**Modular Electronics Learning (ModEL) Project**

**Signal Coupling and Noise**

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Chapter 1

Introduction

An often severe and generally poorly-understood problem in electronic circuits is unwanted coupling between conductors carrying different signals or power. The electric and/or magnetic fields generated by one conductor may induce voltages and/or currents on one or more adjacent conductors, that interference commonly called noise. This module explores the foundational concepts underlying these phenomena and also discusses practical mitigations.

Important concepts related to signal coupling and noise include capacitance, inductance, electric fields, magnetic fields, rates of change, filter networks, harmonic frequencies, fundamental frequency, mutual inductance, analog versus digital signaling, digital logic levels, shielding, ground loops, common-mode voltage, differential signaling, and magnetic permeability.

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

• How might an experiment be designed and conducted to prove the existence of noise generated within a circuit component? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?

• How might an experiment be designed and conducted to demonstrate the effective shielding from electric fields? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?

• How might an experiment be designed and conducted to demonstrate the effective shielding from magnetic fields? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?

• What is a rate of change?

• How do rates of change relate to the phenomena of capacitance and inductance?

• How do electric and magnetic fields differ from one another?

• What does it mean to say that a signal contains “harmonic” frequencies?
• What are some practical ways to minimize signal coupling between different conductors?
• What do the terms “victim” and “aggressor” refer to in this context?
• Which type of signal, analog or digital, typically tolerates greater noise?
• How may electric fields be re-directed away from conductors?
• How may magnetic fields be re-directed away from conductors?
• What purpose does the “shield” conductor serve in a cable?
• What role does frequency play in signal coupling between conductors?
• Where should a cable’s shield conductor be bonded to Earth?
• What purpose do “twisted” pairs of conductors serve in a cable?
• What is “common-mode” voltage for a signal?
• How does differential signaling work to avoid noise problems?
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: capacitive coupling within cable

Capacitance varies inversely with separation distance, which means there will be more capacitance between two conductors spaced closer together, all other factors being equal. We may demonstrate this by using two conductors within a common cable, held in close proximity to each other within the confines of that cable.

Pictorial diagram:

Equivalent schematic diagram:

Interference voltage indicated by voltmeter will increase as source voltage increases, and/or as source frequency increases. In this circuit, load current is irrelevant to the signal coupling, and so for a demonstration you are welcome to use any load suitable for the AC source. Electric fields are proportional to voltage, and so it is voltage that matters.
Re-drawn another way, we may look at the cable’s parasitic capacitance as a capacitive reactance \((X_C)\) forming an AC voltage divider with the voltmeter’s internal resistance:

Since the internal (“insertion”) resistance of a high-quality digital voltmeter is typically in the tens of millions of Ohms, even a very small amount of capacitance translating into a capacitive reactance in the millions of Ohms will present the voltmeter with a substantial percentage of the source’s voltage.
2.2 Example: inductive coupling within cable

Magnetic coupling varies inversely with separation distance, which means there will be more mutual inductance between two parallel conductors spaced closer together, all other factors being equal. We may demonstrate this by using two conductors within a common cable, held in close proximity to each other within the confines of that cable.

Pictorial diagram:

![Pictorial diagram of inductive coupling within cable]

Equivalent schematic diagram:

![Equivalent schematic diagram of inductive coupling within cable]

Interference voltage indicated by voltmeter will increase as source current increases, and/or as source frequency increases. In order to generate a strong enough interference signal to register on an AC voltmeter, I suggest using a power cable (e.g. SO-type power cord) of substantial length, as well as a load drawing at least several Amperes of AC current. Magnetic fields are proportional to current and so it is load current that matters in this demonstration. In one instance a student built this circuit using 2-conductor SO cable 50 feet in length, and a hot-air gun drawing in excess of 12
2.2. EXAMPLE: INDUCTIVE COUPLING WITHIN CABLE

Amperes from a 120 VAC source, and was able to measure approximately 0.7 Volts RMS along the length of the conductor alongside the power conductor.

If we run both load conductors through the same cable, however, their magnetic fields tend to cancel out because at any given moment in time the directions of current through them will be equal in magnitude and opposite in direction. This means at any given time the individual wires’ magnetic fields will be equally strong but directly opposed to each other. This results in a net magnetic field that is nearly zero, and therefore little or no coupled signal detectable by the voltmeter:

**Pictorial diagram:**

![Pictorial diagram](image)

**Equivalent schematic diagram:**

![Equivalent schematic diagram](image)
Chapter 3

Tutorial

Simply defined, *noise* is any stimulus found in conjunction with a signal that itself carries no useful information and tends to obscure the signal of interest. In colloquial terms, noise is generally associated with audible sounds that make it more challenging to hear or interpret sounds we are interested in such as speech or music. However, in electrical circuit theory “noise” consists of spurious voltages and/or currents interfering with other voltages and/or currents bearing useful information. The general term “noise” applies to any circuit, even those unassociated with audio signals.

*Frequency* is a very important parameter of noise, and the fact that many noise sources are random rather than periodic in nature means the noise often spans a broad range of frequencies. Although it may seem strange at first, especially if your definition of “noise” is anchored to audible experience, but it is true that noise may take the form of an extremely low frequency or band of frequencies. If an adjacent AC power conductor causes an audio amplifier system to reproduce a constant “hum” due to the AC power circuit’s frequency, we would certainly recognize that as a form of noise. However, another form of noise in this same audio amplifier system might be alterations in the circuit’s gain (the amount it amplifies) caused by changes in room temperature, even though room temperature may require minutes or even hours of time to complete a single cycle. Literally *any* form of unwanted variation in a signal, regardless of how rapid or slow, is a form of noise.

Noise sources may be external to our circuit, or internal to it. External sources of noise include nearby circuits and environmental factors such as sound, temperature, radiation, etc. Internal sources consist of phenomena within the components themselves generating unwanted fluctuations in the signal of interest. External and internal noise sources will be treated separately in this Tutorial.
# 3.1 Signal coupling and cable separation

If sets of wires lie too close to one another, electrical signals may “couple” from one wire (or set of wires) to the other(s). This can be especially detrimental to signal integrity when the coupling occurs between AC power conductors and low-voltage signal wiring, but it also occurs between sets of signal wires. Terms commonly used to describe such “crosstalk” is to call the conductor generating the interference the *aggressor* and the conductor receiving the interference the *victim*.

Two mechanisms of electrical “coupling” exist: inductive and capacitive. Both are capable of “coupling” signals from one conductor to another, and they usually exist in tandem.

- Inductance is a property intrinsic to any conductor, whereby energy is stored in the magnetic field formed by current through the wire. Mutual inductance existing between parallel wires forms another “bridge” whereby an AC current through one wire is able to induce an AC voltage along the length of another wire. Specifically, the amount of voltage induced across the length of the victim conductor is proportional to the mutual inductance between the victim and aggressor conductors as well as the rate-of-change of current through the aggressor conductor.

- Capacitance is a property intrinsic to any pair of conductors separated by a dielectric (an insulating substance), whereby energy is stored in the electric field formed by voltage between the wires. The natural capacitance existing between mutually insulated wires forms a “bridge” for AC signals to cross between those wires. Specifically, the amount of current induced in the victim conductor is proportional to the capacitance and to the rate-of-change of voltage between the victim and aggressor conductors.

