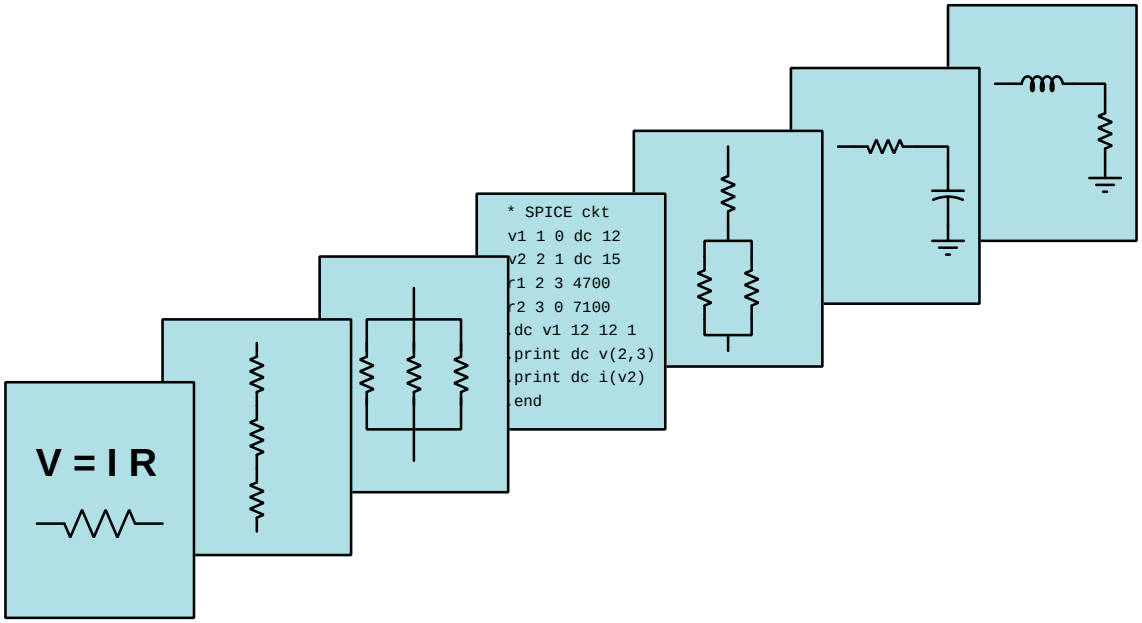
Modular Electronics Learning (ModEL) project



Thermal Management

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Chapter 1

Introduction

1.1 Recommendations for students

Inefficiencies in electrical and electronic devices result in some electrical energy being converted into heat, and this can be destructive to those devices if it results in excessive temperature. This module discusses some of the basic principles of heat transfer and of temperature calculations for electronic components.

Important concepts related to thermal management include **energy** (both potential and kinetic), **heat** versus **temperature**, the **First and Second Laws of Thermodynamics**, **power**, **efficiency**, **heat transfer**, **thermal conduction**, **thermal convection**, **thermal radiation**, **thermal conductivity**, **thermal resistance**, **Ohm's Law**, **Joule's Law**, **surface area**, heat **sources** versus **sinks**, **de-rating**, and **potentiometers**.

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

- How might an experiment be designed and conducted to measure the thermal resistance of an electronic component or a heat sink? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What is the difference between potential and kinetic energy?
- What is the difference between heat and temperature?
- What are some of the methods by which heat transfers from one location to another?
- What parameters affect the ease of which heat transfers from one location to another?
- How do we define efficiency?
- Where does the "wasted" energy go in a system that is less than perfectly efficient?
- What does the First Law of Thermodynamics tell us, and how does this relate to heat dissipation?

- What does the Second Law of Thermodynamics tell us, and how does this relate to heat dissipation?
- How may heat-transfer processes be related to Ohm's Law?
- How does a "heat pipe" work?
- What does it mean to "de-rate" a component?

1.2 Challenging concepts related to thermal management

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

- **Heat flow modeled as electriciy** – relating thermal energy flow and thermal resistance to electric current and electrical resistance, respectively, is at once a convenience as it leverages pre-existing conceptions of Ohm's Law and of series/parallel resistor networks, but it may also cause confusion when the solution of a practical problem also involves electrical quantities which must be kept distinct and separate!

A helpful strategy for solving thermal problems is to sketch a *thermal diagram* just the way you would sketch a schematic diagram, and then annotate that diagram with all known parameters. Having a diagram serve to "placehold" numerical quantities greatly enhances one's ability to identify relevant principles and organize calculated results.

1.3 Recommendations for instructors

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

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

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

  Assessment – Students show how quantitative results were obtained by the author in the Tutorial chapter's examples.

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

- **Outcome** – Determine operational electrical/thermal limits for an electronic component

  Assessment – Calculate maximum power dissipation and maximum drain current for a MOSFET; e.g. pose problems in the form of the "Transistor without a heat sink" Quantitative Reasoning question.

  Assessment – Calculate necessary heat sink size (i.e. thermal resistance) to keep a semiconductor device from overheating; e.g. pose problems in the form of the "Heat sink requirements" Quantitative Reasoning question.

- **Outcome** – Independent research

  Assessment – Locate heat sink datasheets and properly interpret some of the information contained in those documents including physical dimensions, thermal resistance without forced-air cooling, thermal resistance with given airflow velocities, etc.

Chapter 2

Case Tutorial

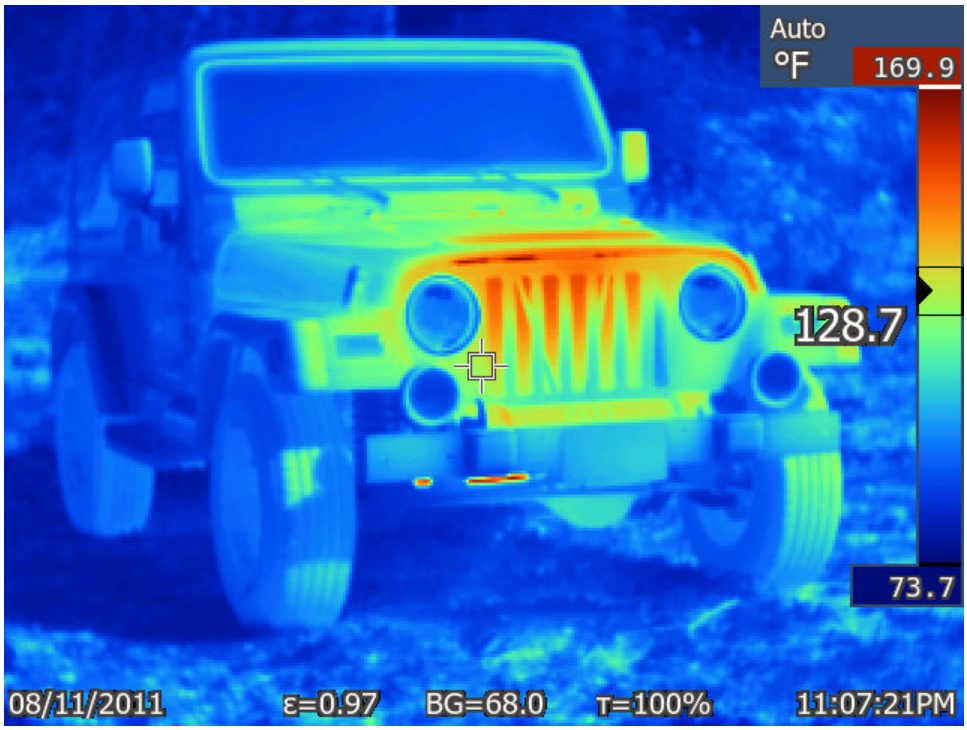
The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as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

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

2.1 Example: thermal imaging camera photos

The following photographs were taken with a thermal imaging camera, where color is used to show differences in perceived surface temperatures (red is warm, blue is cool).

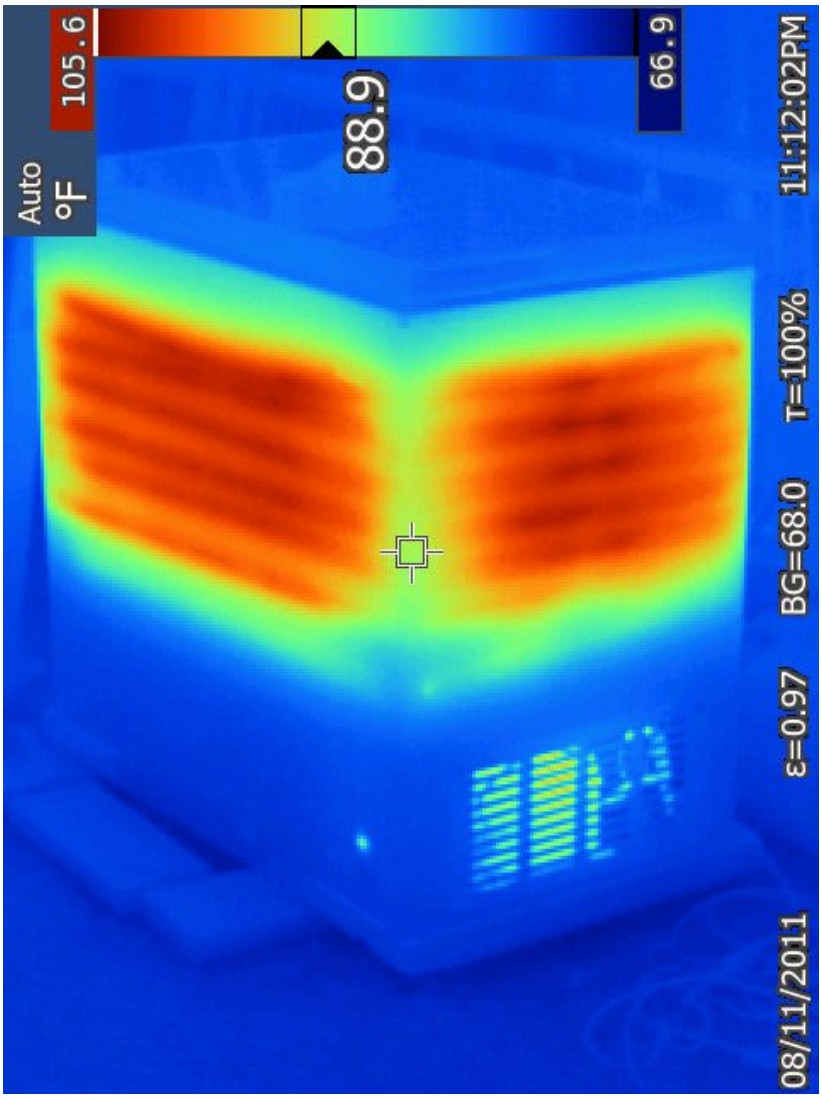
Motor vehicle after being driven:



Note the engine's heat clearly visible through the grille and hood. Thermal cameras only show *surface* temperature, so they cannot "see" temperature differences *behind* surfaces, only temperature differences manifesting *on* surfaces.

