## Modular Electronics Learning (ModEL) PROJECT



## RF Link Budgets

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## Chapter 1

## Introduction

Given the inherent power limitations of all radio transmitters, as well as the limited sensitivity of all radio receivers, the design of a robust radio communication "link" between transmitter and receiver must take into account all power gains and losses in between those devices. This module explores the basic principles involved with the calculation of "RF link budgets".

Important concepts related to RF link budgets include decibels, effective radiated power (ERP), antenna gain, path loss, fade loss, noise figure, signal-to-noise ratio, receiver sensitivity, bit error rate (BER), inverse square law, fade margin, Fresnel zones, line-ofsight, , and .

Due to the heavy application of math to link budget analysis, the reader is urged to apply the mathematical principles as soon as possible. The link budget examples contained in the tutorial serves this purpose well, as they allow you to apply the formulae discussed previously to an example and then check your work against the completed example to see if your application was correct. Do not simply read the example and assume you understand it just because nothing in the presentation seemed confusing. Until you can perform the analysis yourself without assistance, you haven't mastered it!

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

- How might an experiment be designed and conducted to site-test a radio transmitter/receiver pair for effective operation? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- Why do we typically use decibels to express power gains and losses in RF systems?
- How can an antenna have a gain as a purely passive device, without violating the Law of Energy Conservation?
- What do the following terms mean: $d B, d B m, d B d$, and $d B i$ ?
- Where does noise originate in an RF system?
- What might happen if an RF link is not properly budgeted?
- How does the inverse square law apply to RF systems?
- What is "fade" and how do we compensate for it in an RF system?
- What accounts for path loss in an RF link?
- How do path loss and fade loss differ from one another?
- Can path loss ever be completely eliminated?
- Can fade loss ever be completely eliminated?
- What does BER represent, and why is it important in a digital radio system?
- What does it mean to have a "margin" built into a budget calculation of any type?
- What factors determine the dimensions of a Fresnel zone, and why is this concept important to RF links?
- What is a site test, and why is this a good idea to conduct for any RF system?


## 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: simple decibel values

Decibels are a logarithmic representation of power ratios, with negative decibel values representing power attenuation and positive decibel values representing power gain. Every addition or subtraction of 10 dB exactly represents a 10 -fold multiplication or division of power ratio. A simple approximation that is useful in decibel calculations is that an addition or subtraction of 3 dB approximately represents a two-fold multiplication or division of power ratio.

Here are some numerical examples based on the equivalence of $\pm 10 \mathrm{~dB}$ with orders of magnitude:

- Power ratio gain of $10=\mathbf{1 0} \mathbf{~ d B}$
- Power ratio gain of $100=\mathbf{2 0} \mathbf{~ d B}$
- Power ratio gain of $1000=\mathbf{3 0} \mathbf{~ d B}$
- Power ratio gain of $10000=40 \mathrm{~dB}$
- Power ratio reduction of $\frac{1}{10}=-\mathbf{1 0} \mathbf{~ d B}$
- Power ratio reduction of $\frac{1}{100}=\mathbf{- 2 0} \mathbf{~ d B}$
- Power ratio reduction of $\frac{1}{1000}=-\mathbf{3 0} \mathbf{d B}$
- Power ratio reduction of $\frac{1}{10000}=-40 \mathrm{~dB}$

Here are some numerical examples based on the approximation of $\pm 3 \mathrm{~dB}$ being equivalent to doubling or halving of power ratio:

- Power ratio gain of $2 \approx 3 \mathbf{d B}$
- Power ratio gain of $4 \approx 6 \mathbf{d B}$
- Power ratio gain of $8 \approx \mathbf{9} \mathbf{d B}$
- Power ratio gain of $16 \approx \mathbf{1 2} \mathbf{d B}$
- Power ratio reduction of $\frac{1}{2} \approx-\mathbf{3} \mathbf{d B}$
- Power ratio reduction of $\frac{1}{4} \approx-\mathbf{6} \mathbf{d B}$
- Power ratio reduction of $\frac{1}{8} \approx-\mathbf{9} \mathbf{d B}$
- Power ratio reduction of $\frac{1}{16} \approx \mathbf{- 1 2} \mathbf{d B}$

Example approximations:

- Power ratio of $500=10 \times 10 \times 10 \times \frac{1}{2} \approx(10+10+10-3) \mathrm{dB}=\mathbf{2 7} \mathbf{d B}$
- Power ratio of $80=10 \times 2 \times 2 \times 2 \approx(10+3+3+3) \mathrm{dB}=19 \mathrm{~dB}$
- Power ratio of $0.2=\frac{1}{10} \times 2 \approx(-10+3) \mathrm{dB}=-7 \mathrm{~dB}$
- Power ratio of $0.005=\frac{1}{10} \times \frac{1}{10} \times \frac{1}{2} \approx(-10-10-3) \mathrm{dB}=-\mathbf{2 3} \mathbf{~ d B}$


### 2.2 Example: cable loss calculations

If a radio transmitter sends 15 Watts of power into a coaxial cable having a loss rating of -0.16 dB per meter, and the cable is 20 meters in length, the power available at the far end of the cable must be 7.1795 Watts.

If an RF signal source sends 10 mW into one end of a 5 -meter cable and the other end of the cable outputs 8 mW of signal power, the cable must have a loss rating of $\mathbf{- 0 . 1 9 4} \mathrm{dB}$ per meter.

An RF signal of 2 Watts exits a cable 3 meters in length having a loss rating of -0.14 dB per meter. The amount of power being input to this cable must be 2.203 Watts.