The fundamental “Ohm’s Law” formulae for inductance and capacitance is central to the phenomenon of signal coupling between conductors:

\[ V = L \frac{dI}{dt} \quad I = C \frac{dV}{dt} \]

For the particular case of coupling between conductors, the inductive “Ohm’s Law” formula could be written more precisely as \( V_{\text{victim}} = L_M \frac{dI_{\text{aggressor}}}{dt} \), with \( L_M \) representing mutual inductance.
These “Ohm’s Law” formulae relate voltage and current to rate-of-change of the other. That is, voltage across an inductance is proportional to the speed at which current rises or falls; current through a capacitance is proportional to the speed at which voltage rises or falls. These rates of change, represented mathematically as $\frac{dI}{dt}$ and $\frac{dV}{dt}$, respectively, are distinct from the instantaneous values of current and voltage even though they are related. An analogy is the relationship between the speed of a vehicle and its distance from some starting point: a vehicle’s speed in kilometers per hour is related to, but not the same as, its distance away from a starting point in kilometers.

To clarify the concept of a rate-of-change, we will examine a screenshot from an oscilloscope measuring a sawtooth-shaped voltage waveform. The annotations overlaid on the photograph after it was captured on camera from the display of an oscilloscope:

Here the yellow line follows the downward slope of the voltage waveform, while the red lines mark a time interval along that slope and the blue lines mark the voltage fall over that time interval. With the values shown here, −10 milliVolts of fall over 5 milliseconds of time, the estimated $\frac{dV}{dt}$ for this signal’s downward slope is −2 Volts per second. This value of −2 Volts per second is the rate-of-change (or “speed”) of the voltage over time, not the amount of voltage at some particular point in time. Note how the amplitude of this sawtooth waveform is only about 10 mV peak-to-peak, yet it falls at a rate of approximately −2000 milliVolts per second. The rising slope of this sawtooth waveform is steeper yet, somewhere in the neighborhood of +10 Volts per second².

Interestingly, the downward “glitch” seen near the lower-right area of this oscillograph exhibits much larger rates-of-change than the relatively gentle slopes. Even though the vertical height of this transient is not very large, its extremely short timespan means its leading edge will have a large rate-of-change.

²If you project the rising edge over one major division of time (2 ms) you see that it rises approximately 20 mV. 20 mV divided by 2 ms is 10 Volts per second.
negative slope \((-\frac{dV}{dt})\) and its trailing edge will have a large positive slope \( (+\frac{dV}{dt}) \), possibly hundreds or even thousands of Volts per second each.

Since coupling between adjacent conductors happens due to shared inductance and/or capacitance, and the “Ohm’s Law” formulae for both \(L\) and \(C\) predict coupling proportional to rates-of-change, the rates-of-change of current and of voltage are major factors for signal coupling. In other words, how quickly currents and voltages rise or fall over time is a more significant predictor of signal coupling than their absolute values at any given time.

Inductive (magnetic) coupling between an AC power conductor and a DC signal conductor is shown in the following diagram:

![Diagram of inductive coupling](image-url)

The magnitude of the noise induced within the “victim” (DC) signal circuit by the “aggressor” (AC) power circuit is proportional to the amount of mutual inductance \((L_M)\) existing between the two conductors and also the “speed” that the aggressor current increases or decreases \((\frac{dI}{dt})\). This rate-of-change over time for any AC current is a function of both peak amplitude and frequency: higher peak value results in greater \(\frac{dI}{dt}\) and therefore more coupled noise; higher frequency also results in greater \(\frac{dI}{dt}\).
3.1. SIGNAL COUPLING AND CABLE SEPARATION

Capacitive (electric) coupling between an AC power conductor and a DC signal conductor is shown in the following diagram:

\[ V_{\text{difference}} \]

The magnitude of the noise induced within the “victim” (DC) signal circuit by the “aggressor” (AC) power circuit is proportional to the amount of capacitance \( C \) existing between the two conductors and also the “speed” that the aggressor voltage increases or decreases between the two \( \left( \frac{dV}{dt} \right) \). This rate-of-change over time for any AC voltage is a function of both peak amplitude and frequency: higher peak value results in greater \( \frac{dV}{dt} \) and therefore more coupled noise; higher frequency also results in greater \( \frac{dV}{dt} \).

Since both types of coupling favor higher-frequency aggressor voltages/currents, we may think of these natural phenomena as functioning like high-pass filters between the aggressor and victim circuits. Aggressor circuits carrying non-sinusoidal and pulse waveforms are particularly problematic because these embody a wide range of frequencies as described by Fourier analysis\(^3\): the fundamental frequency and multiple harmonics whose frequencies are multiples of the fundamental.

A practical example of this is the greater interference from AC power conductors carrying voltages and currents rich in harmonics, as opposed to purely sinusoidal AC with just one (fundamental) frequency. Electronic power-control devices such as variable-frequency motor drives (VFDs) are a good case-in-point because they function by rapidly pulsing power to loads, and as such they output power having a broad spectrum of frequencies. The higher of these frequencies couple well to nearby signal conductors, causing interference problems if steps are not taken to mitigate the coupling. 50 Hz or 60 Hz fundamental noise simply does not “couple” as effectively to victim circuits than the 11th harmonic (550 Hz or 660 Hz), the 12th harmonic (600 Hz or 720 Hz), etc.

\(^3\)The basic concept here is that any waveshape, however complex, is mathematically equivalent to a series of sinusoids at different frequencies and amplitudes.
A good way to minimize signal coupling is to simply separate conductors carrying incompatible signals. This is one reason why electrical power conductors and signal cables are almost never found in the same raceway (e.g., conduit, electrical ductwork) together. Separation decreases capacitance between the conductors because \( C = \frac{A \varepsilon}{d} \) where \( d \) is the distance between the conductive surfaces. Separation also decreases the coupling coefficient between inductors, which in turn decreases mutual inductance (recall that \( M = k \sqrt{L_1 L_2} \) where \( k \) is the coupling coefficient and \( M \) is the mutual inductance between two inductances \( L_1 \) and \( L_2 \)). In control panel wiring, it is customary to route AC power wires in such a way that they do not lay parallel to low-level signal wires, so that both forms of coupling may be reduced.

If conductors carrying incompatible signals must cross paths, it is advisable to orient the conductors perpendicular to each other rather than parallel, like this:

![Perpendicular Conductor Orientation](image)

Perpendicular conductor orientation reduces both inter-conductor capacitance and mutual inductance by two mechanisms. Capacitance between conductors is reduced by means of minimizing overlapping area \( (A) \) resulting from the perpendicular crossing. Mutual inductance is reduced by decreasing the coupling coefficient \( (k) \) to nearly zero since the magnetic field generated perpendicular to the aggressor conductor will be parallel and not perpendicular to the victim conductor. Since the vector for induced voltage is perpendicular to the magnetic field (i.e., parallel with the aggressor current vector) there will be no voltage induced along the length of the victim conductor.

The problem of power-to-signal line coupling is most severe when the signal in question is analog rather than digital. In analog signaling, even the smallest amount of coupled “noise” corrupts the signal. A digital signal, by comparison, will become corrupted only if the coupled noise is so great that it pushes the signal level above or below a detection threshold it should not cross. This disparity is best described through illustration.
Two signals are shown here, coupled with equal amounts of noise voltage:

The peak-to-peak amplitude of the noise on the analog signal is almost 20% of the entire signal range (the distance between the 0% and 100% values), representing a substantial degradation of signal integrity. Analog signals have infinite resolution, which means any change in signal amplitude has meaning. Therefore, any noise whatsoever introduced into an analog signal will be interpreted as variations in the quantity that signal is supposed to represent.