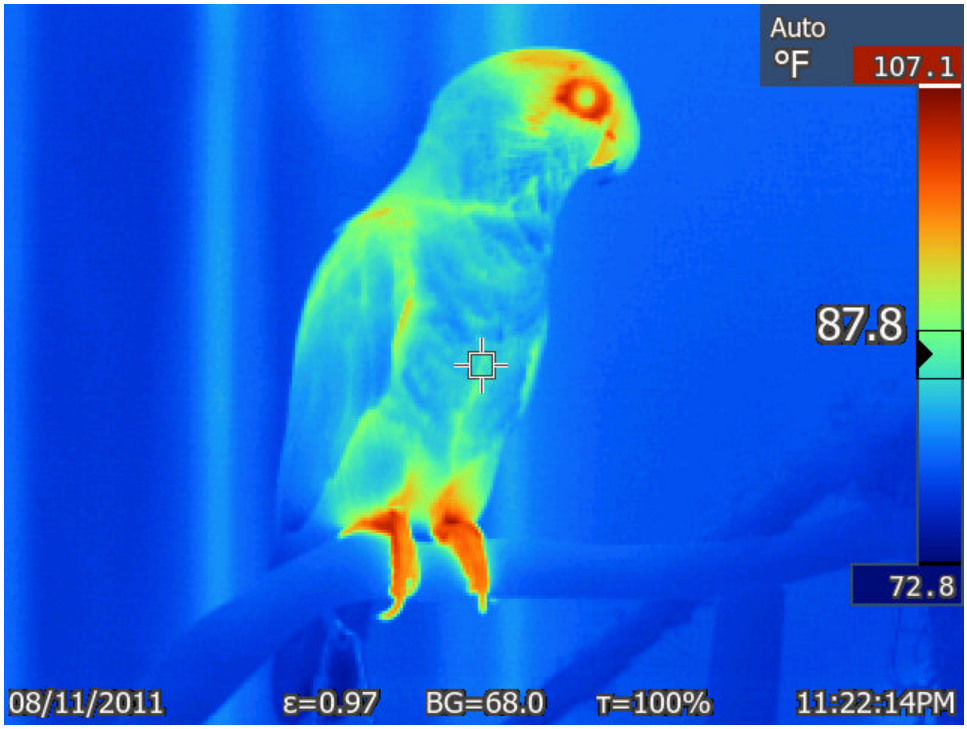
Another artifact of thermography is that *reflected* light may falsely register as higher temperature. Shadows may be clearly seen in this thermal image, a result of sunlight being interpreted by the camera as surface heat.

Chest-style freezer running:



Refrigerators and freezers alike are *heat pumps* using externally-supplied energy to move heat from the inside to outside. This is why they become warm to the touch when operating. Heat is shed by the "condenser" tubes where vaporous refrigerant condenses into liquid under high pressure, the phase change from vapor to liquid releasing large amounts of latent heat for relatively small masses of refrigerant fluid. Some units have exposed condenser tubes on one side. This particular unit has condenser tubes located just beneath the sheet-metal skin, being the red-orange lines visible in this thermal image. The compressor also sheds some heat, this one located behind the grille at the bottom of the freezer unit.

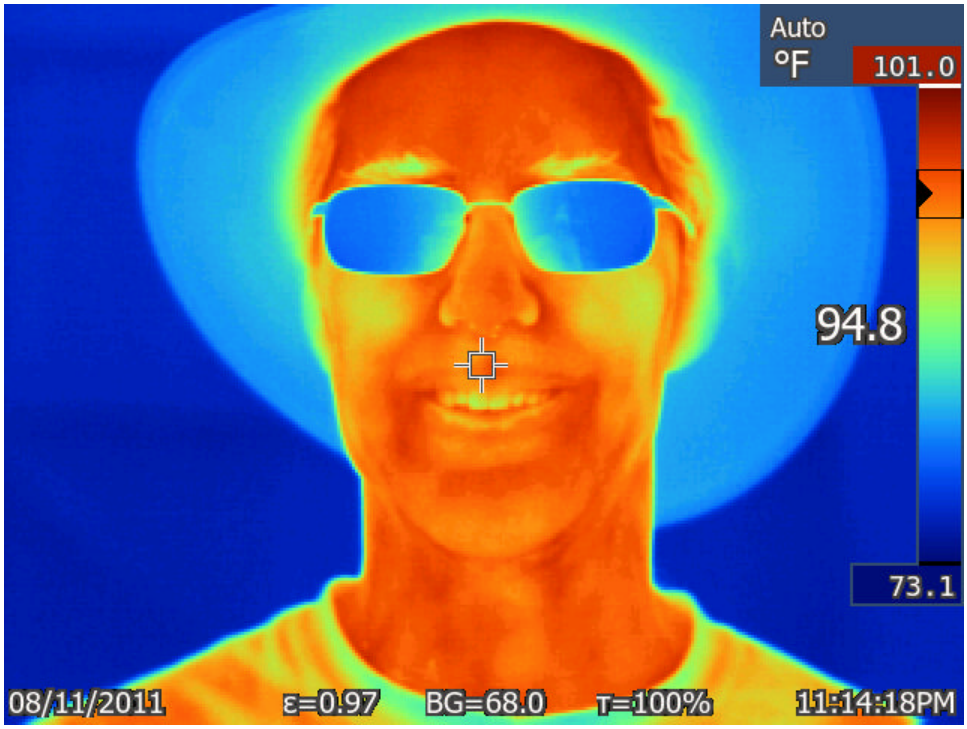
Parrot resting on a perch:



A bird's feathers provide excellent thermal insulation, evident in this photograph. Birds also run a higher body temperature than humans, which is visible by the coloration around this bird's eyes and parts of the bird's feet. Incidentally, veterinary science is making increasing use of thermal imaging cameras to help diagnose medical problems, as their patients tend to be less accepting of thermometer probes than your average human as well as being less able to articulate their complaints.

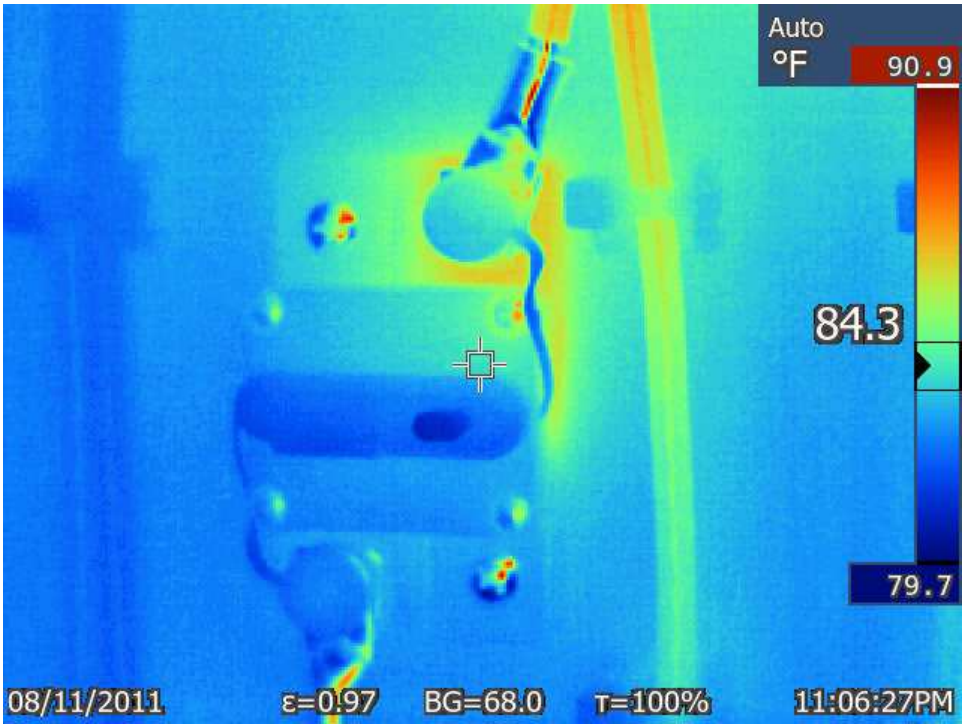
On exceptionally warm days, birds will lift their wings away from their bodies as a means to increase cooling, by decreasing the thermal resistance separating their skin from ambient air.

Author wearing a wide-brim hat and eyeglasses:



Regular glass blocks most infra-red light from passing through, which is why the author's glasses appear cold (blue) and the eyes are hidden from view.

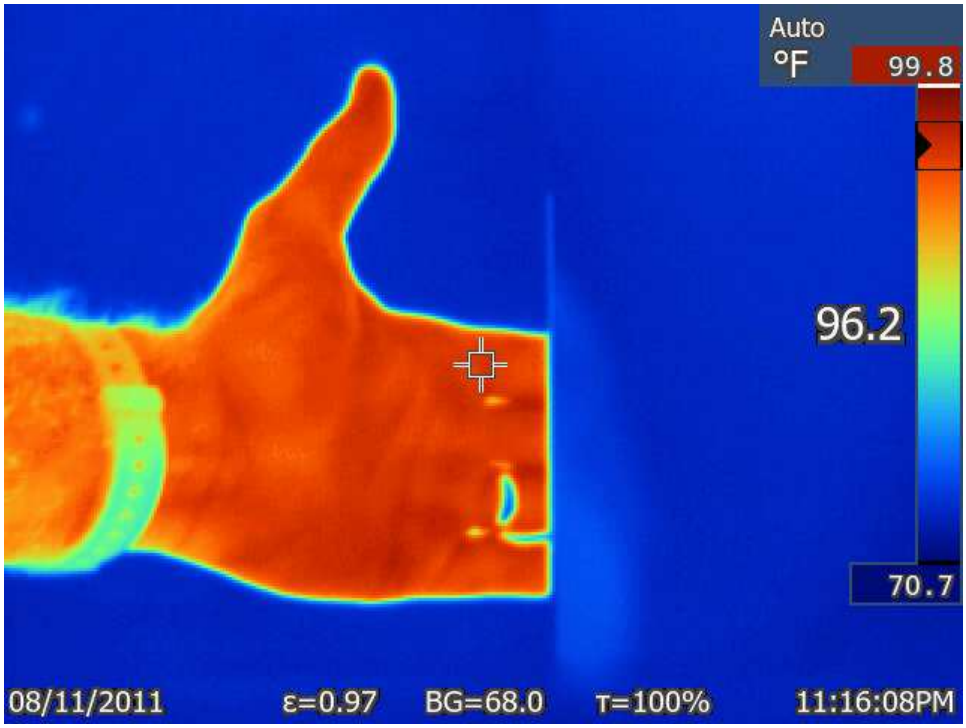
Low-voltage circuit breaker:



This is a circuit breaker in a 24 Volt DC solar electric power system, with #4 AWG stranded wire connecting to two terminals (upper-right and lower-left) using compression-style ring lugs. The circuit breaker's base underneath the upper-left terminal is definitely warmer than the rest of its surface. The wires themselves are also slightly warmer than the surrounding surfaces due to the effects of power dissipation (Joule's Law, $P = I^2R$).