An RF signal of 15 Watts enters one end of a cable having a loss rating of -0.21 dB per foot, and an RF signal of 10 Watts exits the other end of that same cable. The cable's length must be $\mathbf{8 . 3 8 5 3 0}$ feet.

A 50-Watt radio transmitter connected to a 12 -foot cable having a loss rating of $0.041 \mathrm{~dB} /$ foot terminates at a lightning arrestor with a loss rating of 0.5 dB , and finally to an antenna. The amount of power received by this antenna will be 39.7896 Watts.

### 2.3 Example: path loss calculations

A radio transmitter broadcasts a 800 kHz RF signal at a power level of 10 kW into the surrounding environment. At a distance of 40 kilometers away from the transmitting antenna, the signal power has spread out to just $\mathbf{0 . 0 0 5 5 6 5 7 3 8 8}$ Watts.

A radio transmitter broadcasts a 92 MHz RF signal such that the antenna's actual power output into the surrounding environment is 75 kW , and a radio receiver unit requires a signal that is at least -50 dBm at its antenna to reliably interpret this broadcast. The maximum distance away that this receiver can pick up the transmitter's signal is $\mathbf{7 1 0 . 6 4 7}$ kilometers, assuming no fade loss.

A 900 MHz radio transmitter using a +6 dBi antenna is able to broadcast a signal to a single receiving station 50 km away with bare-minimum signal integrity. If the transmitter's antenna is upgraded to a more directional model having a gain of +18 dBi , that maximum distance now becomes 199.054 km .

A 900 MHz radio transmitter is able to broadcast a signal to a single receiving station 10 km away with bare-minimum signal integrity. If the entire radio system is changed from 900 MHz to 2.4 GHz , the new maximum distance will be $\mathbf{3 . 7 5} \mathbf{~ k m}$ assuming identical cable losses, identical antenna gains, identical transmitter power, identical receiver sensitivity, and identical operating conditions (weather, obstacles, no Fresnel zone interference in either case, etc.).

Suppose a radio transmitting antenna radiates 45 Watts of RF energy in a particular direction, and a receiving antenna intercepts 1.4 microWatts of RF energy from it. Assuming a frequency of 700 kHz and clear (uninterrupted) space in between with no Fresnel zone interference or fade loss, the distance between these two antennas must be 193.22 km .

### 2.4 Examples: RF link budget calculations

The following parameters describe an RF communication system:

- Frequency $=900 \mathrm{MHz}$
- Path distance $=720$ meters
- Receiver sensitivity $=-109 \mathrm{dBm}$
- Transmitter cable $=-0.25 \mathrm{~dB}$ per foot @ $900 \mathrm{MHz} ; 12$ feet long
- Transmitter lightning arrestor $=-0.2 \mathrm{~dB}$ insertion loss
- Transmitter antenna $=6 \mathrm{~dB}$ gain
- Receiver lightning arrestor $=-0.2 \mathrm{~dB}$ insertion loss
- Receiver cable $=-0.25 \mathrm{~dB}$ per foot $@ 900 \mathrm{MHz} ; 16$ feet long
- Receiver antenna $=13 \mathrm{~dB}$ gain

From these figures, we may calculate the bare-minimum minimum transmitter power required in this application (with no fade margin) to be $-31.93 \mathbf{d B m}$ or $\mathbf{0 . 6 4 3} \mathbf{~ m i c r o W a t t s . ~}$


Lightning arrestors are installed at both the MTU and the RTU antennas in a two-station radio SCADA system. Each arrestor has an advertised power loss of -0.55 dB . A new transmitter with increased power output is specified to overcome these arrestor losses. Given that the old transmitter had an output power of 3.2 milliWatts, the new transmitter must have an output power of $\mathbf{4 . 1 2 2}$ milliWatts to overcome these new losses.

Suppose an RTU in a radio SCADA system is able to receive an RF signal strength of 0.17 microWatts from the MTU using a standard "whip" antenna having a gain of 5.8 dBi . If we were to replace this whip antenna with a Yagi having a gain of 11.4 dBi , the RTU would now receive $\mathbf{0 . 6 1 7}$ microWatts of RF power.

Suppose a radio receiver unit is equipped with a lightning arrestor that presents a signal power attenuation of -0.4 dB . During a storm, this arrestor is damaged. Lacking a replacement on hand, you decide to remove it from the system and re-connect the antenna directly to the receiver with no lighting arrestor at all, at least until you can purchase and install a new arrestor. If the receiver originally was able to intercept an RF signal of 0.8 microWatts with the arrestor in place, the new received signal power level without the arrestor in place will be $\mathbf{0 . 8 7 7 2}$ microWatts.

## Chapter 3

## Tutorial

All radio transmitters are limited in power output. All radio receivers are limited in sensitivity to weak signals. Every device, every obstacle, and even empty space itself affects the attenuation of the radio-frequency (RF) signal from transmitter to receiver. Energy is always conserved, and so in order to design a reliable radio communication system one must carefully budget the available power in the same way one must budget financial resources when embarking on a project to ensure it may be successfully completed.

Each of the sections in this Tutorial outline a different aspect of $R F$ link budgeting, and should be considered an introduction to the topic rather than a comprehensive tutorial.

