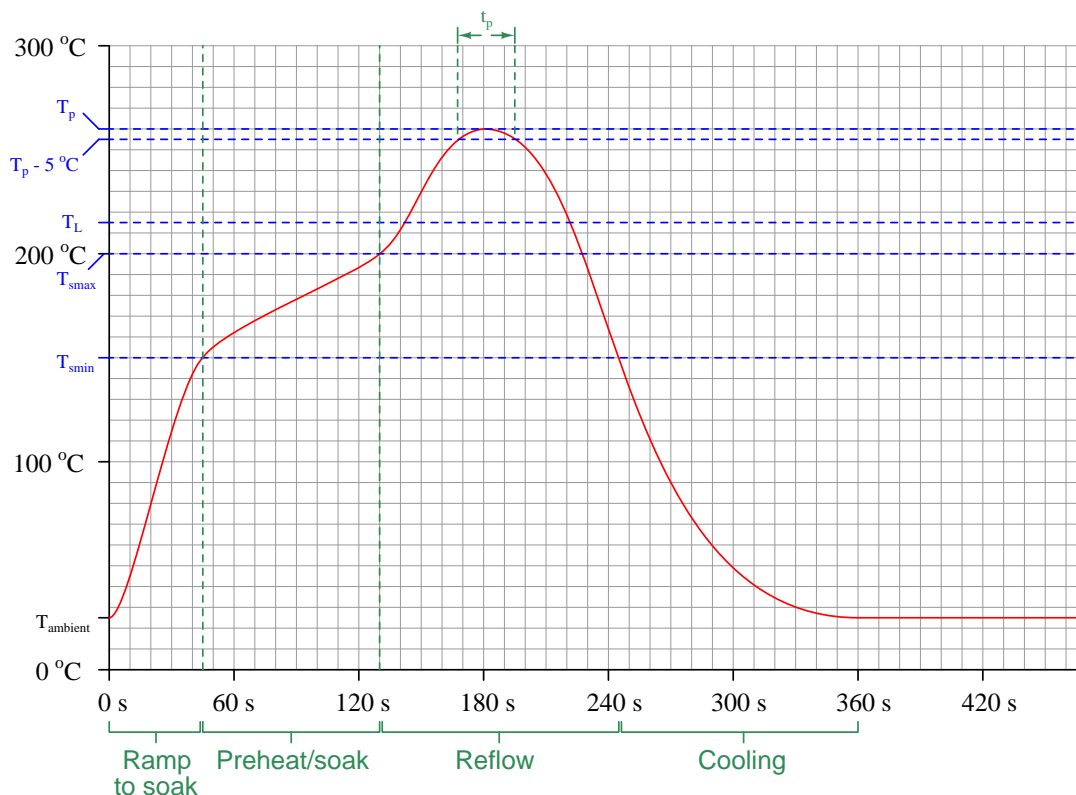
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of 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.

4.3.1 Soldering profile temperature rates

The following graph shows the *profile* for soldering temperature of a PCB assembly as it passes through a reflow oven to solder surface-mount devices (SMDs) to the board. This profile is common for lead-free SMD soldering, with a minimum soak temperature of $T_{smin} = 150\text{ }^{\circ}\text{C}$, a maximum soak temperature of $T_{smax} = 200\text{ }^{\circ}\text{C}$, a liquidous temperature of $T_L = 217\text{ }^{\circ}\text{C}$, and a peak/classification temperature of $T_p = 260\text{ }^{\circ}\text{C}$:



The time spent between peak temperature and 5 degrees C less than peak temperature should be at least 20 seconds but no more than 40 seconds. Is this profile consistent with that standard?

The time spent where the solder is in a liquid state should be at least 60 seconds but no more than 150 seconds. Is this profile consistent with that standard?

How would you discern the *rate* at which temperature rises or falls on this profile?

Sketch a straight line on this graph anywhere representing a rate of temperature rise of 1 degree C per second.

Challenges

- The maximum recommended ramp-up rate from T_L to T_p is 3 degrees C per second. Have we exceeded that ramp-up rate at any point in this profile?
- How fast is the maximum rate of temperature rise anywhere on this graph?
- The maximum recommended ramp-down rate from T_p to T_L is -6 degrees C per second. Have we exceeded that ramp-down rate at any point in this profile?

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 environment¹ 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 Socratic² 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 absurdity³ 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

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 varied⁴ 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 challenge⁵ one another.

To high standards of education,

Tony R. Kuphaldt

⁴As 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.