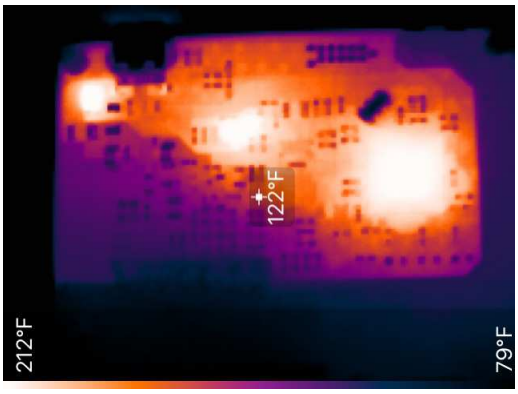
Some artifacts worthy of note in this image include the "hot" spots seen on some of the bare metal surfaces (compression lugs and mounting screw-heads). This is nothing more than reflected sunlight, which the camera falsely interprets as "hot spots" emitting intense infra-red light.

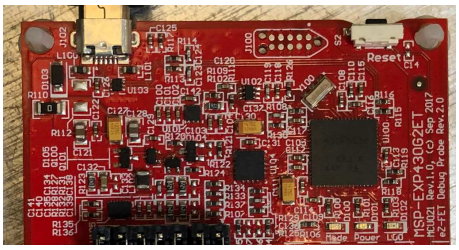
Invisibility behind glass:



Here we see the author's left hand reaching around the back side of a pane of ordinary window glass. With visible light the fingers behind the glass are clear to see, but using only infra-red light the glass all but blocks them from view.

Faulted circuit board:





This thermal image (left) was taken with a relatively inexpensive thermal imaging camera that attaches to a smart phone. Its resolution and clarity are inferior to the previous images taken with a much more expensive camera, but even with this cheap tool it is possible to identify "hot spots" on a circuit board with a failed microcontroller (the largest hot spot seen in the image, toward the right-hand end of the board). The photograph on the right is the same board taken with a normal camera.

Only the microcontroller is failed on this PCB, but the other two "hot spots" are operating at excessive temperature because they are part of the PCB's power-conditioning circuitry. The failed microcontroller is drawing excessive current from the board's power supply, and these other two components are overheating as they try to meet that abnormal demand in current.

2.2 Example: power transistor junction temperatures

The model IRF3415 MOSFET power transistor has an advertised "on" drain-source resistance ($R_{DS(on)}$) of 42 milliOhms, a junction-to-case thermal resistance (R_{thJC}) of 0.75 ^{o}C/W, and a case-to-sink thermal resistance (R_{thCS}) of 0.5 ^{o}C/W when properly greased and attached to a heat sink. Its junction-to-ambient thermal resistance (R_{thJA}) with no heat sink attached is 62 ^{o}C/W. The upper limit for this transistor's junction operating temperature is 175 ^{o}C.

Conducting 250 mA, ambient temperature of 30 ^{o}C, no heat sink attached:

Junction temperature = 30.163 ^{o}C

Conducting 1.7 A, ambient temperature of 20 ^{o}C, no heat sink attached:

Junction temperature = 27.526 ^{o}C

Conducting 5.2 A, ambient temperature of 25 ^{o}C, no heat sink attached:

Junction temperature = 95.412 ^{o}C

Conducting 14 A, ambient temperature of 22 ^{o}C, attached to heat sink with 10.4 ^{o}C/W of thermal resistance:

Junction temperature = 117.90 ^{o}C

Conducting 25 A, ambient temperature of 19 ^{o}C, attached to heat sink with 8.3 ^{o}C/W of thermal resistance:

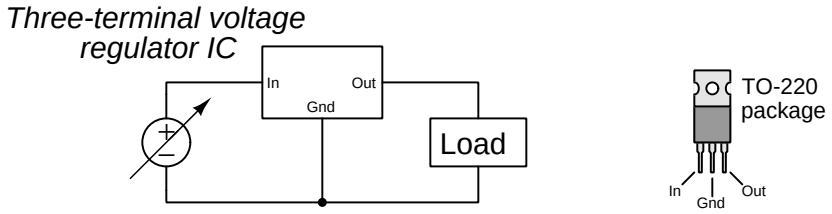
Junction temperature = 269.69 ^{o}C – *this will destroy the transistor!*

Conducting 26 A, ambient temperature of 20 ^{o}C, attached to heat sink with 2.1 ^{o}C/W of thermal resistance:

Junction temperature = 115.11 ^{o}C

2.3 Example: 7805 power dissipation

Suppose we decide to use a model 7805 fixed-voltage regulator to reduce a DC power supply voltage of 14.5 Volts down to 5.0 Volts to power a load known to draw a current of 0.73 Amperes:



The 7805 regulator achieves this reduction of voltage by dropping the excess between its "In" and "Out" terminals. Current through those same two terminals is nearly equal, with a negligible amount flowing through the "Gnd" pin. This means we may treat the regulator much like a resistance connected in series with the load, its "resistance" value constantly adjusting to maintain 5 Volts at the load despite any changes in load current and/or source voltage.

P_{load} = (5 Volts)(0.73 Amperes) = 3.65 Watts

P_{source} = (14.5 Volts) (0.73 Amperes) = 10.585 Watts

$P_{regulator}$ = (14.5 Volts − 5 Volts)(0.73 Amperes) = 6.935 Watts

Efficiency = $\frac{P_{out}}{P_{in}} = \frac{P_{load}}{P_{src}}$ = 34.48%

An important consideration for any power-controlling electronic device is temperature, raised above ambient temperature by its own power dissipation. In the case of the model 7805 regulator, it has a maximum junction (internal semiconductor) operating temperature of 150 ^{o}C. Without any heat-sink devices attached, the model 7805 regulator packaged in a style TO-220 case has a junction-to-ambient thermal resistance of 24 ^{o}C/W, which means for every Watt of power dissipation its temperature will rise 24 degrees Celsius hotter than the ambient air temperature. If we assume a room temperature of 20 ^{o}C, then we are allowed a 130 ^{o}C temperature rise at the regulator's internal semiconductor junctions resulting from power dissipation. Dividing that 130 ^{o}C allowed rise by the thermal resistance of 24 ^{o}C/W yields a maximum power dissipation of 5.417 Watts. Since we know our regulator must dissipate 6.935 Watts, we know the regulator will not be able to shed all the heat it needs to on its own and so we must attach a heat sink to the regulator's metal tab to assist its cooling.

Calculating the maximum thermal resistance allowed with this power dissipation and an ambient temperature of 20 ^{o}C:

Thermal resistance (max) = $\frac{130\ ^o\text{C}}{6.935\ \text{W}}$ = 18.7455 ^{o}C/W

Total thermal resistance for a device like this connected to a heat sink is its junction-to-tab thermal resistance plus the thermal resistance of the thermal grease interface between the tab and the heat sink (usually less than 1 ^{o}C/W) plus the sink-to-ambient thermal resistance of the heat

sink itself. A typical junction-to-tab thermal resistance for this TO-220 device is about 1.7 ^{o}C/W, and if we assume 0.5 ^{o}C/W for the thermal grease it means our heat sink cannot have more than 16.5455 ^{o}C/W of sink-to-ambient thermal resistance.

Chapter 3

Tutorial

Excessive temperature damages electrical and electronic components. This simple fact poses a range of challenges to anyone involved with the manufacture, assembly, design, and/or maintenance of electrical and electronic systems. Generally speaking, the cooler we are able to keep electrical and electronic components, the greater their service life.

Managing the temperature of these systems requires at least an elementary understanding of *thermodynamics*: the study of heat.

3.1 Heat versus Temperature

Most people use the words *heat* and *temperature* interchangeably. This is unfortunate for every student of thermodynamics, because it means they must first deconstruct this false conception and replace it with one more scientifically accurate before any progress may be made. While "heat" and "temperature" are related concepts, they are not identical.

Both concepts relate very closely to *energy*: that which sets matter into motion. *Potential energy* is energy that has not *yet* set matter into motion, but could if given the right conditions. A compressed spring or an elevated weight both possess potential energy. *Kinetic energy* is energy expressed in moving matter. A flying projectile has kinetic energy.

We know that energy is always *conserved* which means it cannot appear from nothing or disappear into nothing, but its sum total quantity remains constant over time. Energy can, however, change between different forms (e.g. between potential and kinetic, between different forms of potential and different forms of kinetic), and it may also move from one location to another. We call this the *Law of Energy Conservation*, or alternatively the *First Law of Thermodynamics*.

When discussing heat and temperature, we are dealing with a very specific form of kinetic energy embodied as the random motion of individual atoms and molecules. We will refer to this specific form of kinetic energy as *thermal energy*.

Temperature is a measure of an individual molecule's kinetic energy expressed as random vibrations. It is easiest to define mathematically for a monatomic gas[1]:

$$\frac{1}{2}m\overline{v^2} = \frac{3}{2}kT$$

Where,

m = Mass of each molecule
v = Velocity of a molecule in the sample
$\overline{v}$ = Average ("mean") velocity of all molecules in the sample
$\overline{v^2}$ = Mean-squared molecular velocities in the sample
k = Boltzmann's constant ($1.3806504 \times 10^{-23}$ J / K)
T = Absolute temperature (Kelvin), 273.15 more than degrees Celsius

The "hotter" a mass is, the more energetically its constituent molecules vibrate; the "colder" it is, the less its molecules vibrate. A temperature of absolute zero (i.e. zero Kelvin) is where all molecular motion ceases, which is the lowest temperature physically possible.

Heat, by contrast, is the sum total of energy possessed by a mass in the form of its molecular vibrations. It is very easy to confuse heat with temperature, so we must take care to differentiate these concepts from one another. An individual molecule vibrating with a particular velocity possesses both heat and temperature. If we combine that molecule with others just like it, all sharing the same vibrational velocity, they will all possess the same temperature, but the heat increases because their total combined kinetic energy is the *sum* of their individual kinetic energies. Temperature, therefore, is an expression of thermal energy *per molecule*. Heat is an expression of the *total* thermal energy for a sample of molecules.