That same amount of noise imposed on a digital signal, however, causes no degradation of the signal except for one point in time where the signal attempts to reach a “low” state but fails to cross the threshold due to the noise. Other than that one incident represented in the pulse waveform, the rest of the signal is completely unaffected by the noise, because digital signals only have meaning above the “high” state threshold and below the “low” state threshold. Changes in signal voltage level caused by induced noise will not affect the meaning of digital data unless and until the amplitude of that noise becomes severe enough to prevent the signal’s crossing through a threshold (when it should cross), or causes the signal to cross a threshold (when it should not).

From what we have seen here, digital signals are far more tolerant of induced noise than analog signals, all other factors being equal.
3.2 Electric field (capacitive) de-coupling

The fundamental principle invoked in shielding signal conductor(s) from external electric fields is that no substantial electric field can exist within a solid conductor. Electric fields exist due to imbalances of electric charge. If such an imbalance of charge ever were to exist within a conductor, charge carriers (typically electrons) in that conductor would quickly move to equalize the imbalance, thus eliminating the electric field. Another way of saying this is to state that electric fields only exist between points of different potential, and therefore cannot exist between equipotential points. Thus, electric flux lines may be found only in the dielectric (insulating media) between conductors, not within a solid conductor:

![Diagram showing electric field lines around a solid metal sphere.](image)

This also means electric flux lines cannot span the diameter of a hollow conductor:

![Diagram showing electric field lines around a hollow metal sphere.](image)

The electrical conductivity of the hollow sphere’s wall ensures that all points on the circumference of the sphere are equipotential to each other. This in turn prohibits the formation of any electric...
3.2. **ELECTRIC FIELD (CAPACITIVE) DE-COUPLING**

flux lines within the interior air space of the hollow sphere. Thus, all points within the hollow sphere are *shielded* from any electric fields originating outside of the sphere.

The only way to allow an external electric field to penetrate a hollow conductor from the outside is if that conductive shell is left “floating” with respect to another conductor placed within the shell. In this case the lines of electric flux do not exist between different points on the conductive sphere, but rather between the shell of the sphere and the conductor at the center of the sphere because those are the points between which a potential difference (voltage) exists. To illustrate:

However, if we make the hollow shell electrically common to the negative side of the high-voltage source, the flux lines inside the sphere vanish, since there is no potential difference between the internal conductor and the conductive shell:
If the conductor within the hollow sphere is elevated to a potential different from that of the high-voltage source’s negative terminal, electric flux lines will once again exist inside the sphere, but they will reflect this second potential and not the potential of the original high-voltage source. In other words, an electric field will exist inside the hollow sphere, but it will be completely isolated from the electric field outside the sphere. Once again, the conductor inside is shielded from external electrostatic interference:

If conductors located inside the hollow shell are thus shielded from external electric fields, it means there cannot exist any capacitance between external conductors and internal (shielded) conductors. If there is no capacitance between conductors, there will never be capacitive coupling of signals between those conductors, which is what we want for signal cables to protect those signals from external interference.\(^4\)

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\(^4\)Incidentally, cable shielding likewise guards against strong electric fields within the cable from capacitively coupling with conductors outside the cable. This means we may elect to shield “noisy” power cables instead of (or in addition to) shielding low-level signal cables. Either way, good shielding will prevent capacitive coupling between conductors on either side of a shield.
All this discussion of hollow metal spheres is just an introduction to a discussion of *shielded cable*, where electrical cables are constructed with a conductive metal foil wrapping or conductive metal braid surrounding the interior conductors. Thus, the foil or braid creates a conductive tube which may be connected to ground potential (the “common” point between external and internal voltage sources) to prevent capacitive coupling between any external voltage sources and the conductors within the cable:

No AC "noise" will be imposed on the signal load.
The following photograph shows a set of signal cables with braided shield conductors all connected to a common copper “ground bus.” This particular application happens to be in the control panel of a 500 kV circuit breaker, located at a large electrical power substation where strong electric fields abound:

This next photograph shows a four-conductor USB cable stripped at one end, revealing a metal-foil shield as well as silver-colored wire strands in direct contact with the foil, all wrapped around the four colored power and signal conductors:

At the terminating end we typically twist the loose shield conductor strands together to form a wire which is then attached to a ground point to fix the cable’s shield at Earth potential.
It is very important to ground only one end of a cable's shield, or else you will create the possibility for a ground loop: a path for current to flow through the cable's shield resulting from differences in Earth potential at the cable ends. Not only can ground loops induce noise in a cable's conductor(s), but in severe cases it can even overheat the cable and thus present a fire hazard:

*A ground loop: something to definitely avoid!*

---

An important characteristic of capacitively-coupled noise voltage is that it is common-mode in nature: the noise appears equally on every conductor within a cable because those conductors lie so close to each other (i.e. because the amount of capacitance existing between each conductor and the noise source is the same). One way we may exploit this characteristic in order to help escape the unwanted effects of capacitive coupling is to use differential signaling. Instead of referencing our signal voltage to ground, we let the signal voltage “float.” The following schematic diagram illustrates how this works:

---

The lack of a ground connection in the DC signal circuit prevents capacitive coupling with the AC voltage from corrupting the measurement signal “seen” by the instrument. Noise voltage will still appear between either signal wire and ground as a common-mode voltage, but noise voltage will not appear between the two signal wires where our signal of interest exists. In other words, we
side-step the problem of common-mode noise voltage by making common-mode voltage irrelevant to the sensor and to the signal receiver.

Multiple digital communication standards employ differential signaling for its noise immunity, and this may be easily understood by graphical comparison. Noise is modeled below as a voltage source in series along the ungrounded conductor, near the receiving end. In reality, it is more likely to be distributed along the bulk of the cable length:

![Diagram showing common-mode noise](image1.png)

By contrast, any noise superimposed on ungrounded conductors in a differential signaling circuit cancel at the receiver, because the close proximity of those two conductors ensures any induced noise will be the same. Since the receiver responds only to differential voltage between its two inputs, this common-mode noise cancels, revealing a “clean” data signal at the end:

![Diagram showing differential signaling](image2.png)

Some digital data communications standards such as EIA/TIA-485 (RS-485), Ethernet, and Universal Serial Bus (USB) use differential signaling to minimize the corrupting effects of electrical noise. Other standards such as EIA/TIA-232 (RS-232) use single-ended signaling, and must overpower noise by using much higher-amplitude signal voltages.
3.3 Magnetic field (inductive) de-coupling

Magnetic fields, unlike electric fields, are exceedingly difficult to completely shield. Magnetic flux lines do not terminate, but rather loop. Thus, one cannot “stop” a magnetic field, only re-direct its path. A common method for magnetically shielding a sensitive instrument is to encapsulate it in an enclosure made of some material having an extremely high magnetic permeability ($\mu$): a shell offering much easier passage of magnetic flux lines than air. A material often used for this application is mu-metal, or $\mu$-metal, so named for its excellent magnetic permeability:

![Diagram of magnetic field and shielding](image)

This sort of shielding is impractical for protecting signal cables from inductive coupling, as mu-metal is rather expensive and must be layered relatively thick in order to provide a sufficiently low-reluctance path to shunt most of the external magnetic flux lines.