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

Appendix C

Tools used

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

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

The GNU/Linux computer operating system

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

Bram Moolenaar's **Vim** text editor

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

Donald Knuth's \TeX typesetting system

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

Leslie Lamport's \LaTeX extensions to \TeX

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

Tim Edwards' **Xcircuit** drafting program

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

Gimp graphic image manipulation program

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

SPICE circuit simulation program

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

Andrew D. Hwang's ePiX mathematical visualization programming library

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

`gnuplot` mathematical visualization software

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

Python programming language

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

Appendix D

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Appendix E

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Appendix F

Version history

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

28 November 2023 to 16 January 2024 – document first created.

Index

- Activity, flux, 15
- Adding quantities to a qualitative problem, 90
- Alloy, 6, 12
- Ampacity, 10
- Annotating diagrams, 89
- AutoCAD, 8

- Brazing, 11
- Bridge, thermal, 21, 29

- CAD, 8
- Checking for exceptions, 90
- Checking your work, 90
- Code, computer, 97
- Cold solder joint, 20
- Compound, chemical, 11
- Conformal coating, 9, 22
- Contamination, copper, 13
- Corrosion, 6, 7

- Datasheet, 13, 15
- De-ionized water, 24
- Dimensional analysis, 89
- Dwell time, 12, 21

- Edwards, Tim, 98
- Eutectic, 13

- Fiberglass, 7
- Filler metal, 11
- Flux activity, 15
- Flux, soldering, 6, 10, 12
- FR4, 8

- Graph values to solve a problem, 90
- Greenleaf, Cynthia, 71
- Gun, soldering, 19

- Hot air pencil, 22
- How to teach with these modules, 92
- Hwang, Andrew D., 99

- Identify given data, 89
- Identify relevant principles, 89
- Instructions for projects and experiments, 93
- Intermediate results, 89
- Intermetallic layer, 11
- Inverted instruction, 92
- Iron, soldering, 17

- Joule's Law, 10

- Knuth, Donald, 98

- Lamport, Leslie, 98
- Lead, 6, 12
- Limiting cases, 90

- Metacognition, 76
- Micron, 11
- Microscope, 23
- Moolenaar, Bram, 97
- Murphy, Lynn, 71

- Open-source, 97
- Orange stick, 22
- Oxidation, 24

- PCB, 8
- Pigtail splice, 7
- Pitch, component lead, 23
- Printed Circuit Board, 8
- Problem-solving: annotate diagrams, 89
- Problem-solving: check for exceptions, 90
- Problem-solving: checking work, 90
- Problem-solving: dimensional analysis, 89

- Problem-solving: graph values, 90
- Problem-solving: identify given data, 89
- Problem-solving: identify relevant principles, 89
- Problem-solving: interpret intermediate results, 89
- Problem-solving: limiting cases, 90
- Problem-solving: qualitative to quantitative, 90
- Problem-solving: quantitative to qualitative, 90
- Problem-solving: reductio ad absurdum, 90
- Problem-solving: simplify the system, 89
- Problem-solving: thought experiment, 89
- Problem-solving: track units of measurement, 89
- Problem-solving: visually represent the system, 89
- Problem-solving: work in reverse, 90
- Qualitatively approaching a quantitative problem, 90
- Reading Apprenticeship, 71
- Reductio ad absurdum, 90–92
- Schoenbach, Ruth, 71
- Scientific method, 76
- Silkscreen, 9
- Silver, 12
- Simplifying a system, 89
- SMD, 10, 23, 27
- Socrates, 91
- Socratic dialogue, 92
- Solder paste, 10, 15, 26
- Soldering, 11
- Soldering flux, 6, 10, 12
- Soldering gun, 19
- Soldering iron, 17
- Soldering iron tip temperature, 18, 21
- Soldering temperature, 12
- Soldermask, 9
- SPICE, 71
- Splice, pigtail, 7
- Stallman, Richard, 97
- Surface-mount device, 10, 23, 27
- Temperature of soldering process, 12
- Temperature, soldering iron tip, 18, 21
- Thermal bridge, 21, 29
- Thought experiment, 89
- Through-hole components, 8
- Time, dwell, 21
- Tin, 6, 12
- Tinning, 9, 24
- Torvalds, Linus, 97
- Transformer, 19
- Units of measurement, 89
- Visualizing a system, 89
- Welding, 11
- Wetting, 12
- Work in reverse to solve a problem, 90
- Work, soldering, 17
- WYSIWYG, 97, 98