### 3.1 Effective radiated power

When determining the effectiveness of a radio system, one must include losses in cables, connectors, lightning arrestors, and other elements in the signal path in addition to the antenna itself. A commonly accepted way to quantify this effectiveness is to rate a radio system against a standard reference consisting of an ideal dipole antenna connected to a 1 milliWatt transmitter with no losses. Typically expressed in units of decibels, this is called the Effective Radiated Power, or ERP. If the ideal antenna model is isotropic instead of a dipole, then the calculation result is called the Effective Isotropic Radiated Power, or EIRP.

Let us consider the following example, where a 2.4 GHz radio transceiver outputs 250 milliWatts ${ }^{1}$ of radio-frequency (RF) power to a Yagi antenna through a type LMR 195 coaxial cable 12 feet in length. A lightning arrestor with 0.5 dB loss is also part of the cable system. We will assume an antenna gain of 9 dBi for the Yagi and a loss of 0.19 dB per foot for the LMR 195 cable:


The EIRP for this radio system is 30.2 dBm : the sum of all gains and losses expressed in decibels. This means our Yagi antenna will radiate 30.2 dB (1047 times) more RF power in its most effective

[^0]direction than an isotropic antenna would radiate in the same direction powered by a 1 milliWatt transmitter. Note that if our hypothetical radio system also included an RF amplifier between the transceiver and the antenna, its gain would have to be included in the EIRP calculation as well.

A practical application of EIRP is how the Federal Communications Commission (FCC) sets limits on radio transmitters within the United States. Not only is gross transmitter power limited by law within certain frequency ranges, but also the EIRP of a transmitting station. This makes sense, since a more directional transmitting antenna (i.e. one having a greater gain value) will make it appear as though the transmitter is more powerful than it would be radiating from a lessdirectional antenna. If FCC limits were based strictly on transmitter power output rather than EIRP, it might still be possible for an otherwise power-compliant transmitting station to generate excessive interference through the use of a highly directional antenna. This is why it is illegal, for example, to connect a large antenna to a low-power transmitting device such as a two-way ("walkie-talkie") radio unit: the two-way radio unit may be operated license-free only because its EIRP is low enough not to cause interference with other radio systems. If someone were to connect a more efficient antenna to this same two-way radio, its effective radiated power may increase to unacceptable levels (according to the FCC) even though the raw power output by the transmitter circuitry has not been boosted.

### 3.2 Link budget fundamentals

Electromagnetic radiation is a medium useful for conveying information, "linking" data from one physical location to another. In order for this to work, the amount of signal loss between transmitter and receiver must be small enough that the signal does not become lost in radio-frequency "noise" originating from external sources and from within the radio receiver itself. We may express radiofrequency ( RF ) power in terms of its comparison to 1 milliWatt: 0 dBm being 1 milliWatt, 3.01 dBm being 2 milliWatts, 20 dBm being 100 milliWatts, etc. We may use dBm as an absolute measurement scale for transmitted and received signal strengths, as well as for expressing how much ambient RF noise is present (called the "noise floor" for its appearance at the bottom of a spectrum analyzer display showing the frequency-domain view of the electromagnetic spectrum for a given test). We may use plain dB to express relative gains and losses along the signal path.

The basic idea behind an "RF link budget" is to add all gains and losses in an RF system from transmitter to receiver with all intermediate elements accounted for - to ensure there is a large enough difference between signal and noise to ensure good data communication integrity. If we account all gains as positive decibel values and all losses as negative decibel values, the signal power at the receiver will be the simple sum of all the gains and losses:

$$
P_{r x}=P_{t x}+G_{t o t a l}+L_{t o t a l}
$$

Where,
$P_{r x}=$ Signal power delivered to receiver input (dBm)
$P_{t x}=$ Transmitter output signal power (dBm)
$G_{t o t a l}=$ Sum of all gains (amplifiers, antenna directionality, etc.), a positive dB value
$L_{\text {total }}=$ Sum of all losses (cables, filters, path loss, fade, etc.), a negative dB value
This formula tells us how much signal power will be available at the radio receiver, but usually the purpose of calculating a link budget is to determine how much radio transmitter power will be necessary in order to have adequate signal strength at the receiver. More transmitter power adds expense, not only due to transmitter hardware cost but also to FCC licenses that are required if certain power limitations are exceeded. Excessive transmitter power may also create interference problems with other radio and electronic systems. Suffice it to say we wish to limit transmitter power to the minimum practical value.

In order for a radio receiver to reliably detect an incoming signal, that signal must be sufficiently greater than the ambient RF noise. All masses at temperatures above absolute zero radiate electromagnetic energy, with some of that energy falling within the RF spectrum. This noise floor value may be calculated ${ }^{2}$ or empirically measured using an RF spectrum analyzer as shown in this simulated illustration:

## Spectrum analyzer display



On top of the ambient noise, we also have the noise figure of the receiver itself $\left(N_{r x}\right)$ : noise created by the electronic circuitry within the radio receiver. Thus, the minimum signal power necessary for the receiver to operate reliably $\left(P_{r x(\min )}\right)$ is equal to the decibel sum of the noise floor and the noise figure, by a margin called the minimum signal-to-noise ratio:

$$
P_{r x(\min )}=N_{f}+N_{r x}+S
$$

Where,
$P_{r x(\text { min })}=$ Minimum necessary signal power at the receiver input $(\mathrm{dBm})$
$N_{f}=$ Noise floor value (dBm)
$N_{r x}=$ Noise figure of radio receiver (dB)
$S=$ Desired signal-to-noise ratio margin (dB)
Substituting this decibel sum into our original RF link budget formula and solving for the minimum necessary transmitter power output $\left(P_{t x(\min )}\right)$, we get the following result:

$$
P_{t x(\min )}=N_{f}+N_{r x}+S-\left(G_{t o t a l}+L_{t o t a l}\right)
$$

[^1]It is common for radio receiver manufacturers to aggregate the noise floor, noise figure, and a reasonable signal-to-noise ratio into a single parameter called receiver sensitivity. The "sensitivity" of a radio receiver unit is the minimum amount of signal power (usually expressed in dBm ) necessary at the input connector for reliable operation despite the inevitable presence of noise. If we simply express receiver sensitivity as $P_{r x(\text { min })}$ and substitute this term for the sum of noise floor, noise figure, and signal-to-noise margin $\left(N_{f}+N_{r x}+S\right)$ in the last formula, we see that the difference in receiver sensitivity (expressed in absolute decibels) and the sum of any gains and losses in the link (also expressed in decibels) tells us the minimum transmitter power required:

$$
P_{t x(\min )}=P_{r x(\min )}-\left(G_{t o t a l}+L_{t o t a l}\right)
$$

Where,
$P_{t x(\min )}=$ Minimum necessary transmitter output signal power, in dBm
$P_{r x(\text { min })}=$ Receiver sensitivity (minimum necessary received signal power), in dBm
$G_{\text {total }}=$ Sum of all gains (amplifiers, antenna directionality, etc.), a positive dB value
$L_{\text {total }}=$ Sum of all losses (cables, filters, path loss, fade, etc.), a negative dB value
For digital radio receivers, sensitivity is a function of error rate: the fewer errors desired, the more signal power required. To give a practical example, the datasheet for a particular model of industrial 900 MHz radio transceiver shows a sensitivity of -110 dBm at a bit error rate (BER) of $10^{-4}$ bits (one error for every $10^{4}$ bits received) and a sensitivity of -108 dBm at a BER of $10^{-6}$ bits. This relationship between signal power and error rate should make intuitive sense: the more powerful the signal compared to any background noise, the more reliably it will be received; the weaker the signal, the more it will become corrupted by noise and therefore the more errors we would expect to see over time.

Among the losses encompassed in $L_{\text {total }}$ are path loss and fade. Path loss is the natural loss of signal strength with increasing distance from the radiation source. As electromagnetic waves propagate outward through space, they inevitably spread. The degradation in signal strength with increasing distance follows the inverse square law ${ }^{3}$, where power decreases with the square of distance. Thus, doubling the distance from transmitting antenna to receiving antenna attenuates the signal by a factor of four $\left(\frac{1}{2^{2}}\right.$, or $\left.-6.02 \mathrm{~dB}\right)$. Tripling the distance from transmitting antenna to receiving antenna attenuates the signal by a factor of nine $\left(\frac{1}{3^{2}}\right.$, or $\left.-9.54 \mathrm{~dB}\right)$.

Path loss for free-space conditions is a rather simple function of distance and wavelength:

$$
L_{p}=-20 \log \left(\frac{4 \pi D}{\lambda}\right)
$$

Where,
$L_{p}=$ Path loss, a negative dB value
$D=$ Distance between transmitting and receiving antennas
$\lambda=$ Wavelength of transmitted RF field, in same physical unit as $D$
It should be emphasized that this simple path loss formula only applies to completely clear, empty space where the only mechanism of signal attenuation is the natural spreading of radio waves as they radiate away from the transmitting antenna. Path loss will be significantly greater if any objects or other obstructions lie between the transmitting and receiving antennas.

[^2]This same spreading effect also accounts for "fade" - also known as multipath-induced fading - where radio waves taking different paths deconstructively interfere with each other, resulting in weakened signals at some locations but not in others equidistant from the transmitter. You may have personally experienced fade while driving a vehicle over long distances and listening to an analog (AM or FM) radio: sometimes a particular radio station's signal will "fade out" as you drive and then "fade in" again while driving in the same direction, for no obvious reason (e.g. no immediate obstructions to the signal). This is due to radio waves from the station emanating in all directions, then reflecting off of large objects and/or ionized regions high in the earth's atmosphere. There will inevitably be locations around that station where the incident wave from the transmitting antenna destructively interferes with those reflected waves, the result being regions of "dead" space where the signal is much weaker than one would expect from path loss alone:


This is not unlike the phenomenon of certain seats in a concert hall having better acoustical properties than others, even when equidistant from the stage. Sound waves don't just travel straight from the performers to the audience members; they also reflect off of the concert hall's wall surfaces, and as a result there will be some seats where there is deconstructive interference between the direct sound wave (straight from the performer) and the reflected sound wave (bouncing off the wall) resulting in less volume at that particular seat location. Moving just a few seats away will avoid this "fade zone" and result in better sound quality.

Fade is a far more difficult factor to predict than path loss because of the complexity of modeling the interference patterns between all possible travel pathways from transmitter to receiver, and so generally radio system designers combat this loss by including a generous margin ${ }^{4}$ of excess transmitter power to overcome the effects of fade. This fade margin is typically 20 dB to 30 dB , although it can be greater in scenarios where there are many signal paths due to reflections.