The most practical method of granting magnetic field immunity to a signal cable follows the differential signaling method discussed in the electric field de-coupling section, with a twist (literally). If we twist a pair of wires rather than allow them to lie along parallel straight lines, the effects of electromagnetic induction are vastly minimized.
The reason this works is best illustrated by drawing a differential signal circuit with two thick wires, drawn first with no twist at all. Suppose the magnetic field shown here (with three flux lines entering the wire loop) happens to be increasing in strength at the moment in time captured by the illustration:

According to Lenz’s Law, a current will be induced in the wire loop in such a polarity as to oppose the increase in external field strength. In other words, the induced current tries to “fight” the imposed field to maintain zero net change. According to the right-hand rule of electromagnetism (tracing current in conventional flow notation), the induced current must travel in a counter-clockwise direction as viewed from above the wire loop in order to generate a magnetic field opposing the rise of the external magnetic field. This induced current works against the DC current produced by the sensor, detracting from the signal received at the instrument.

When the external magnetic field strength diminishes, then builds in the opposite direction, the induced current will reverse. Thus, as the AC magnetic field oscillates, the induced current will also oscillate in the circuit, causing AC “noise” voltage to appear at the measuring instrument. This is precisely the effect we wish to mitigate.

Immediately we see a remarkable difference between noise voltage induced by a magnetic field versus noise voltage induced by an electric field: whereas capacitively-coupled noise is always common-mode, here we see inductively-coupled noise as differential.⁵

⁵This is not to say magnetic fields cannot induce common-mode noise voltage: on the contrary, magnetic fields are
3.3. MAGNETIC FIELD (INDUCTIVE) DE-COUPLING

If we twist the wires so as to create a series of loops instead of one large loop, we will see that the inductive effects of the external magnetic field tend to cancel:

Not all the lines of flux go through the same loop. Each loop represents a reversal of direction for current in the instrument signal circuit, and so the direction of magnetically-induced current in one loop directly opposes the direction of magnetically-induced current in the next. So long as the loops are sufficient in number and spaced close together, the net effect will be complete and total opposition between all induced currents, with the result of no net induced current and therefore no AC “noise” voltage appearing at the instrument.

In order to enjoy the benefits of magnetic and electric field rejection, instrument cables are generally manufactured as twisted, shielded pairs. The twists guard against magnetic (inductive) interference, while the grounded shield guards against electric (capacitive) interference. If multiple wire pairs are twisted within the same cable, the twist rates of each pair may be made different so as to avoid magnetic coupling from pair to pair.

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*capable of inducing voltage in any electrically-conductive loop. For this reason, both differential and ground-referenced signals are susceptible to interference by magnetic fields.

*An example of this is the UTP (Unshielded, Twisted Pair) cabling used for Ethernet digital networks, where four pairs of wires having different twist rates are enclosed within the same cable sheath.
3.4 Intrinsic noise

Although noise may enter a circuit from some outside influence, such as nearby conductors belonging to another circuit, this is not the only source of noise in circuits. A variety of intrinsic (i.e. internal) noise sources exist as well. This is where the circuit’s own components act to generate noise, even if isolated perfectly from anything else. Intrinsic noise tends to be more random than extrinsic noise, and for this reason intrinsic noise often spans a range of frequencies. Recall that any periodic waveform is mathematically equivalent to a series of sinusoidal waves summed together, and that the frequencies of these summed sinusoids could be expressed as whole-number multiples of some fundamental frequency called harmonics. Noise that is random, however, is necessarily non-periodic, and so the relationship to definite frequencies is not so simple. Random noise generally manifests as continuous bands covering ranges of frequency.

A practical example of this phenomenon is the noise floor seen on the display of a spectrum analyzer. In the screenshot shown below, the strong “peak” represents a 2 kHz sinusoidal signal while the “fuzz” spanning the rest of the spectrum represents random noise coexisting with that pure 2 kHz signal:

![Noise Floor Screenshot]

Note how the noise floor appears to be more or less uniform across the entire width of the spectrum, from 0 kHz to 6 kHz. This is called white noise because the noise is equally spread across all frequencies just as white light is a combination of all colors. Not all noise is so evenly distributed across the frequency spectrum, though, and various color names describe noise with uneven spectra. Red noise and pink noise are both more heavily-weighted at the low-frequency end of the spectrum: that is to say, a “pink” or “red” noise source generates stronger signal variations at low frequency than at high frequency, like white noise after low-pass filtering. Blue noise and violet noise are both more heavily-weighted at the high-frequency end of the spectrum, like white noise following high-pass filtering. The distinction between pink/red and blue/violet is in the rolloff rate, as shown in the following spectra:

![Noise Spectra]
3.4. INTRINSIC NOISE

3.4.1 Thermal noise

All matter existing at temperatures greater than absolute zero possess motion on a molecular or atomic scale. In fact, temperature may be thought of in terms of this atomic or molecular motion, with absolute zero being that temperature where all motion ceases. These random motions of atoms and molecules is itself an intrinsic source of noise for electrical and electronic components, because electrical charge carriers are directly affected. As strange as it may seem, even a component such as a resistor which we typically consider a load, actually behaves as a noise source at all temperatures other than absolute zero:

\[ I_{\text{noise}} = \sqrt{\frac{4kT\Delta f}{R}} \]
\[ V_{\text{noise}} = \sqrt{4kT\Delta f R} \]

Where,
- \( I_{\text{noise}} \) = Thermal noise current through short-circuited resistor (AC Amperes RMS)
- \( V_{\text{noise}} \) = Thermal noise voltage across open-circuited resistor (AC Volts RMS)
- \( k \) = Boltzmann’s constant (1.3806504 × 10^{-23} J / K)
- \( T \) = Absolute temperature (Kelvin), 273.15 more than degrees Celsius
- \( \Delta f \) = Band-width of frequency over which noise is measured (Hertz)
- \( R \) = Resistor value (Ohms)

All conductors exhibit thermal noise, and this includes the conductive channels of field-effect transistors (FETs).

Thermal noise is also known as Johnson noise, or Johnson-Nyquist noise after its discoverers John Johnson and Harry Nyquist at Bell Labs in 1926. Since it arises from thermally-motivated charge carriers passing through a resistance, it is fundamental and unavoidable, which is to say all resistances exhibit this phenomenon. It is also quite small, as one might conclude by the extremely small value of Boltzmann’s constant. For example, the noise voltage produced by a 1000 Ohm resistor at 25 degrees Celsius (298.15 Kelvin) over a bandwidth of 15 kiloHertz (e.g. from 0 to 15 kHz, or from 40 kHz to 55 kHz) is only 0.496975 microVolts.