[1] That is, a gas comprised of individual un-bound atoms, such as helium gas.

Practical illustrations are helpful to distinguish between heat and temperature. Consider, for example, a lit candle. The temperature of the candle's flame is very high – the vibrational velocities of the gas molecules being so high that they emit light – but given the small amount of mass involved with a single candle flame its heat is fairly low. Now consider a lake full of cool water. The temperature of this water much lower than the temperature of a candle flame, but the *heat* of the lake's total water mass vastly exceeds that of the flame simply because there are *far* more molecules of water in the lake than in the flame. To summarize, temperature is about the vibrations of individual molecules while heat is about the sum total of thermal energy in a sample.

When we consider thermal effects on electrical and electronic components, the danger comes from excessive temperature, not excessive heat. High temperature is what damages components because high temperature means the individual molecules vibrate at high speeds, and at high enough speeds the molecules begin to lose their integrity. High temperatures can cause solid substances to liquefy, and even to vaporize, as their once-bound molecules tear apart from each other. High temperatures can also cause atoms to chemically react: breaking the bonds that hold atoms together to form molecules, and facilitating the formation of new bonds with different atoms. *Fire* is an extreme example of this, where high temperatures cause certain substances to react with oxygen in the surrounding air and form new bonds, releasing potential energy in doing so which causes temperatures to rise even more. Certain types of electronic components such as *semiconductors* (diodes, transistors, thyristors) stop functioning properly when they become too warm, and this generally occurs well before reaching the temperature of combustion or melting.

3.2 Energy, power, and efficiency

Energy may be defined as that which has the ability to set matter into motion. *Thermal* energy is energy taking the form of vibrating molecules, since vibration is a form of motion. The metric unit of measurement for energy – in any form – is the *Joule*.

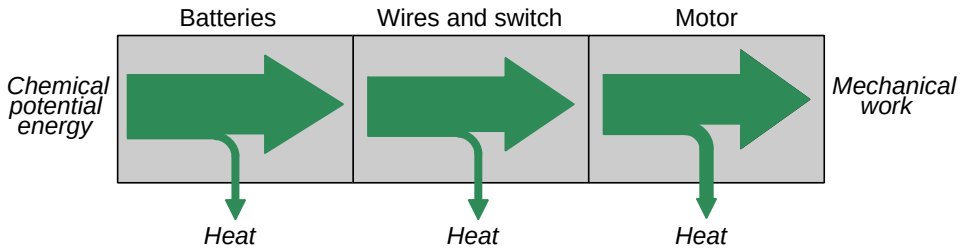
Energy *transfer* is the conversion of energy from one form into another, or the movement of it from one location to another. When speaking of thermal energy transfer, we mean the transference of vibrating molecules' thermal energy to other molecules that are not vibrating as vigorously – in other words, the natural "flow" of heat moving from hotter masses to colder masses. We may measure the *rate* at which energy converts or moves, in units of Joules per second. This is the definition of the *Watt*, the metric unit of measurement for *power* (energy rate).

$$[\text{Watt}] = \frac{[\text{Joule}]}{[\text{second}]}$$

When an electrical or electronic device dissipates thermal energy, it does so at a fraction of the total electrical energy sourced to the device, this fraction known as the device's *efficiency*. For example, if an electric motor is 90% efficient it means 90% of the electrical energy sourced to it gets converted into mechanical work while the remaining 10% converts to heat or other dissipative forms. The "waste" energy must leave the motor or else it would accumulate in the form of a rising temperature. This is why motors always have some provision for cooling: to shed the heat resulting from less-than-perfect efficiency. The same is true for any energized electrical or electronic device: heat must be able to move away from that device, lest its temperature rise uncontrolled.

$$\text{Efficiency} = \frac{\text{Energy converted to intended form}}{\text{Energy input to system}}$$

For example, a simple electric circuit consisting of nothing but batteries, a switch, and an electric motor works to convert the batteries' stored chemical potential energy into mechanical work at the motor's shaft. Each component in this circuit is less than perfectly efficient, though, and so some energy is "lost" in each step of the conversion process from chemical to mechanical energy. This may be represented as a series of arrows, the width of each arrow representing the quantity of energy transferred:



3.3 Heat transfer and thermal resistance

If a hot (high-temperature) object touches a cold (low-temperature) object, thermal energy must move from the former to the latter. This makes perfect sense if we consider temperature to be molecular vibration: a hot object's molecules vibrate vigorously, while a cold object's molecules vibrate slowly. Direct contact between two such objects permits collisions to occur between the molecules of each. As fast-moving molecules in the hot object collide with slow-moving molecules in the cold object, those collisions cause the slow-moving molecules to move faster and the fast-moving molecules to move slower. This gradual progression spreads throughout the volume of the two objects, as adjacent molecules within each object collide with each other and exchange kinetic energy. The end result is that the hot object's temperature falls while the cold object's temperature rises, until they are (eventually) at the same temperature with their individual molecules all moving at approximately the same speeds.

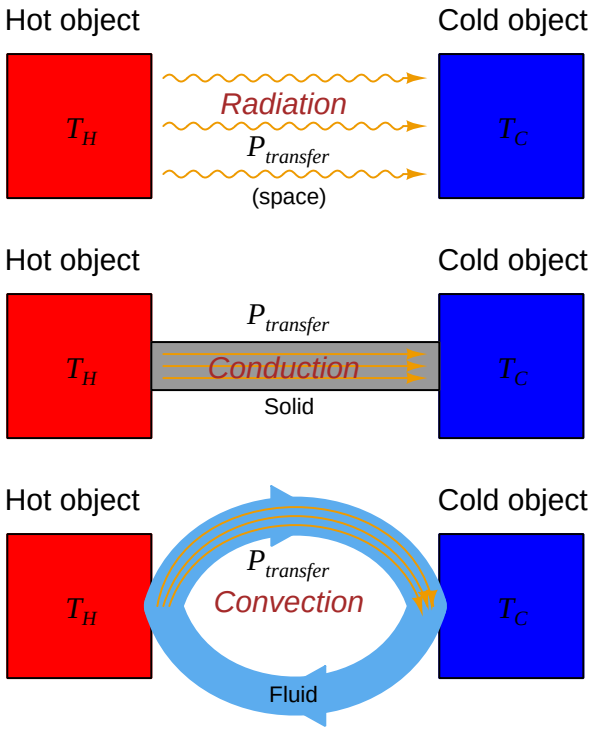
This is an example of heat transfer via the mechanism of *conduction*: direct contact between two objects. If the hot and cold masses in question are fluid rather than solid, this equalization of temperature tends to happen more rapidly. Similarly, if a fluid acts as an intermediate mass between a hot solid and a cold solid, the moving fluid molecules act like a conveyor belt for thermal energy. This is heat transfer via *convection*.

A third method of heat transfer also exists, but it is far less effective than either conduction or convection, and that is *radiation*. All moving matter emits energy in the form of electromagnetic waves, which means anything at a temperature greater than absolute zero emits some amount of electromagnetic radiation. These waves, in turn, have the ability to set molecules into motion and thereby cause an object's temperature to rise. If a hot and cold object exist with completely empty space between them – no direct contact to transfer thermal energy by conduction, and no fluid between them to convect thermal energy – they may still exchange energy by way of their radiated waves. The hot object loses energy faster than it gains, and the cold object gains energy faster than it loses. This causes thermal energy transfer from hot to cold, so that ultimately both objects will be at the same temperature.

The natural transfer of thermal energy from hot to cold is actually a fundamental property of the universe, and it is called the *Second Law of Thermodynamics*. It simply means that *energy spreads to become more diffuse over time*.

Just because thermal energy transfer is guaranteed to equalize the temperatures of objects in proximity to each other, though, does not mean all modes of heat transfer are equally effective. Radiation, for example, is extremely ineffective compared to either conduction or convection. The rate at which heat transfers is a function of the temperature difference between the objects in question: the greater the difference in temperature, the faster the rate at which energy transfers from hot to cold. However, a given temperature difference equates to a much smaller radiative transfer rate than a conductive or convective transfer rate. In all cases, an important factor is *surface area* of the objects. Greater surface area enhances radiative heat transfer by allowing electromagnetic waves to escape from more molecules; greater surface area enhances conductive heat transfer by providing more opportunity for hot and cold molecules to collide; greater surface area enhances convective heat transfer by allowing the circulating fluid molecules to contact (and collide with) more of the solid objects' molecules.

In order to be precise in these matters, we need to quantity "effectiveness" for different heat-transfer methods. We know that heat transfer only occurs where a difference of temperature exists, and so a good way to quantify the effectiveness of any heat-transfer method would be to express the *rate* at which heat transfers (i.e. the *thermal power*)[2] for any given difference in temperature:



Expressed mathematically, the *thermal conductivity* of any heat-transfer system is the quotient of thermal power to temperature difference:

$$\text{Thermal conductivity} = \frac{P_{thermal}}{T_H - T_C}$$

A relatively ineffective heat-transfer method such as radiation will exhibit low rates of heat transfer (i.e. small power values) even for very large temperature differences. An effective heat-transfer method such as forced[3] convection will result in high rates of heat transfer even for small temperature differences.

[2] The definition of power, in any physical context, is a rate of energy transfer. We measure energy in *Joules* and power in *Joules per second* which is also known as a *Watt*.

[3] When the heat-transfer fluid is forced to circulate by a fan or a pump.

This concept of thermal conductivity is not unlike *electrical* conductance (G), being the ratio of current to voltage. If we consider the flow of electric charge carriers (current) to be analogous to the flow of thermal energy, and the difference of electrical potential to be analogous to the difference in temperature between the hot and cold objects, the similarity is unmistakable:

$$G = \frac{I}{V} \qquad \text{Thermal conductivity} = \frac{P_{thermal}}{T_H - T_C}$$

Likewise, we may relate electrical resistance to *thermal resistance* by reciprocating both equations, resulting in a *thermal equivalent of Ohm's Law*:

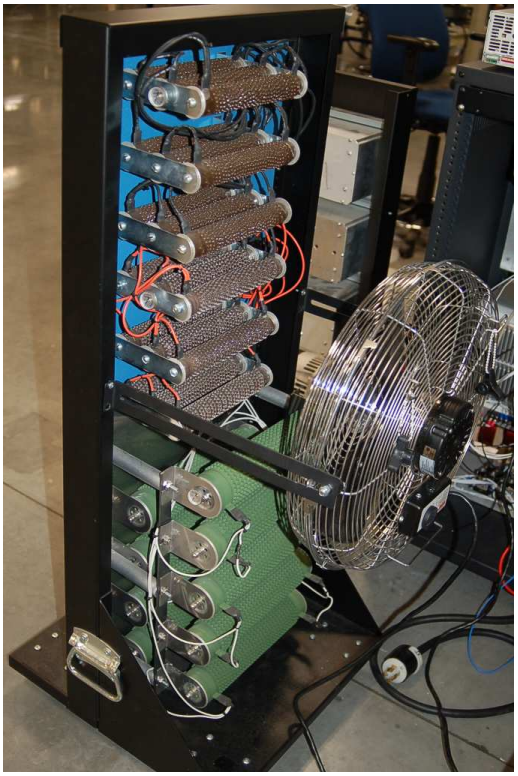
$$R = \frac{V}{I} \qquad \text{Thermal resistance} = \frac{T_H - T_C}{P_{thermal}}$$

Just as electric current passing through an Ohmic resistance is accompanied by a voltage drop, heat passing through a thermal resistance is accompanied by a temperature drop. Likewise, just as a potential difference (voltage) is necessary for current to pass through an Ohmic resistance, a temperature difference is necessary for heat to pass through a thermal resistance.