[^3]To illustrate, we will calculate the RF link budget for a 900 MHz radio transmitter/receiver pair directionally oriented toward each other with Yagi antennas. All sources of signal gain and loss will be accounted for, including the "path loss" of the RF energy as it travels through open air. The gains and losses of all elements are shown in the following illustration:


The path loss value shown in the illustration is a calculated function of the 900 MHz wavelength ( $\lambda=\frac{c}{f}=0.3331$ meters) and the distance between antennas ( 500 feet $=152.4$ meters), assuming a completely obstruction-free path between antennas:

$$
L_{p}=-20 \log \left(\frac{4 \pi(152.4)}{0.3331}\right)=-75.19 \mathrm{~dB}
$$

According to the receiver manufacturer's specifications, the receiver in this system has a sensitivity of -75 dBm , which means our transmitter must be powerful enough to deliver an RF signal at least as strong as -75 dBm at the receiver's input connector in order to reliably communicate data. Inserting this receiver sensitivity figure into our RF link budget formula:

$$
\begin{gathered}
P_{t x(\min )}=P_{r x(\min )}-\left(G_{t o t a l}+L_{t o t a l}\right) \\
P_{t x(\min )}=-75 \mathrm{dBm}-\left(G_{t o t a l}+L_{t o t a l}\right)
\end{gathered}
$$

Now we need to tally all the gains and losses between the transmitter and the receiver. I strongly recommend making a table (as shown below) to hold all the different gain and loss values, as it becomes easy to miss or wrongly apply one of the many decibel values required for a full link budget calculation if these values are not neatly organized in one place. We will use a value of -20 dB for fade margin (i.e. our budget will leave room for up to 20 dB of power loss due to the effects of fade):

| Gain or Loss | Decibel value |
| :---: | :---: |
| Transmitter cable loss | -5.64 dB |
| Transmitter arrestor loss | -0.5 dB |
| Transmitter antenna gain | +12.1 dBi |
| Path loss | -75.19 dB |
| Fade margin | -20 dB |
| Receiver antenna gain | +12.1 dBi |
| Receiver arrestor loss | -0.5 dB |
| Receiver cable loss | -4.23 dB |
| $G_{\text {total }}+L_{\text {total }}$ | $-\mathbf{8 1 . 8 6} \mathbf{~ d B}$ |

Inserting the decibel sum of all gains and losses into our RF link budget formula:

$$
\begin{gathered}
P_{t x(m i n)}=-75 \mathrm{dBm}-(-81.86 \mathrm{~dB}) \\
P_{t x(\text { min })}=6.86 \mathrm{dBm}
\end{gathered}
$$

Converting a dBm value into milliWatts of $R F$ power means we must manipulate the dBm power formula to solve for $P_{m W}$ :

$$
\begin{gathered}
P_{d B m}=10 \log \left(\frac{P_{m W}}{1 \mathrm{~mW}}\right) \\
P_{m W}=1 \mathrm{~mW} \times 10^{\left(\frac{P_{d B m}}{10}\right)} \\
P_{t x}=1 \mathrm{~mW} \times 10^{\left(\frac{6.86}{10}\right)}=4.85 \text { milliWatts }
\end{gathered}
$$

At this point we would do well to take stock of our assumptions. Power gains and losses inherent to the components (cables, arrestors, antennas) are quite certain because these are tested components, so we should not doubt these figures. Less certain are the environmental factors: noise floor can change, path loss will differ from our calculation if there is any obstruction near the signal path or under certain weather conditions (e.g. rain or snow dissipating RF energy), and fade loss is known to change dynamically as moving objects (people, vehicles) pass anywhere between the transmitter or receiver antennas. Our RF link budget calculation is really only a rough estimate of the transmitter power needed to get the job done.

How then do we improve our odds of building a reliable system? One way is to over-build it by equipping the transmitter with more power than the most pessimistic link budget predicts. However, this can cause other problems such as interference with nearby electronic systems if we are not careful. A preferable method is to conduct a site test where the real equipment is set up in the field and tested to ensure adequate received signal strength.

### 3.3 Link budget graph

Many of the concepts previously explored may be represented in a single graph ${ }^{5}$, showing RF signal strength as a function of physical position within the RF link (from transmitter to receiver). The horizontal axis of this graph represents the position along the link path from transmitter to receiver, while the vertical axis represents RF signal strength in dBm :


At the very bottom of this graph we see the noise floor, representing natural RF noise that is unavoidable. Above that we see the added noise figure and signal/noise ratios summing up to a higher line representing the receiver's sensitivity, which is the minimum amount of signal power it must receive in order to reliably function.

Near the top of this graph we see a series of thicker line segments representing the various losses and gains within the system. Single-point losses such as lightning arrestors appear as vertical downward steps, while progressive losses such as cables and path loss appear as downward slopes. Single-point gains such as antennas appear as vertical upward steps. Note where EIRP appears on this graph: the amount of signal power at the transmitting antenna's output, factoring in the antenna's gain as well as any losses between the transmitter and the transmitting antenna. As previously mentioned, the Federal Communications Commission (FCC) sets regulatory limits for EIRP in the United States, because if only the transmitter's output power were regulated, it would be possible to thwart that limit using high-gain antennas.

At the far right-hand end of the graph, we see the difference between the receiver's input signal power and the receiver's sensitivity as a margin for the link budget. This margin must exist in order to grant the system tolerance to unexpected power losses such as those resulting from inclement weather, interference from objects within the link path, cable deterioration, coupling corrosion, increases in noise floor, etc.

[^4]
### 3.4 Fresnel zones

One of the many factors affecting RF link power transfer from transmitter to receiver is the openness of the signal path between the transmitting and receiving antennas. As shown in the previous section, path loss is relatively simple to calculate given the assumption of totally empty space between the two antennas. With no obstacles in between, path loss is simply a consequence of wave dispersion (spreading). Unless we are calculating an RF link budget between two airplanes or two spacecraft, though, there really is no such thing as totally empty space between the transmitting and receiving antennas. Buildings, trees, vehicles, and even the ground are all objects potentially disrupting what would otherwise be completely open space between transmitter and receiver.