The “color” of thermal noise is white, being constant in magnitude across all frequencies.
3.4.2 Shot noise

Another form of intrinsic and random noise is \textit{shot noise}. Unlike thermal noise which depends only on temperature and resistance, shot noise is a function of current through any component where charge carriers traverse a gap, and it originates from the fact that electric current is not a continuous substance but rather a passage of discrete electrical charges. A good mental image of shot noise is that of dropping grains of sand onto a hard surface: each grain of sand makes an impact sound when it strikes the surface. Shot noise was investigated in vacuum tubes by Walter Schottky in 1918, arising from the effect of individual electrons reaching the tube’s plate one at a time through the gap separating the plate from the tube’s cathode. Semiconductor PN junctions (including the junctions of bipolar junction transistors and junction field-effect transistors) also exhibit shot noise, as do photoelectric devices where each incident photon results in a liberated charge carrier.

\[ I_{\text{noise}} = \sqrt{2eI_{\text{DC}}\Delta f} \]

Where,
- \( I_{\text{noise}} \) = Shot noise current through component (AC Amperes RMS)
- \( e \) = Charge of a single electron (\(1.602176487 \times 10^{-19}\) C)
- \( I_{\text{DC}} \) = Constant current through component (DC Amperes)
- \( \Delta f \) = Band-width of frequency over which noise is measured (Hertz)

Shot noise is also called \textit{Poisson noise} in honor of its probability distribution. As the equation describes, shot noise is proportional to the intensity of the DC current passing through a component. That is to say, components generate more shot noise as more current passes through them. Shot noise is unrelated to device temperature and therefore is distinctly different from thermal (Johnson) noise which exists independent of circuit current.

The “color” of shot noise is white, being constant in magnitude across all frequencies.

3.4.3 Flicker noise

A type of intrinsic noise found in many types of electrical and electronic devices is \textit{flicker noise}, which grows in proportion to the DC current through the device similar to shot noise. Unlike shot noise, though, flicker noise has a “pink” spectrum which means it is stronger at low frequencies than at high frequencies. The degree to which any device generates flicker noise depends on not only the amount of DC current passing through, but also on the type of device.

It is well known, for example, that carbon-composition resistors generate more flicker noise than either metal-film or metal-wire resistors. The tendency for some types of components to generate more flicker noise than others has led to flicker noise sometimes being referred to as \textit{excess noise}. We know that thermal (Johnson) noise is present in all conductive components and cannot be avoided, but that flicker noise varies with component type. Interestingly, the metal alloy Manganin\footnote{Manganin is a metal alloy consisting of 84% copper, 12% manganese, and 4% nickel.} which is often chosen for high-precision metal-wire resistor construction because it has a zero temperature coefficient (i.e. its resistivity remains constant over wide ranges of ambient temperature) exhibits zero flicker noise as well.
3.4. INTRINSIC NOISE

3.4.4 Burst noise

A type of intrinsic noise unique to semiconductor devices is burst noise, also known as popcorn noise. As the name suggests, this type of noise takes the form of discrete jumps or bursts in signal strength happening at random times, like the sound of popcorn popping in a hot pan. The frequency range at which burst noise typically occurs is well within the human audio range and indeed may sound like popcorn popping if heard through a loudspeaker.

Burst noise seems to be primarily the result of defects within the crystalline structure of semiconductor devices, and with improvements in semiconductor manufacturing this type of noise has become less and less of a problem for modern circuit designers.

3.4.5 Avalanche noise

When a PN semiconductor junction is operated with a reverse bias of sufficient voltage, minority charge carriers moving “backwards” through the junction may occasionally gain enough kinetic energy to liberate additional electron/hole pairs when they collide with stationary atoms. These liberated charge carriers then drift with the applied voltage and likewise gain kinetic energy. If the voltage is sufficient, these charge carriers may also liberate more charge carriers when they collide with stationary atoms, the result being an “avalanche” of mobile charge carriers which increases conductivity of the PN junction. The avalanche effect does not result in a constant current, though, but rather pulses of current that constitute noise which we call avalanche noise.

3.4.6 Intrinsic noise mitigation

Given the random nature of intrinsic noise, a simple and effective means to mitigate its effects is to average many samples of the signal over a period of time, the principle being that the random positive and negative variations of the noise will cancel out to yield a more steady signal. Of course, this incurs the price of having to wait longer periods of time to reliably measure the signal, and it also only works in cases where the signal of interest has a low enough frequency that the averaging process will not substantially corrupt it by filtering out (legitimate) fast rates-of-change.
Chapter 4

Derivations and Technical References

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

A useful definition of electric field (\(E\)) is in terms of the force (\(F\)) exerted on an electric charge (\(Q\)) influenced by that field:

\[
\vec{F} = Q \vec{E}
\]

Where,
- \(\vec{F}\) = Force exerted on the charge (Newtons)
- \(Q\) = Charge quantity (Coulombs\(^1\))
- \(\vec{E}\) = Electric field (Newtons per Coulomb)

The small “arrow” symbols above the variables for force and electric field in the equation denote those variables as vector quantities, having both magnitude and direction. Charge is a scalar quantity having only magnitude but no direction, and as a scalar quantity when multiplied by the electric field vector it simply magnifies the magnitude but does not alter the direction. Therefore, the force and electric field vectors always point in the same direction.

Alternatively electric field may be defined in terms of the voltage between the end-points and the distance separating them, in which case we may express the electric field in units of Volts per meter as an alternative to Newtons per Coulomb:

\[
\vec{E} = \frac{V}{d}
\]

This measurement of electric field strength is very important for quantifying the breakdown of electrical insulators: the point at which the electric field becomes so powerful that otherwise immobile charges within the insulating substance are torn free to constitute a current and that substance is no longer an insulator. For rating the dielectric strength of insulating materials, we often see electric fields expressed in units of kiloVolts per millimeter rather than Volts per meter just to make the numerical quantities easier to manage (1 kV/mm = 1 million V/m).

\(^1\)One Coulomb of electric charge is equal to 6.2415 \times 10^{18} electrons.
4.1. ELECTRIC FIELD QUANTITIES

The vector arrows shown in the previous illustration representing the electric field between two metal plates actually represent electric flux \( \Phi_E \). The electric field \( E \) is related to electric flux by area \( A \), the field being a measurement of how densely-packed those flux lines are per unit area:

\[
\vec{E} = \frac{\Phi_E}{A}
\]

Where,
- \( \vec{E} \) = Electric field, or electric flux density (Newtons per Coulomb)
- \( \Phi_E \) = Electric flux (Newton-meter squared per Coulomb)
- \( A \) = Area over which flux is distributed (square meters)

The mere presence of an unbalanced electric charge at any point in space is sufficient to generate lines of electric flux, the total magnitude of that flux predicted by the following equation:

\[
\Phi_E = \frac{Q}{\epsilon}
\]

Where,
- \( \Phi_E \) = Electric flux (Newton-meter squared per Coulomb)
- \( Q \) = Charge quantity (Coulombs)
- \( \epsilon \) = Electric permittivity of the surrounding space (Coulombs squared per Newton-meter squared, approximately \( 8.85 \times 10^{-12} \) for empty space)

By convention, these flux vectors point away from positive charges and point toward negative charges, their direction indicating force exerted on any positively-charged particle influenced by that field. As the equation states, the amount of flux depends on how much charge exists at each particle as well as the permittivity of the surrounding space:

For example, identical charges suspended in a vacuum versus in a substance such as oil will have different amounts of flux associated with them as a result of oil and vacuum having different permittivity values. Perfectly empty space has the least amount of permittivity, which means anything else (gas, liquid, or solid matter) has greater \( \epsilon \) which acts to diminish the amount of electric flux surrounding any charged particle. Superconducting materials have infinite permittivity, which means they forbid the existence of any electric field inside their bulk.