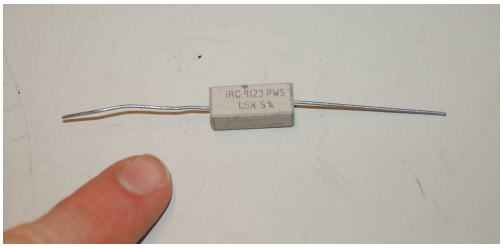
In order to keep heat-dissipating electrical and electronic components operating at safe temperatures, we must provide low-resistance thermal pathways from the device to a cooler environment. An energized component dissipating some definite amount of power (i.e. thermal energy at a defined rate) is analogous to a current source forcing a fixed electric current through a resistance: with a given flow rate, our only hope for avoiding high temperature (high voltage) is to provide a low-resistance path for that flow. This becomes more challenging in conditions of high ambient temperature, when there is less available temperature differential between the environment and the maximum device temperature to motivate heat flow. Factors influencing thermal resistance include the following:

- General: **surface area** (more A means less $R_{thermal}$)
- Conduction: **surface finish** (smooth finish optimizes solid-solid contact area, decreases $R_{thermal}$)
- Conduction: **material type** (higher thermal conductivity k decreases $R_{thermal}$)
- Convection: **forced flow** (higher fluid flow rates decrease $R_{thermal}$)
- Convection: **turbulence** (more turbulent fluid flow rates decrease $R_{thermal}$)
- Convection/Radiation: **surface finish** (rough finish magnifies fluid contact area, decreases $R_{thermal}$)
- Radiation: **emissivity** (dark color decreases $R_{thermal}$)

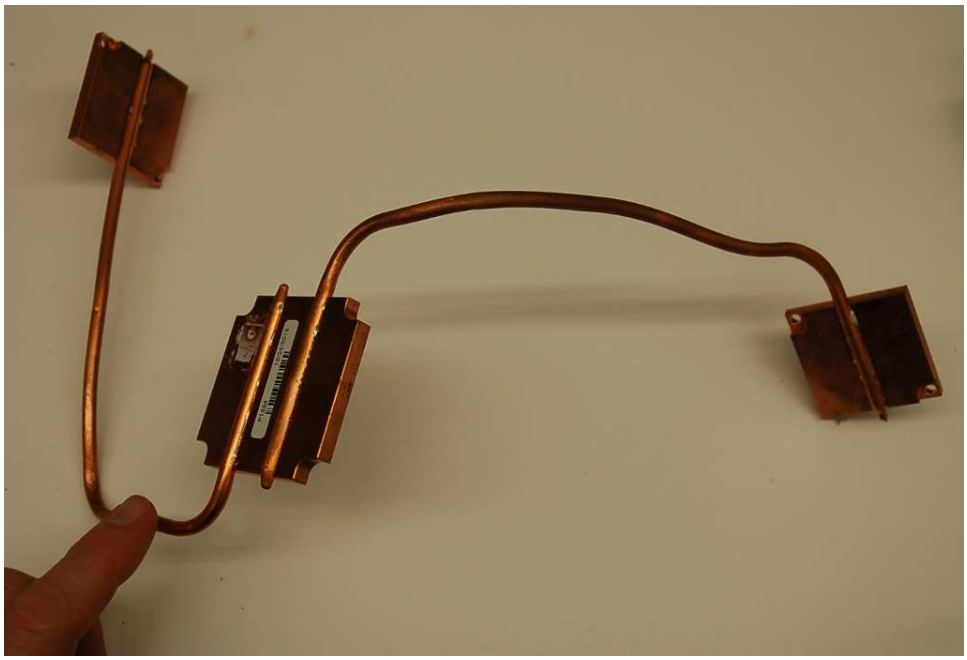
Practical applications of these factors may be seen in the following photographs. The photo shown below is of a high-power *decade box* allowing the user to select resistance values from a range provided by several fixed-value resistors. Those resistors all have high power dissipation ratings resulting from high surface area (the metal "spiral" fins helping to "wick" heat from the resistor to the surrounding air), and convection is enhanced by the use of a fan blowing air over the resistors:



The left-hand resistor shown below (5 Watt rating) uses a rough-surface material to maximize its surface area, while the right-hand resistor shown below (250 Watt rating) uses a housing made of aluminum (a metal with high thermal conductivity) complete with fins for maximizing surface area, a dark anodized finish for maximizing emissivity, and a smooth-flat bottom profile for bolting to a metallic *heat sink* to maximize conductive transfer:



In the next photograph we see a device called a *heat pipe* used to transport heat away from hot electronic devices (e.g. computer microprocessor "chips") to large-area metallic surfaces designed to dissipate that heat into the ambient air. This particular heat pipe is defective and has been removed from the electronic assembly, which explains its "mangled" appearance:



Each copper pad attaches to either a heat-sourcing device (e.g. an electronic component dissipating thermal energy) or a heat-shedding device (i.e. a "heat sink"). Inside the sealed copper tube connecting the pads is a water vapor at sub-atmospheric pressure, the pressure being low enough that the liquid water boils at modest temperatures (well below 100 degrees Celsius, the boiling point of water at sea level). When placed against a hot electronic device, any liquid droplets at that end of the tube boil into vapor which travels through the tube to reach a cooler copper pad. At the cooler pad this vapor gives up its heat and cools down to form water droplets again, which drain down the tube until they reach the hot pad once more. Thus, the convection current of liquid water and vapor conveys heat from the hotter pad to the colder pad. The amount of heat absorbed in the process of boiling and the amount of heat liberated in the process of condensation is quite large even for small amounts of water/vapor mass, which makes this convection process much more effective[4] than a similar mass of gaseous air or liquid water or solid metal convecting heat away from the electronic device.

[4] A convincing demonstration of this fact may be experienced by placing one of these "heat pipe" tubes into a cup filled with scalding hot water, adjacent to a similarly-sized solid copper rod. Within a matter of seconds the heat pipe is too hot to safely touch, while the copper rod is just slowly beginning to warm.

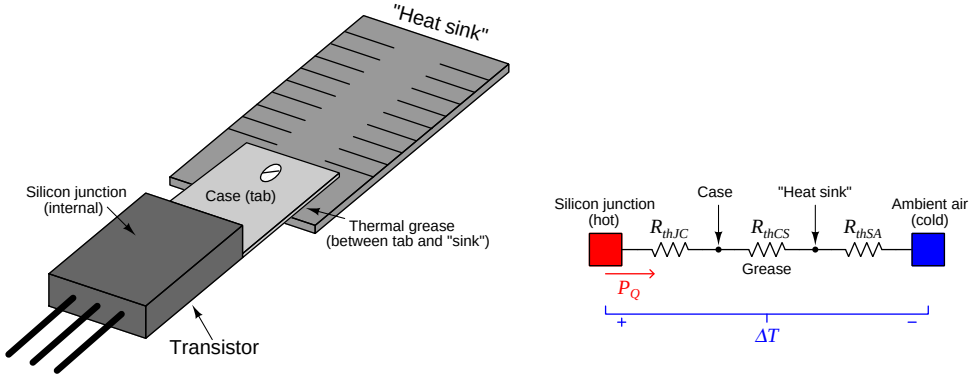
3.4 Thermal calculations

Calculations of temperature given power dissipation and thermal resistance follow the thermal equivalent of Ohm's Law:

$$R = \frac{V}{I} \qquad \text{Thermal resistance} = \frac{\Delta T}{P_{thermal}}$$

There is no special unit of measurement for thermal resistance as there is for electrical resistance (the Ohm), so you will generally find $R_{thermal}$ specified in the compound unit of *degrees Celsius per Watt* or *Kelvin per Watt*[5].

When heat must pass through multiple thermal resistances to go from source to sink, those resistances *add* to make a larger total resistance, just like series electrical resistances add. A good example of this is the thermal path for a power transistor with an attached "heat sink"[6]: inside the transistor case is the silicon junction where the heat originates, but there is thermal resistance between that junction and the outer surface of the transistor's case. Then, there is a small amount of thermal resistance between the case and the metal "heat sink" structure we attach to it. Finally, there is thermal resistance in the "heat sink's" ability to shed heat to ambient air:



[5]The only difference between the Celsius temperature scale and the Kelvin temperature scale is an offset of 273.15: the Kelvin starts at 0 K = absolute zero (−273.15 °C), while the Celsius scale starts at 0 °C = freezing point of water (273.15 K). Incrementally, a rise of one degree Celsius is exactly equal to a rise of one Kelvin, and so it makes no difference at all whether we express thermal resistance as °C/W or K/W.

[6]The use of the term *heat sink* to refer to a metal structure affixed to the case of an electronic component is thermodynamically incorrect. The true *sink* is the surrounding environment, while the metal finned structure is just a conduit for heat flow to that surrounding environment.