A common expression in microwave radio communication is line-of-sight, or LoS. The very wording of this phrase evokes an image of being able to see a straight path between transmitting and receiving antennas. Obviously, if one does not have a clear line-of-sight path between antennas, the signal path loss will definitely be more severe than through open space. However, a common error is in thinking that the mere existence of an unobstructed straight line between antennas is all that is needed for unhindered communication, when in fact nothing could be further from the truth:


In fact, the free space necessary to convey energy in electromagnetic wave form takes on the form of football-shaped zones: the first one solid followed by annular (hollow) zones concentrically surrounding the first. These elliptical volumes are called Fresnel zones:

Fresnel zones


The precise shapes of these Fresnel zones are a function of wavelength and distance between antennas, not the size or configurations of the antennas themselves. In other words, you cannot change the Fresnel zone sizes or shapes by merely altering antenna types. This is because the

Fresnel zones do not actually map the distribution of electromagnetic fields, but rather map the free space we need to keep clear between antennas ${ }^{6}$.

If any object protrudes at all into any Fresnel zone, it diminishes the signal power communicated between the two antennas. In microwave communication ( GHz frequency range), the inner-most Fresnel zone carries most of the power, and is therefore the most important from the perspective of interference. Keeping the inner-most Fresnel zone absolutely clear of interference is essential for maintaining ideal path-loss characteristics (equivalent to open-space). A common rule followed by microwave system designers is to try to maintain an inner Fresnel zone that is at least $60 \%$ free of obstruction.

In order to design a system with this goal in mind, we need to have some way of calculating the width of that Fresnel zone. Fortunately, this is easily done with the following formula:

$$
r=\sqrt{\frac{n \lambda d_{1} d_{2}}{D}}
$$

Where,
$r=$ Radius of Fresnel zone at the point of interest
$n=$ Fresnel zone number (an integer value, with 1 representing the first zone)
$d_{1}=$ Distance between one antenna and the point of interest
$d_{2}=$ Distance between the other antenna and the point of interest
$D=$ Distance between both antennas
$\lambda=$ Wavelength of transmitted RF field, in same physical unit as $D, d_{1}$, and $d_{2}$
Note: the units of measurement in this formula may be any unit of length, so long as they are all the same unit.


[^5]To illustrate by example, let us calculate the radius of the first Fresnel zone for two microwave antennas operating at 2.4 GHz , separated by one mile ( 1.609 km ), at the widest portion of that zone. The wavelength of a 2.4 GHz signal is 0.1249 meters, from the formula $\lambda=\frac{c}{f}$. Distances $d_{1}$ and $d_{2}$ will both be equal to one-half of the total distance, since the widest portion of the Fresnel zone will be exactly at its mid-point between the two antennas ( $d_{1}=d_{2}=804.7$ meters). Here, we solve for $r$ as follows:

$$
\begin{gathered}
r=\sqrt{\frac{n \lambda d_{1} d_{2}}{D}} \\
r=\sqrt{\frac{(1)(0.1249)\left(804.7^{2}\right)}{1609}} \\
r=7.089 \text { meters }
\end{gathered}
$$

Consider for a moment the significance of this dimension. At the very least, it means the antennas must be mounted this high off the ground in order to avoid having the most important Fresnel zone contact the earth itself (assuming level terrain), not to mention any objects above ground level such as buildings, vehicles, or trees between the two antennas. Consider also that the Fresnel zone is football-shaped, and therefore this 7.089 meter radius extends horizontally from the centerline connecting both antennas as well as vertically. This means that in order for this Fresnel zone to be untouched, there must be a clear path 14.18 meters wide in addition to the antennas being at least 7.089 meters off the ground! If we were to consider a 900 MHz signal - another common frequency for industrial wireless devices - the minimum height above ground would be 11.58 meters, and the minimum clear path width 23.16 meters!

As you can see, "line of sight" is not as simple as it may first appear.

## 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 Decibels

One of the mathematical tools popularly used to gauge increases and decreases of electrical power is the common logarithm, expressed as a measurement unit called the decibel. The basic idea of decibels is to express a ratio of two electrical power quantities in logarithmic terms. Every time you see the unit of "decibel" you can think: this is an expression of how much greater (or how much smaller) one power is to another. The only question is which two powers are being compared.

Electronic amplifiers are a type of electrical system where comparisons of power are useful. Students of electronics learn to compare the output power of an amplifier against the input power as a unitless ratio, called a gain. Take for example an electronic amplifier with a signal input of 40 milliWatts and a signal output of 18.4 Watts:


An alternative way to express the gain of this amplifier is to do so using the unit of the Bel, defined as the common logarithm of the gain ratio:

$$
\log \left(\frac{P_{\text {out }}}{P_{\text {in }}}\right)=\log \left(\frac{18.4 \mathrm{~W}}{40 \mathrm{~mW}}\right)=2.66276 \mathrm{~B}
$$

When you see an amplifier gain expressed in the unit of "Bel", it's really just a way of saying "The output signal coming from this amplifier is $x$ powers of ten greater than the input signal." An amplifier exhibiting a gain of 1 Bel outputs 10 times as much power as the input signal. An amplifier with a gain of 2 Bels boosts the input signal by a factor of 100 . The amplifier shown above, with a gain of 2.66276 Bels, boosts the input signal 460 -fold.