\(^2\)Conversely, the flux vectors point exactly opposite the direction of force applied to any negatively-charged particle within that field. This makes sense of the aphorism that like charges repel and opposite charges attract. If you consider the two charges shown in this illustration, the positive charge will be pulled in the direction of the flux vectors pointing toward the negative charge, as the negative charge will also be pulled opposite the direction of the flux vectors pointing away from the positive charge (i.e. the negative charge will be pulled toward the positive charge) – thus the positive and negative charges feel mutual attraction.
4.2 Magnetic field quantities

A useful definition of electric field \((E)\) is in terms of the force \((F,\) called the Lorentz force) exerted on an electric charge \((Q)\) influenced by that field:

\[
\vec{F} = Q \vec{v} \times \vec{B}
\]

Where,
\[
\begin{align*}
\vec{F} & = \text{Force exerted on the charge (Newtons)} \\
Q & = \text{Charge quantity (Coulombs\textsuperscript{3})} \\
\vec{v} & = \text{Velocity of moving charge (meters per second)} \\
\vec{B} & = \text{Magnetic field (Tesla, or Newtons per Ampere-meter)}
\end{align*}
\]

The small “arrow” symbols above the variables for force and velocity and magnetic field in the equation denote those variables as vector quantities, having both magnitude and direction. Charge is a scalar quantity having only magnitude but no direction, and as a scalar quantity when multiplied by the velocity vector it simply magnifies the magnitude but does not alter the direction. The “cross-product” \((\times)\) is a specific form of vector multiplication, and it results in a product at right angles to the vector directions of both terms. Therefore, the force and velocity and electric field vectors never all point in the same direction.

\textsuperscript{3}One Coulomb of electric charge is equal to \(6.2415 \times 10^{18}\) electrons.
4.2. MAGNETIC FIELD QUANTITIES

Vector cross-products conveniently relate to the fingers of the right hand, which is where the “right-hand rule” originates:

\[
C = A \times B
\]

For vector cross-products

When holding the index finger, middle finger, and thumb of your right hand perpendicular to each other, your index finger points in the direction of the velocity vector (\(\vec{v}\)), your middle finger in the direction of the magnetic field vector (\(\vec{B}\)), and your thumb in the direction of the force vector (\(\vec{F}\)). A simple mnemonic I use to remember these relationships of fingers to vectors is that the Index finger points in the direction of current\(^ 4\) (\(I\)), the Middle finger points in the direction of the magnetic field (\(B\)), and the Thumb points in the direction of the thrust (i.e. force) acting upon the moving charge.

The Lorentz force’s effect on electrically-charged particles in motion has many applications, from redirecting the paths of charged-particle beams in particle accelerator machines, to bending the trajectory of electron beams in a cathode-ray tube (CRT), to forcing electrons to travel in spiral or circular trajectories inside of magnetron (microwave oscillator) tubes. An illustration of a positively-charged particle curving perpendicular to a magnetic field appears here:

\[\text{Magnetic field (arrow tail going into the page)}\]

Positive charge

Lorentz force

Positively-charged particle

Magnetic field

4 Some textbooks speak of a “left-hand rule” which is intended to make sense of electric charge motion (current) in terms of electron flow. As we know, electrons are the only real mobile charge carriers within metal conductors, and so technically “electron flow” notation is most physically accurate when describing the motion of electric charges in metallic circuits. However, the right-hand rule is a mathematical definition for vector cross products, the concept of the cross product arising in the late 18th century when electrical science was still in its infancy. Early explorers of electricity used the established mathematical tools of their time and applied it to their work with electric currents and magnetism. At that time, charge carriers in metal wires were assumed to be “positive” and this is how the motion of positively-charged carriers became associated with the first vector of the cross-product. As a result of this assumption which was later proven false, we have two different conventions for denoting the motion of electricity: electron-flow which is physically accurate (for metal wires, at least), and conventional flow which is mathematically accurate. This, perhaps more than any other reason, is why educational programs designed for mathematically rigorous fields (e.g. electrical engineering) exclusively use conventional flow notation rather than electron flow notation to denote the direction of current.
If the moving charge in question is not a single charged particle but rather part an electric current passing through a conductor parallel to the first, both conductors will experience a mutually-attracting force given by the following equation:

\[
\vec{F} = I\vec{l} \times \vec{B}
\]

Where,
- \(\vec{F}\) = Force exerted on both conductors (Newtons)
- \(I\) = Current (Amperes)
- \(\vec{l}\) = Length of wire (meters)
- \(\vec{B}\) = Magnetic field (Tesla, or Newtons per Ampere-meter)

The point-charge Lorentz force equation and the two-conductor Lorentz force equation are not that different from one another. Dimensional analysis validates this: the Lorentz force on a moving charge uses that charge quantity (Coulombs) multiplied by the point-charge’s velocity in meters per second to give Coulomb-meters per second for the first term:

\[
Q\vec{v} = \left[ \text{C} \right] \left[ \frac{\text{m}}{\text{s}} \right] = \left[ \text{C} \cdot \frac{\text{m}}{\text{s}} \right]
\]

The Lorentz force on a current-carrying conductor uses the current (Amperes, which is Coulombs per second) multiplied by length in meters, for the same composite units of Coulomb-meters per second:

\[
I\vec{l} = \left[ \frac{\text{C}}{\text{s}} \right] \left[ \text{m} \right] = \left[ \frac{\text{C} \cdot \text{m}}{\text{s}} \right]
\]

This dimensional equivalence makes conceptual sense as well: an electrically-charged particle moving through empty space is an electric current in its own right, and an electric current flowing through a conductor is just a collection of charged particles moving through space (just not empty space). In either case, the basis for the Lorentz force remains the same: the moving charge(s) create their own magnetic field, which reacts with the magnetic field of the original current-carrying wire to produce forces acting on both.

If the two currents flow in the same direction, their mutual forces attract. If the two currents flow in opposite directions, their mutual forces repel. This is the basis of electric motors: causing
4.2. MAGNETIC FIELD QUANTITIES

mechanical motion by electro-magnetic attraction and repulsion. It also represents an interesting contrast with electric fields:

With electric fields, opposite charges attract and like charges repel.

With magnetic fields, opposite poles attract and like poles repel.

With parallel currents, opposite directions repel and like directions attract\(^5\).

Two parallel current-carrying conductors of length \(l\) and separated by a distance \(d\) will generate a mutual force proportional to both their currents:

\[
F = \frac{l \mu I_1 I_2}{2\pi d}
\]

\(^5\)That is, assuming it’s like charges moving in these directions! If the charges in question are opposite each other, then like directions will repel and opposite directions will attract!
The circular loops surrounding the current-carrying conductors in the previous illustrations represent the magnetic lines of flux \( \Phi_B \) surrounding each of those conductors. The magnetic field \( B \) is related to magnetic flux by area \( A \), the field being a measurement of how densely-packed those flux lines are per unit area:

\[
\vec{B} = \frac{\Phi_B}{A}
\]

Where,
- \( \vec{B} \) = Magnetic field (Tesla, or Webers per square meter)
- \( \Phi_B \) = Magnetic flux (Webers)
- \( A \) = Area over which flux is distributed (square meters)

An older unit of measurement for magnetic fields is the Gauss which is much smaller than a Tesla, with one Tesla equivalent to 10,000 Gauss. To put things into perspective, the Earth’s natural magnetic field has a strength of approximately one-half of one Gauss\(^6\).