Supposing our transistor must dissipate 10 Watts of thermal power while keeping its junction temperature to a maximum of 110 ^{o}C in an ambient temperature of 30 ^{o}C, for the following thermal resistances:

- R_{thJC} (junction-to-case thermal resistance) = 6.4 ^{o}C/W
- R_{thCS} (case-to-sink grease thermal resistance) = 0.5 ^{o}C/W
- R_{thSA} (sink-to-ambient thermal resistance) = *unknown*

Dividing the temperature differential by power, we obtain a total thermal resistance value:

$$R_{thTOTAL} = \frac{\Delta T}{P} = \frac{110^o\text{C} - 30^o\text{C}}{10\text{ W}} = 8^o\text{C/W}$$

Next, solving for the thermal resistance of the "heat sink":

$$R_{thTOTAL} = R_{thJC} + R_{thCS} + R_{thSA}$$

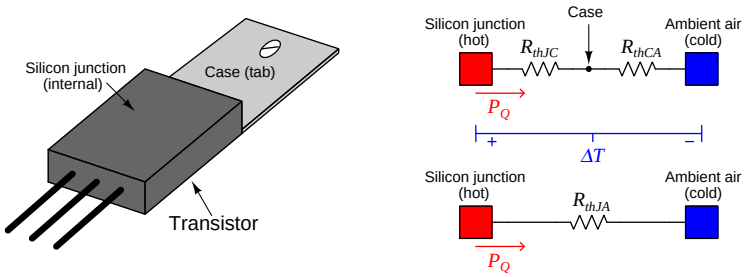
$$R_{thSA} = R_{thTOTAL} - (R_{thJC} + R_{thCS})$$

$$R_{thSA} = 8^o\text{C/W} - (6.4^o\text{C/W} + 0.5^o\text{C/W})$$

$$R_{thSA} = 1.1^o\text{C/W}$$

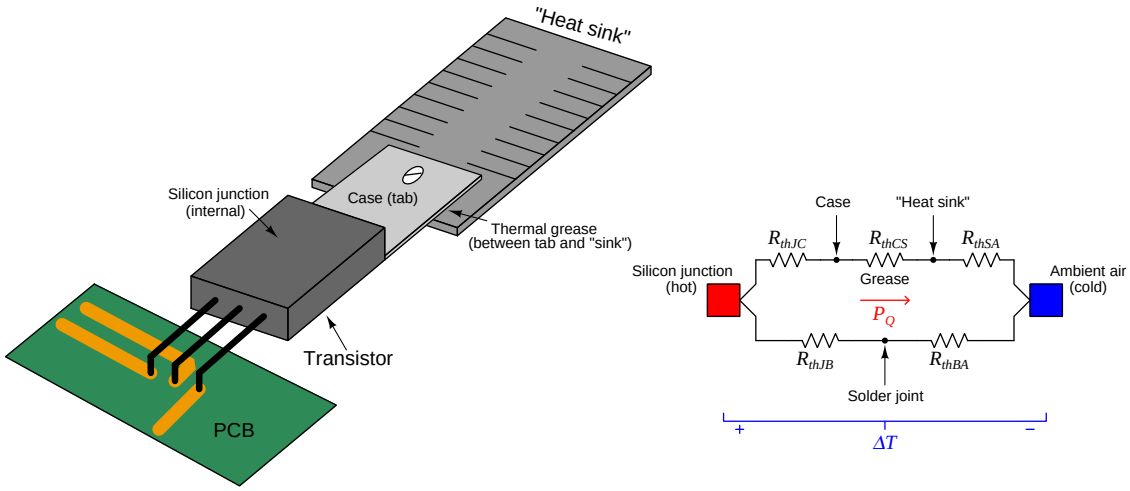
Therefore, the "heat sink" we attach this transistor to must have a thermal resistance of 1.1 ^{o}C/W or less in order to maintain the transistor's junction temperature at or below 110 ^{o}C in 30 ^{o}C ambient conditions. How we achieve a thermal resistance of 1.1 ^{o}C/W or less is a more complicated matter than applying a simple "Ohm's Law" equation because it depends on factors such as material composition, surface area, finish, and air velocity. For this reason, manufacturers of "heat sink" devices typically provide software or web-based calculator applications predicting thermal resistance based on material type, dimensions, and forced air velocities.

If we omit the "heat sink" and operate the transistor by itself in open air, the thermal resistance from junction-to-case will remain the same, but the thermal resistance from case to ambient will be far greater because the metal case tab on the transistor has little surface area to radiate or convect heat. Many manufacturers advertise a thermal resistance they call "junction to ambient" or R_{thJA} which is the "series" thermal combination of $R_{thJC} + R_{thCA}$:



Typical junction-to-ambient total thermal resistances for a bare TO-220 style power semiconductor range from about 60 to 70 ^{o}C/W. If we attempted to make this transistor dissipate 10 Watts of power with no "heat sink" attached, its junction temperature would soar between 600 and 700 degrees Celsius hotter than ambient, most certainly destroying it!

Both of the previous examples are simplified, and represent "heat circuits" with greater thermal resistance than we would actually have with the component soldered into a printed circuit board (PCB). The metal terminals (pins) of the device also function as conduits for heat flow, and the copper traces and pads on a PCB function as heat sinks. In order to create a more comprehensive thermal model, we must show the metal terminals as part of a *parallel* "heat circuit" as shown below:



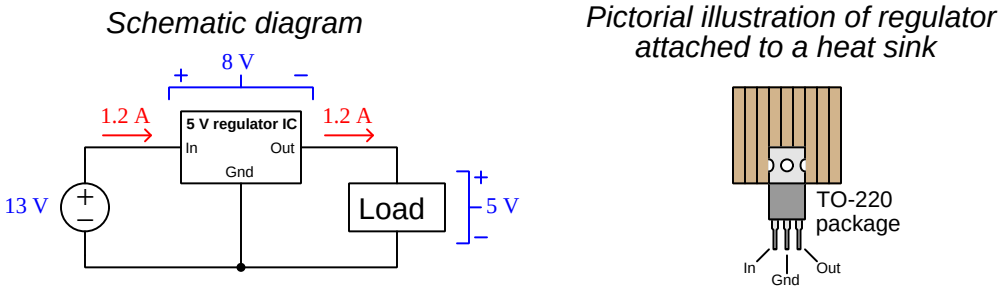
In addition to the junction-to-case thermal resistance (R_{thJC}), the case-to-sink thermal resistance (R_{thCS}), and the sink-to-ambient thermal resistance (R_{thSA}) explored previously, we now have a parallel path for heat flow out of the device junction through the thermal resistance of the metal terminals (junction-to-board R_{thJB}) and the thermal resistance of the PCB traces to surrounding air (board-to-ambient R_{thBA}). Just like paralleled electrical resistances, paralleled thermal resistances diminish to create a lesser total thermal resistance than either of the pathways alone. For the example shown above:

$$R_{thTOTAL} = \frac{1}{\frac{1}{R_{thJC}+R_{thCS}+R_{thSA}} + \frac{1}{R_{thJB}+R_{thBA}}}$$

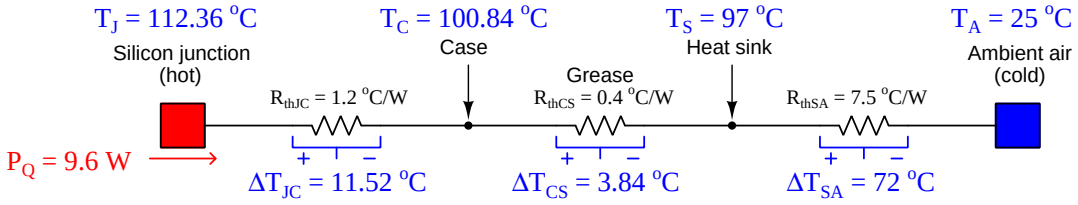
For many surface-mount devices (SMDs) lacking attachment points for traditional heat sinks, the soldered connections to the printed circuit board actually constitute the dominant pathway for heat dissipation from the devices' internal junctions. PCB designers often specify large copper "pour" areas on the board without a soldermask layer in order to allow those bare-metal areas to be as effective as possible in radiating and convecting heat to the surrounding environment.

3.5 Thermal calculation scenarios

Thermal calculations are made more comprehensible by example. The following scenario shows the temperatures resulting from a transistor-based three terminal linear voltage regulator IC passing 1.2 Amperes of current while dropping 8 Volts (i.e. dissipating 9.6 Watts of power across its internal power transistors) between source and load, attached firmly to a heat sink with a thermal resistance of 7.5 ^{o}C/W with a 0.4 ^{o}C/W case-to-sink thermal resistance. The voltage regulator IC itself has a junction-to-case thermal resistance of 1.2 ^{o}C/W:

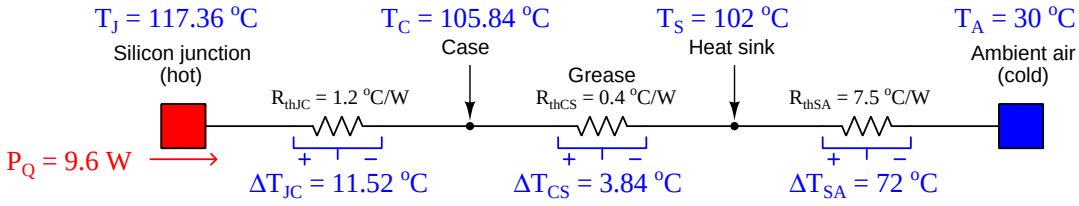


A thermal diagram (below) shows the temperature differentials across each of the three thermal resistances given the thermal power of 9.6 Watts shed by the voltage regulator, as well as the temperatures of the device junction, device case, and the heat sink for a given ambient air temperature of 25 ^{o}C:



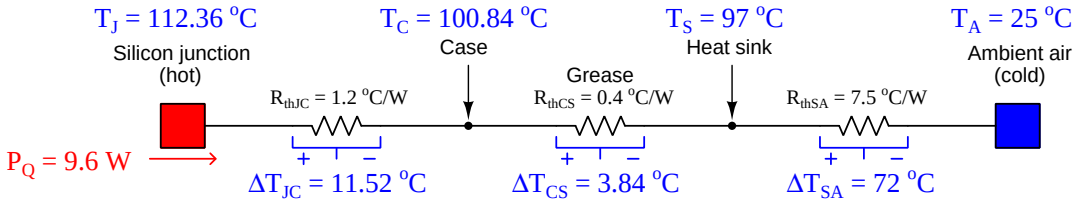
If we re-do the calculations for an ambient temperature of 30 ^{o}C at the same electrical conditions for the regulator (dropping from 13 Volts source to 5 Volts load at 1.2 Amperes), we see each of the point temperatures rise by 5 ^{o}C while the temperature differentials remain the same:

With higher ambient temperature:

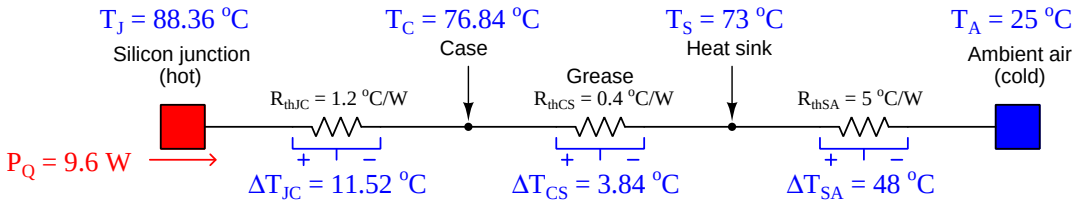


Now, compare the original scenario (at 25 ^{o}C ambient temperature and 9.6 Watts power dissipation) against one where the heat sink has been increased in surface area to have a lesser thermal resistance of 5 ^{o}C/W instead of 7.5 ^{o}C/W. This means the new heat sink is able to shed more heat for a given temperature differential, or exhibit less temperature differential for the same heat flow:

Original scenario:



With larger heat sink:



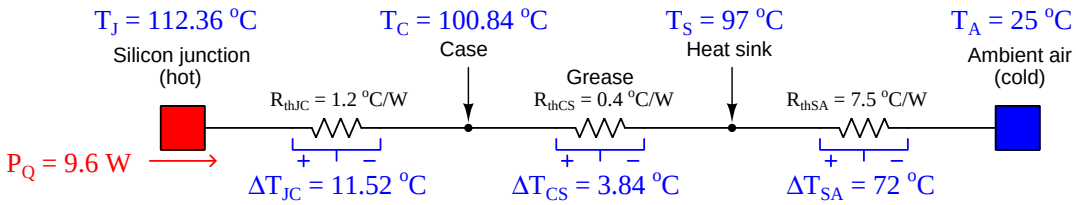
As the example shows, the more effective heat sink has a lesser temperature differential than before, and this has the cascading effect of reducing point temperatures along the entire thermal pathway given the same ambient temperature as before.