At some point in technological history it was decided that the "Bel" (B) was too large and cumbersome, and so it became common to express powers in fractions of a Bel instead: the deciBel $\left(1 \mathrm{~dB}=\frac{1}{10}\right.$ of a Bel). Therefore, this is the form of formula you will commonly see for expressing electrical signal power gains or losses:

$$
\mathrm{dB}=10 \log \left(\frac{P_{\text {out }}}{P_{\text {in }}}\right)
$$

The gain of our hypothetical electronic amplifier, therefore, would be more commonly expressed as 26.6276 dB rather than 2.66276 B , although either expression is technically valid ${ }^{1}$.

[^6]An operation students often struggle with is converting a decibel figure back into a ratio, since the concept of logarithms seems to be universally perplexing. Here I will demonstrate how to algebraically manipulate the decibel formula to solve for the power ratio given a dB figure.

First, we will begin with the decibel formula as given, solving for a value in decibels given a power ratio:

$$
\mathrm{dB}=10 \log (\text { Ratio })
$$

If we wish to solve for the ratio, we must "undo" all the mathematical operations surrounding that variable. One way to determine how to do this is to reverse the order of operations we would follow if we knew the ratio and were solving for the dB value. After calculating the ratio, we would then take the logarithm of that value, and then multiply that logarithm by 10: start with the ratio, then take the logarithm, then multiply last. To un-do these operations and solve for the ratio, we must un-do each of these operations in reverse order. First, we must un-do the multiplication (by dividing by 10 ):

$$
\begin{gathered}
\frac{\mathrm{dB}}{10}=\frac{10 \log (\text { Ratio })}{10} \\
\frac{\mathrm{~dB}}{10}=\log (\text { Ratio })
\end{gathered}
$$

Next, we must un-do the logarithm function by applying its mathematical inverse to both sides of the formula - making each expression a power of 10 :

$$
\begin{gathered}
10^{\frac{\mathrm{dB}}{10}}=10^{\log (\text { Ratio })} \\
10^{\frac{\mathrm{dB}}{10}}=\text { Ratio }
\end{gathered}
$$

To test our algebra, we can take the previous decibel value for our hypothetical amplifier and see if this new formula yields the original gain ratio:

$$
\begin{gathered}
\text { Ratio }=10^{\frac{26.6276 \mathrm{~dB}}{10}} \\
\text { Ratio }=10^{2.66276 \mathrm{~B}} \\
\text { Ratio }=460
\end{gathered}
$$

Sure enough, we arrive at the correct gain ratio of 460, starting with the decibel gain figure of 26.6276 dB .

[^7]We may also use decibels to express power losses in addition to power gains. There are many practical applications of this in signaling systems, both electronic and optical. One such application is filtering, where a "filter" circuit screens out certain components of the signal while letting others pass through (e.g. the bass or treble control for an audio system). Another application is attenuation, where the entirety of a signal is reduced in magnitude (e.g. the volume control for an audio system).

We will explore yet another application of signal power reduction as a case study for decibels: cable loss. Cables designed to convey signals over long distances are not perfect conduits of energy, as some of the signal's energy is inevitably lost along the way. This is true for different types of signals, electrical and optical being two popular examples. In the following illustration we see a signal cable losing power along its length ${ }^{2}$, such that the power out is less than the power in:


Contrasting this result against the previous result (with the amplifier) we see a very important property of decibel figures: any power gain is expressed as a positive decibel value, while any power loss is expressed as a negative decibel value. Any component outputting the exact same power as it takes in will exhibit a "gain" value of 0 dB (equivalent to a gain ratio of 1 ).

Remember that Bels and decibels are nothing more than logarithmic expressions of "greater than" and "less than". Positive values represent powers that are greater while negative values represent powers that are lesser. Zero Bel or decibel values represent no change (neither gain nor loss) in power.

A couple of simple decibel values are useful to remember for approximations, where you need to quickly estimate decibel values from power ratios (or vice-versa). Each addition or subtraction of 10 dB exactly represents a 10 -fold multiplication or division of power ratio: e.g. +20 dB represents a power ratio gain of $10 \times 10=100$, whereas -30 dB represents a power ratio reduction of $\frac{1}{10} \times \frac{1}{10}$ $\times \frac{1}{10}=\frac{1}{1000}$. Each addition or subtraction of 3 dB approximately represents a 2 -fold multiplication or division or power ratio: e.g. +6 dB is approximately equal to a power ratio gain of $2 \times 2=4$, whereas -12 dB is approximately equal to a power ratio reduction of $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}=\frac{1}{16}$. We may combine $\pm 10 \mathrm{~dB}$ and $\pm 3 \mathrm{~dB}$ increments to come up with ratios that are products of 10 and 2: e.g. +26 dB is approximately equal to a power ratio gain of $10 \times 10 \times 2 \times 2=400$.