Magnetic field strength is an inverse function of distance from any current-carrying wire, and also depends on the magnetic permeability of the space adjacent to the wire:

\[
B = \frac{\mu I}{2\pi d}
\]

Where,
- \( B \) = Magnetic field (Tesla, or Newtons per Ampere-meter)
- \( \mu \) = Magnetic permeability of the surrounding space (Tesla-meters per Ampere, \( 4\pi \times 10^{-7} \) for empty space)
- \( I \) = Current (Amperes)
- \( d \) = Distance from conductor (meters)

\(^6\)Using the online Magnetic Field Calculator application provided by NOAA (the National Oceanic and Atmospheric Administration) at https://ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm, applying the World Magnetic Model WMM modeling algorithm for years 2019-2024, the total magnetic field strength at my home is 53,584.4 nano-Tesla (53,584.4 nT or 0.535844 Gauss), and presently (May 2020) decaying at a rate of \(-104.1 \text{ nT per year}\).
The relation of magnetic flux to current through a conductor follows a similar equation:

$$\Phi = \frac{\mu AI}{2\pi d}$$

Where,

- $\Phi = \text{Magnetic flux (Webers)}$
- $\mu = \text{Magnetic permeability of the surrounding space (Tesla-meters per Ampere, } 4\pi \times 10^{-7} \text{ for empty space)}$
- $A = \text{Area over which flux is distributed (square meters)}$
- $I = \text{Current (Amperes)}$
- $d = \text{Distance from conductor (meters)}$

As this equation makes clear, the amount of magnetic flux surrounding a current-carrying conductor depends not only on the amount of current, but also on the sampled area, the distance from the wire, and also the surrounding material. Most substances (gas, liquid, solid) have permeability values greater than that of empty space, and so this means magnetic flux is usually enhanced by the presence of matter around the current-carrying conductor.

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Interestingly, superconducting materials forbid magnetic fields inside of their bulk, and so the permeability value of any superconductor must be zero!
Chapter 5

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\textsuperscript{1} the tutorials and attempt to answer questions on their own prior to the instructor’s interaction with them. In place of lecture\textsuperscript{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.

\textsuperscript{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 \textit{Reading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms} by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

\textsuperscript{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.
CHAPTER 5. QUESTIONS

GENERAL CHALLENGES FOLLOWING TUTORIAL READING

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

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

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

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

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

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

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

- Devise an experiment to disprove a plausible misconception.

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

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

- **Devise a question** of your own to challenge a reader’s comprehension of the text.
GENERAL FOLLOW-UP CHALLENGES FOR ASSIGNED PROBLEMS

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

GENERAL FOLLOW-UP CHALLENGES FOR EXPERIMENTS OR PROJECTS

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.
• Show how thorough documentation assisted in the completion of this experiment or project.

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

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

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

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

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

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

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

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

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

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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.
5.1.1 Reading outline and reflections

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

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

- Briefly OUTLINE THE TEXT, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do not comprehend.

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

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

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

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

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

5.1.2 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
- Electric field
- Magnetic field
- Electromagnetism
- Faraday’s Law of Electromagnetic Induction
- Lenz’s Law
- Electrical source
- Electrical load
- Capacitance
- Inductance
- AC
- DC
**CHAPTER 5. QUESTIONS**

- Frequency
- Parasitic effect
- Mutual induction
- Sinusoidal decomposition (i.e. Fourier’s Theorem)
- Fundamental frequency
- Harmonic frequency
- Common-mode voltage signal
- Differential voltage signal
- Noise
- Bus
- Permeability
- Ground loop
- Noise immunity
- Filter
5.1.3 Compass in a lightning storm

When lightning strikes, nearby magnetic compass needles may be seen to jerk in response to the electrical discharge. No compass needle deflection results during the accumulation of electrostatic charge preceding the lightning bolt, but only when the bolt actually strikes. What does this phenomenon indicate about voltage, current, and magnetism?

Do you suspect a sensitive electronic circuit might be affected more by the gradual accumulation of electric charge, or by the instantaneous strike of the lightning bolt? Will the circuit be affected at the same time and in the same way as the magnetic compass, or will it be susceptible in different ways?

Challenges

• What would a sensitive electroscope (an instrument designed to detect electric fields) register alongside the compass during a lightning storm.
5.1.4 Phantom voltage measurements

A technician uses a digital multimeter to check for the presence of dangerous voltage between conductor #3 and Earth ground prior to touching that conductor. This safety check is done as a matter of precaution, even though the technician has reason to believe that conductor is electrically distinct (i.e. not electrically common to any other conductors) and should not be “live”. To this technician’s surprise, he measures 43 Volts AC between conductor #3 and ground!

Puzzled, this technician consults another technician to ask how it is possible to measure a possibly dangerous voltage level between a conductor and ground when the conductor in question is not connected to anything else. “Oh,” says the other technician, “That’s probably just a phantom voltage. Don’t worry about it!”

Explain this phenomenon. Exactly how is the AC voltmeter registering a voltage on what should be a “dead” wire?

Should you be concerned about the safety hazard of so-called “phantom voltages”? Why or why not?

Some voltmeters made for general electrical use (rather than precision electronic use) are specially built to have less input impedance than typical: tens of kiloOhms instead of megaOhms. This design helps minimize “phantom” voltage measurements. Explain how a voltmeter with less input impedance (also known as insertion resistance) than usual is less liable to be “fooled” when taking measurements on an unattached conductor such as this.
5.1. CONCEPTUAL REASONING

Challenges

- Are “phantom” voltages strictly an AC phenomenon, or may they manifest in DC circuits as well?

- Identify some parameters of the multi-conductor cable which could be modified (e.g. length, wire gauge, insulation thickness, etc.) to exacerbate the “phantom” voltages effect.

- Experiment with phantom voltages by inserting one test lead of an AC voltmeter into the “hot” socket of a 120 Volt AC power receptacle, and leaving the other test lead “floating” in air. Also, try connecting one test lead of a voltmeter to Earth ground while placing the other lead close to a “hot” AC conductor. What, by definition, makes a conductor “hot”?

5.1.5 Digital versus analog signal cables

Suppose you must run two signal cables from field-mounted instruments to a central room where the control system is located. Two different electrical conduits stretch from the field location to the control system room: one with 480 V AC power wiring in it, and another with low-level control signal wiring in it. The two cables you must run through these conduits are as follows:

- One twisted-pair cable carrying a 4-20 mA analog DC signal
- One twisted-pair cable carrying a Modbus digital signal (RS-485 physical layer)

At first, you plan to run both these cables through the signal wire conduit. However, you soon discover this signal conduit only has room to accommodate one cable but not both. The power wire conduit, however, has plenty of available room.

Which cable would you run through which conduit, and why?

Challenges

- Explain why it is best to run all signal cables in conduit completely separate from power cables.
5.1.6 Sensitive audio detector

A very educational project to construct is this sensitive audio detector, designed to let you listen to very small AC voltages and currents with frequencies in the audio range (approximately 20 Hz to 20 kHz, depending on how acute your hearing is):

Explain how you might detect AC electric fields with this instrument.

Explain how you might detect AC magnetic fields with this instrument.

**Challenges**

- What purpose do the two diodes serve in this circuit? Hint: if you remove the diodes from the circuit, you will not be able to hear the difference in most cases!