An alternative method of decreasing heat sink thermal resistance (R_{thSA}) would be to install a cooling fan to force air flow past the original heat sink. Forced air convection will remove heat at a faster rate from any given surface area than natural convection alone. Of course, adding a cooling fan increases energy usage for the system and also introduces a new point of failure[7] which may be a concern for high-reliability systems.

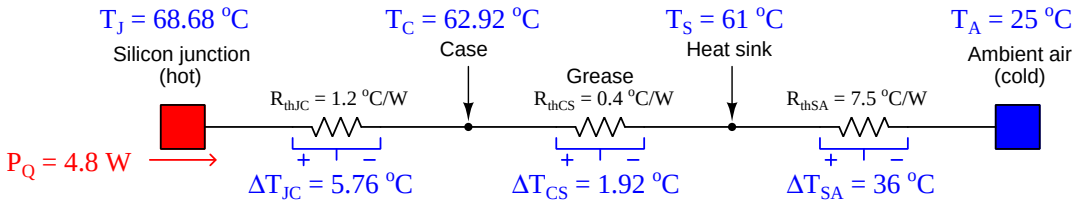
[7] As a general rule, components having moving parts such as air fans are more prone to mechanical failure than components with no moving parts. This is why high-reliability computer systems lack cooling fans and instead have larger-than-normal heat sinks to passively shed heat from their semiconductor components.

Now, compare the original scenario (at 25 ^{o}C ambient temperature) against one where the supply voltage decreases from 13 Volts to 9 Volts. This means the voltage regulator need only drop 4 Volts from source to load instead of 8 Volts, and at the same load current of 1.2 Amperes will dissipate just half the amount of power it did previously (4.8 Watts of power versus the original 9.6 Watts):

Original scenario:



With less regulator voltage drop:



As we can see here, this reduced power dissipation means only half the rate of thermal energy must pass through the case and heat sink to dissipate into the ambient environment, and this means for the same thermal resistances as the original scenario each of those resistances exhibits just half the temperature differential as before.

A more comprehensive thermal analysis of this voltage regulator would also include thermal dissipation through the device's terminals to the printed circuit board's copper traces (and then to air), as well as heat dissipation directly from the other side of the device case directly to ambient air, but these thermal pathways are significantly more resistive than the one from case to heat sink to air, and so this simple analysis of "series" thermal resistances will provide us with a conservative[8] estimate of device junction temperature for different scenarios.

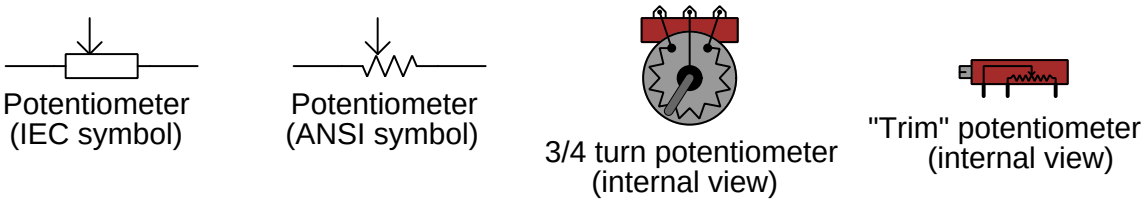
[8] In other words, a more comprehensive thermal analysis with additional heat pathways would result in *lower* device junction temperatures than what we calculated here using only one thermal pathway. Stated in practical terms, *the real device will run cooler than our simplified estimates show.* Conservative estimates such as this are a good engineering practice, in addition to saving calculation work.

3.6 Thermal de-rating

The actual heat-dissipation rating of an electrical or electronic component may be less than its maximum rating if certain conditions impede the transfer of thermal energy away from the device. For example, a resistor with a power rating of 5 Watts may in fact overheat if dissipating 5 Watts of power while covered in dust, because the layer of dust on the resistor's surface adds another thermal resistance between the resistive element and the surrounding air. The same is true if a resistor must operate within a vacuum environment (e.g. in the de-pressurized environment of a space probe) where there is no air to convect thermal energy away from it.

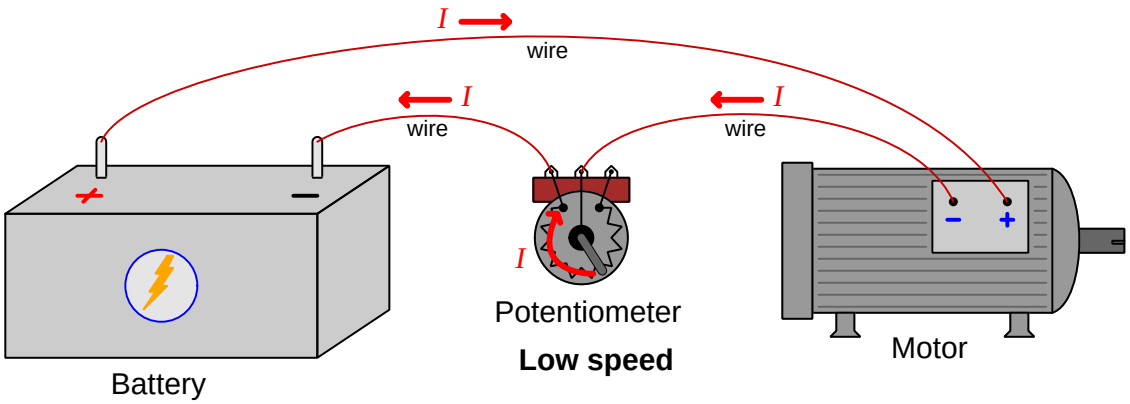
Extremely high ambient temperature conditions also act to thermally de-rate components. If a heat-dissipating component relies on the difference of temperature between it and the surrounding environment (ΔT) to shed thermal energy, any increase in ambient temperature means less ΔT at the device's maximum operating temperature, and therefore less capacity to shed heat. Electric motors used in hot industrial environments are a good example of this, where their power output must be "de-rated" based on ambient temperature; e.g. a 10 horsepower motor may only be capable of continuously outputting 8 horsepower's worth of mechanical power in an unusually hot atmosphere.

An interesting and practical example of thermal de-rating is when a potentiometer is used as a *rheostat* (variable resistor). Examining a potentiometer, we see that a semi-circular strip of resistive material has a contact point at each far end, as well as a movable contact called the *wiper*:

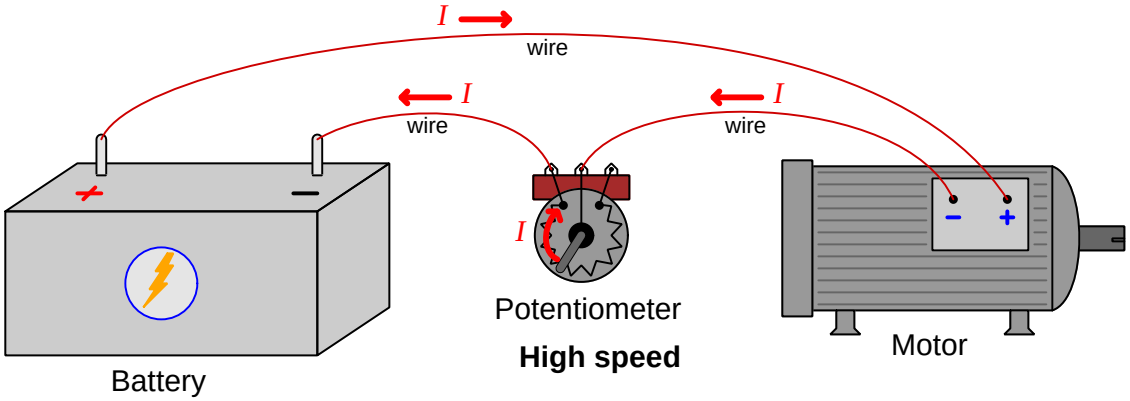


The resistive strip inside of a potentiometer is much like any other resistor, in that it dissipates energy in the form of heat with the passage of electric current (Joule's Law, $P = I^2R$), and this heat must leave the resistor in order to avoid overheating. What is unique about a potentiometer, though, is that not only does its electrical resistance vary as the wiper is moved, but also the amount of surface area available to dissipate heat.

Consider an example circuit where a potentiometer serves to limit current to a load such as an electric motor, allowing speed control by turning the potentiometer's shaft to re-position the wiper:



Turning the potentiometer shaft clockwise moves the wiper to a new position where there is less length of resistive strip between the connected terminals. This, of course, results in less circuit resistance, which results in more current (assuming constant battery voltage) and higher motor speed:



What is less apparent is that by re-positioning the wiper for a lower-resistance setting, we have also de-rated the potentiometer's maximum power dissipation limit. Now there is less of the resistive strip dissipating heat, therefore less surface area operating at an elevated temperature, and therefore less ability to shed heat[9]. This de-rating is approximately proportional to shaft position expressed as a percentage of maximum resistance. A 50 Ohm potentiometer with a full power rating of 1 Watt, for example, would exhibit 25 Ohms at its half-way position and a de-rated power limit of only 0.5 Watt. At the 10% position its resistance would be 5 Ohms and its power limit only 0.1 Watt.

[9] We see here that a decrease in electrical resistance between the two terminals of the potentiometer actually results in an *increase in thermal resistance*.