- The purpose of the transformer in the sensitive audio detector circuit is to increase the effective impedance of the headphones, from 8 Ω to a much larger value. Calculate this larger value, given a transformer turns ratio of 22:1.

- A transformer salvaged from a microwave oven works extremely well for this project. Explain why.
5.2 Quantitative reasoning

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

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

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

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

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

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

Note: constants shown in bold type are exact, not approximations. Values inside of parentheses show one standard deviation ($\sigma$) of uncertainty in the final digits: for example, Avogadro’s number given as $6.02214179(30) \times 10^{23}$ means the center value ($6.02214179 \times 10^{23}$) plus or minus $0.00000030 \times 10^{23}$.

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

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

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

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

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

Electric permittivity of free space ($\varepsilon_0$) = 8.8541878128(13) $\times 10^{-12}$ Farads per meter (F/m)

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

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

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

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

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

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

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

5.2.2 Introduction to spreadsheets

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

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

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

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

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\(^6\)Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels “names”), but for simple spreadsheets such as those shown here it’s usually easier just to use the standard coordinate naming for each cell.
Common arithmetic operations available for your use in a spreadsheet include the following:

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

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

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

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

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

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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.
5.2. QUANTITATIVE REASONING

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

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

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

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.
5.2.3 Induced voltage

If a wire coil with 450 turns is exposed to a magnetic flux increasing at a rate of 0.008 Webers per second, how much voltage will be induced across the coil?

If a wire coil with 320 turns is exposed to a magnetic flux decreasing at a rate of 0.03 Webers per second (as shown in the illustration), how much voltage will be induced across the coil, and what will its polarity be?

Challenges

- Are the motions shown in the illustrations the only valid way to physically expose these coils to changing magnetic flux?

5.2.4 Magnetic field detector coil

Suppose you were designing a wire coil to be used as part of a magnetic field detection apparatus. It will detect the presence of oscillating (AC) magnetic fields by producing a voltage that will be sensed by a voltmeter.

If this coil is to be placed at a distance from an oscillating magnetic field where the coil covers an area large enough to experience a peak rate-of-change of flux \( \frac{d\Phi}{dt} \) equal to 0.2 Webers per second. How many “turns” of wire would this coil have to possess in order to generate a peak voltage of 5 Volts?

Challenges

- Identify one way for the coil to generate this much voltage, given the same magnetic field source, using fewer turns of wire.
5.3 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.
5.3.1 Compressor system wiring

A team of technicians recently built this gas compressor system, and are nearly ready to start it up. The system provides over-current protection for the compressor’s drive motor using fuses, while a data acquisition unit (DAQ) monitors voltage signals from pressure and vibration sensors on the compressor.

Just days before the planned start-up, you happen to perform an inspection of their work. You see 480 V AC (three-phase) power routed to the compressor’s drive motor through fuses in the first enclosure. You also see two sensors at the compressor – a high-pressure alarm switch (24 V DC discrete on/off signal) and a vibration probe (outputting milliVolt signals proportional to compressor vibration) – connected to a data acquisition unit located at the first enclosure. All wiring is in the form of individual conductors, with the exception of the multi-conductor RS-232 cable connecting the DAQ to the operator’s computer display:

Your answer should consist of two parts: (1) identify a definite problem you see in the measurement wiring, and (2) explain how you would remedy that problem.

Challenges

- Suppose an engineer recommends installing a VFD in this compressor system to be able to adjust the speed of the electric motor. How will this alteration affect the signal-measurement system, if at all?
Appendix A

Problem-Solving Strategies

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

- **Study principles, not procedures.** Don’t be satisfied with merely knowing how to compute solutions – learn why those solutions work.

- **Identify** what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any “missing pieces” to a solution. **Annotate** all diagrams with this data.

- **Sketch a diagram** to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function before constructing it.

- **Follow the units of measurement and meaning of every calculation.** If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don’t understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.

- **Perform “thought experiments”** to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform **diagnostic tests** rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.

- **Simplify the problem** until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.

- **Check for exceptions** to see if your solution is incorrect or incomplete. A good solution will work for all known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to **challenge** that new idea to see if it holds up under a battery of tests. The philosophical
principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

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

Instructional philosophy

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

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits.

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

• The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is always more important than particulars of any subject matter, because its application is universal.

• Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.

• Articulate communication is fundamental to work that is complex and interdisciplinary.

• Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of reductio ad absurdum (disproving an assertion by exposing an absurdity) works well to discipline student’s minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.

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

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

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

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1In a traditional teaching environment, students first encounter new information via lecture from an expert, and then independently apply that information via homework. In an “inverted” course of study, students first encounter new information via homework, and then independently apply that information under the scrutiny of an expert. The expert’s role in lecture is to simply explain, but the expert’s role in an inverted session is to challenge, critique, and if necessary explain where gaps in understanding still exist.

2Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato’s many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on any topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

3This rhetorical technique is known by the Latin phrase reductio ad absurdum. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply reductio ad absurdum to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).
from “first principles”. Again, this reflects the goal of developing clear and independent thought in students’ minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

• Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied effort, and never give up!

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

To high standards of education,

Tony R. Kuphaldt

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

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

Tools used

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

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

The GNU/Linux computer operating system

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

Bram Moolenaar’s Vim text editor

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

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

Leslie Lamport’s LaTeX extensions to TeX

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

Tim Edwards’ Xcircuit drafting program

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

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

SPICE circuit simulation program

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

Andrew D. Hwang’s ePiX mathematical visualization programming library

This amazing project is a C++ library you may link to any C/C++ code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as Mathematica or Maple to do. It should be said that ePiX is not a Computer Algebra System like Mathematica or Maple, but merely a mathematical visualization tool. In other words, it won’t determine integrals for you (you’ll have to implement that in your own C/C++ code!), but it can graph the results, and it does so beautifully. What I really admire about ePiX is that it is a C++ programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a C++ library to do the same thing he accomplished something much greater.
Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman’s GNU project, its name being a coincidence. For this reason the authors prefer “gnu” *not* be capitalized at all to avoid confusion. This is a much “lighter-weight” alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I’m developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I’m writing. As with my use of Gimp to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it’s *free* and that it *works well*.

*Python* programming language

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

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Appendix E

References


Vidkjaer, Jens, “Class Notes, 31415 RF-Communication Circuits, Chapter IV, NOISE and DISTORTION”, NB 232, date unknown.
Appendix F

Version history

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

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

26 April 2022 – added more content to the Tutorial about rates of change, including an oscilloscope screenshot of a \( \frac{dV}{dt} \) measurement.

4 November 2021 – edited Case Tutorial examples showing electric and magnetic signal coupling for better clarity.

8 May 2021 – commented out or deleted empty chapters.

29 March 2021 – minor additions to the Tutorial on flicker noise.

22 March 2021 – added content to the Tutorial on noise definitions and also intrinsic sources of noise.

22 February 2021 – edited image_3103 to show AC rather than DC sources.

8 October 2020 – added a Case Tutorial chapter, with examples showing both capacitive coupling and inductive coupling between conductors within a two-conductor cable.

7 October 2020 – minor additions to the Introduction, Tutorial, and Questions chapters.

29 September 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading “inverted” teaching sessions. Also, fixed an omission in the Tutorial where I referred to a section that did not exist.

12 August 2020 – added mention of crosstalk to Tutorial.
APPENDIX F. VERSION HISTORY

1 July 2020 – document first created.
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