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 read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

4.1 Conceptual reasoning

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

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

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

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

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

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

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, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

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

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

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

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

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

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

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

Temperature

Heat

Absolute zero

Second Law of Thermodynamics

Voltage

Current

Resistance

Efficiency

Thermal conduction

Thermal convection

Thermal radiation

Thermal resistance

Ohm's Law

Joule's Law

Celsius

Kelvin

Series connection

4.1.3 Thin versus thick heat sinks

Two students are arguing about how to fabricate the best "heat sink" out of a given mass of metal. One student thinks it best to fabricate the "heat sink" from a piece of thin sheet metal, while the other student prefers using a thick piece of metal bar stock weighing the same.

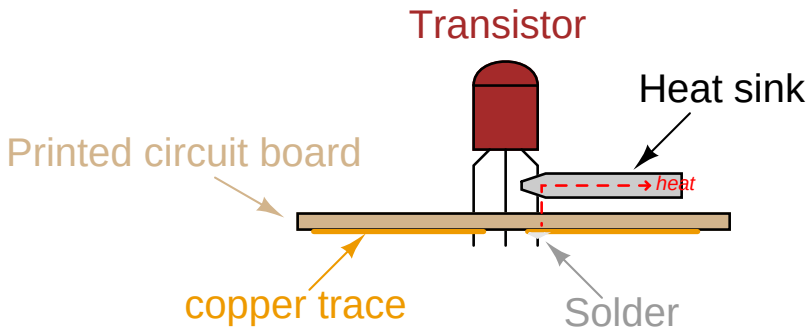
Which student would you agree with, and why?

Challenges

- Identify factors other than thickness influencing the effectiveness of the "heat sink" each student would make.

4.1.4 Heat sink for soldering

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 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 "impromptu" heat sinks out of commonly available tools and/or objects?

Challenges

- Identify at least one passive (i.e. non-semiconductor) type of component that might also be heat-sensitive.

4.1.5 Satellite electronics

Electronic assemblies intended for use aboard satellites and space probes must be designed with different thermal conditions in mind than terrestrial assemblies. Identify some of these differences, and explain their significance.

Challenges

- Could the metal frame of the satellite be used as a heat sink?

4.1.6 Tubes versus transistors

In the April 1998 edition of *IEEE Spectrum* magazine, an article written by Robert Symons of Litton Electron Devices describes the continued use of tube-based oscillators and amplifiers for high-power radar systems in a world where solid-state devices (transistors) made of silicon wafers have all but replaced vacuum tubes made of glass and metal for most consumer and industrial applications.

Explain what the author means with the following paragraphs sampled from page 56 of that magazine, specifically how it applies to tubes versus transistors as power-amplifying devices:

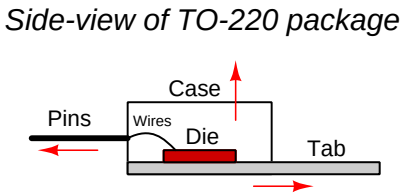
> Solid-state devices cannot replace tubes in high-power radar, countermeasures equipment, or communications equipment without the user paying a very high price indeed. A good transmitter must be a good heat-exchanger. Some high-power solid-state equipment is therefore so heavy it could keep warplanes from flying and make warships capsize during sharp turns if located too far above the water line.
>
> In any high-power electronic system, heat must be dissipated, and that can only be done if the equipment is hotter than the environment. Of course, coolant velocity, and to a lesser extent, coolant channel shape are fairly important variables. But more important, the amount of heat that can be transferred is proportional to the area of the heat transfer surface and the difference between the temperature of that surface and the coolant, be it air, water, or any other fluid. The hotter the equipment – that is, the greater the difference between it and its environment – the smaller and lighter it can be.

Challenges

- Identify manufacturers of *klystron* and other RF power tubes today, and what the continued applications are for these devices.

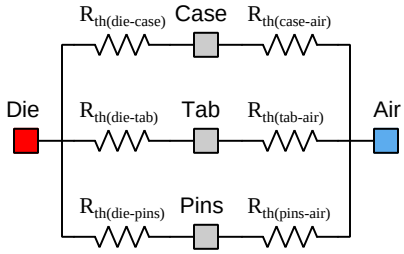
4.1.7 Thermal resistance model

A typical power electronic device such as a transistor in a TO-220 package consists of a silicon wafer (called a *die*) affixed to a metal tab, encased in plastic. A "cutaway" side view of a typical device appears here:



The die has three different thermal paths to dissipate heat: through the tab, through the front of the case, and through the pins.

A resistor-model diagram showing the thermal resistances of these paths represents the degree to which each pathway impedes the flow of heat, adding locations as nodes between the resistances:



What would change in this thermal model by adding a heat sink to the transistor's tab?

Challenges

- Why is $R_{th(pin-air)}$ an unrealistic parameter for a real transistor installed in a printed circuit board?

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 cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

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

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

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 ($m^3/kg\text{-}s^2$)

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

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

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

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

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

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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.2.3 Transistor without a heat sink

Suppose we have a power MOSFET with no "heat sink" device attached, and it has a maximum junction temperature of 150 ^{o}C. Assuming a thermal resistance of 65 ^{o}C/W for the transistor by itself and an ambient temperature of 20 ^{o}C, how much power may this transistor safely dissipate?

Assuming the voltage drop between drain and source terminals on this MOSFET is 14 Volts, how much drain current may it safely conduct?

Challenges

- Besides attaching a "heat sink" device, what else could be done to improve its thermal performance?

4.2.4 Heat sink specification

Locate the website of a "heat sink" manufacturer providing a calculator application for sizing. Experiment with different materials, dimensions, and air velocities to obtain a range of thermal resistance values.

Challenges

- Which metal – aluminum or copper – yields the best thermal resistance?
- Which of the metal options yields the worst thermal resistance?

4.2.5 Heat sink requirements

Suppose a MOSFET dropping 250 milliVolts between drain and source terminals while carrying 10 Amperes of current needs to maintain a junction temperature less than 110 ^{o}C in ambient air of 25 ^{o}C, with a junction-to-case thermal resistance of 30 ^{o}C/W. Determine an appropriate heat sink thermal resistance to keep it cool.

Suppose a silicon rectifying diode must pass 5 Amperes of current while not exceeding a junction temperature of 105 ^{o}C. If the ambient air temperature may range as low as -10 ^{o}C and $+35$ ^{o}C where this diode is installed, and its thermal resistance is 15 ^{o}C/W, determine an appropriate thermal resistance for the heat sink to keep the diode cool.

A bipolar junction transistor operating in saturated mode (as an "on" switch) will carry 15 Amperes of continuous current while operating in ambient temperature conditions ranging from 0 ^{o}C to 40 ^{o}C. Its junction-to-case thermal resistance is 12 ^{o}C/W, while its maximum junction temperature is 140 ^{o}C and its beta value is 30. Determine an appropriate heat sink thermal resistance to keep the transistor cool.

Challenges

- A common error is to specify the necessary heat sink's thermal resistance at that value resulting in the device operating exactly at its maximum junction temperature. Explain what is wrong with this approach, and how to better specify heat sink thermal resistance.

4.2.6 Infinite heat sink

Two students are debating a question: could you theoretically dissipate an unlimited amount of thermal power through a given transistor if it were bolted to an infinitely-large heat sink guaranteed to always be at room temperature?

Answer this question, and give a numerical example to prove your point.

Challenges

- How could you design a heat sink that would *approach* the performance of one that is infinitely large.

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 Find the mistake(s)

Identify the error(s) in this calculation of allowable voltage drop for a power component:

Given conditions:

- Maximum junction temperature = 140 ^{o}C
- Ambient temperature = 30 ^{o}C
- R_{thJC} (junction-to-case) = 7.3 ^{o}C/W
- R_{thCS} (case-to-sink grease) = 0.6 ^{o}C/W
- R_{thSA} (sink-to-ambient) = 4.8 ^{o}C/W
- Device current = 700 mA

1. $140 - 30 = 110$
2. $7.3 + 0.6 + 4.8 = 12.7$
3. $110/12.7 = 8.661$
4. $8.661/700 = 0.01237$
5. Therefore, the device must drop at least 0.01237 Volts

Challenges

- Identify at least one factor that could be changed to permit the device to dissipate more power and not overheat.

Appendix A

Problem-Solving Strategies

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

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

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

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

Appendix B

Instructional philosophy

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

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

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

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

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

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

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

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

References

"IRF9610, SiHF9610 Power MOSFET datasheet", document number 91000, Vishay InterTechnology Incorporated, 8 February 2017.

Symons, Robert S., "Tubes, Still Vital After All These Years", IEEE Spectrum magazine, April 1998.

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.

8 April 2026 – typographical error corrections courtesy of Wyatt Gleason.

30 October 2024 – corrected a typographical error in the "Thermal calculation scenarios" Tutorial section where I stated 9 Watts of power dissipation rather than 9.6 Watts. Also corrected another typographical error where an illustration heading read "With larger heat sink:" rather than "With less regulator voltage drop:" as it should have. Also added a new illustration heading where one was lacking, for the scenario where ambient temperature rose from 25 ^{o}C to 30 ^{o}C, and made other minor edits to the text.

17-18 October 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors. Also added a new Quantitative Reasoning question on heat sink size calculations ("Heat sink requirements").

31 August 2024 – added a new Tutorial section demonstrating thermal calculation scenarios.

4 April 2024 – added content to the Tutorial discussing parallel heat paths.

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

17 November 2021 – added "Example: 7085 power dissipation" to the Case Tutorial chapter.

3 November 2021 – added illustrations and text explaining how to calculate thermal conditions for a power device with no heat sink attached.

29 May 2021 – added photograph of the PCB matching the thermal image showing an overheating

microcontroller.

22 May 2021 – added another subsection to the "Example: thermal imaging camera photos" section of the Case Tutorial chapter, this one showing a PCB with overheating components.

9 May 2021 – commented out or deleted empty chapters.

9 April 2021 – added Case Tutorial example showing calculations of device junction temperature at different currents and ambient temperatures.

30 March 2021 – added efficiency equation to Tutorial, and also added a Quantitative Reasoning question ("Infinite heat sink").

22 March 2021 – added more digits to Boltzmann's constant, and clarified that Kelvin is 273.15 more than Celsius.

3 November 2020 – corrected a typo in the "Find the mistake(s)" question where the ambient temperature should have been 30 degrees but was incorrectly stated (in the given conditions) as 35 degrees. Also, added another Conceptual question.

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

26 September 2020 – added Tutorial section on thermal de-rating, using potentiometers as an example. Also added Case Tutorial chapter with thermal imaging examples.

5 September 2020 – added photograph of a heat pipe.

18 June 2020 – added content to Tutorial and Questions chapters.

17 June 2020 – document first created.

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