[^8]Observe what happens if we combine a "gain" component with a "loss" component and calculate the overall power out versus power in:


The overall gain of this amplifier and cable system expressed as a ratio is equal to the product of the individual component gain/loss ratios. That is, the gain ratio of the amplifier multiplied by the loss ratio of the cable yields the overall power ratio for the system:

$$
\text { Overall gain }=\frac{17.02 \mathrm{~W}}{40 \mathrm{~mW}}=(460)(0.925)=425.5
$$

The overall gain may be alternatively expressed as a decibel figure, in which case it is equal to the sum of the individual component decibel values. That is, the decibel gain of the amplifier added to the decibel loss of the cable yields the overall decibel figure for the system:

$$
\text { Overall gain }=10 \log \left(\frac{17.02 \mathrm{~W}}{40 \mathrm{~mW}}\right)=26.6276 \mathrm{~dB}+(-0.3386 \mathrm{~dB})=26.2890 \mathrm{~dB}
$$

It is often useful to be able to estimate decibel values from power ratios and vice-versa. If we take the gain ratio of this amplifier and cable system (425.5) and round it down to 400, we may easily express this gain ratio as an expanded product of 10 and 2 :

$$
425.5 \approx 400=(10) \times(10) \times(2) \times(2)
$$

Knowing that every 10 -fold multiplication of power ratio is an addition of +10 dB , and that every 2 -fold multiplication of power is an addition of +3 dB , we may express the expanded product as a sum of decibel values:

$$
(10) \times(10) \times(2) \times(2)=(10 \mathrm{~dB})+(10 \mathrm{~dB})+(3 \mathrm{~dB})+(3 \mathrm{~dB})=26 \mathrm{~dB}
$$

Therefore, our power ratio of 425.5 is approximately equal to +26 decibels.

Decibels always represent comparisons of power, but that comparison need not always be $P_{\text {out }} / P_{\text {in }}$ for a system component. We may also use decibels to express an amount of power compared to some standard reference. If, for example, we wished to express the input power to our hypothetical amplifier ( 40 milliWatts) using decibels, we could do so by comparing 40 mW against a standard "reference" power of exactly 1 milliWatt. The resulting decibel figure would be written as "dBm" in honor of the 1 milliWatt reference:

$$
P_{\text {in }}=10 \log \left(\frac{40 \mathrm{~mW}}{1 \mathrm{~mW}}\right)=16.0206 \mathrm{dBm}
$$

The unit of "dBm" literally means the amount of dB "greater than" 1 milliWatt. In this case, our input signal of 40 milliWatts is 16.0206 dB greater than a standard reference power of exactly 1 milliWatt. The output power of that amplifier (18.4 Watts) may be expressed in dBm as well:

$$
P_{\text {out }}=10 \log \left(\frac{18.4 \mathrm{~W}}{1 \mathrm{~mW}}\right)=42.6482 \mathrm{dBm}
$$

A signal power of 18.4 Watts is 42.6482 dB greater than a standard reference power of exactly 1 milliWatt, and so it has a decibel value of 42.6482 dBm .


Notice how the output and input powers expressed in dBm relate to the power gain of the amplifier. Taking the input power and simply adding the amplifier's gain factor yields the amplifier's output power in dBm :

$$
\begin{gathered}
P_{\text {in }}(\mathrm{dB})+P_{\text {gain }}(\mathrm{dB})=P_{\text {out }}(\mathrm{dB}) \\
16.0206 \mathrm{dBm}+26.6276 \mathrm{~dB}=42.6482 \mathrm{dBm}
\end{gathered}
$$

An electronic signal that begins 16.0206 dB greater than 1 milliWatt, when boosted by an amplifier gain of 26.6276 dB , will become 42.6482 dB greater than the original reference power of 1 milliWatt.

We may alternatively express all powers in this hypothetical amplifier in reference to a 1-Watt standard power, with the resulting power expressed in units of "dBW" (decibels greater than 1 Watt):

$$
\begin{aligned}
& P_{\text {in }}=10 \log \left(\frac{40 \mathrm{~mW}}{1 \mathrm{~W}}\right)=-13.9794 \mathrm{dBW} \\
& P_{\text {out }}=10 \log \left(\frac{18.4 \mathrm{~W}}{1 \mathrm{~W}}\right)=12.6482 \mathrm{dBW}
\end{aligned}
$$



Note how the input power of 40 milliWatts equates to a negative dBW figure because 40 milliWatts is less than the 1 Watt reference, and how the output power of 18.4 Watts equates to a positive dBW figure because 18.4 Watts is more than the 1 Watt reference. A positive dB figure means "more than" while a negative dB figure means "less than."

Note also how the output and input powers expressed in dBW still relate to the power gain of the amplifier by simple addition, just as they did when previously expressed in units of dBm. Taking the input power in units of dBW and simply adding the amplifier's gain factor yields the amplifier's output power in dBW:

$$
\begin{gathered}
P_{\text {in }}(\mathrm{dB})+P_{\text {gain }}(\mathrm{dB})=P_{\text {out }}(\mathrm{dB}) \\
-13.9794 \mathrm{dBW}+26.6276 \mathrm{~dB}=12.6482 \mathrm{dBW}
\end{gathered}
$$

An electronic signal that begins 13.9794 dB less than 1 Watt, when boosted by an amplifier gain of 26.6276 dB , will become 12.6482 dB greater than the original reference power of 1 Watt.

This is one of the major benefits of using decibels to express powers: we may very easily calculate power gains and losses by summing a string of dB figures, each dB figure representing the power gain or power loss of a different system component. Normally, any compounding of ratios involves multiplication and/or division of those ratios, but with decibels we may simply add and subtract. One of the interesting mathematical properties of logarithms is that they "transform" ${ }^{3}$ " one type of problem into a simpler type: in this case, a problem of multiplying ratios into a (simpler) problem of adding decibel figures.

For example, we may express the power dissipated along a cable in terms of decibels per foot; the longer the cable, of course, the more power will be lost this way, all other factors being equal. For example, a radio-frequency signal cable having a loss figure of -0.15 decibels per foot at a signal frequency of 2.4 GHz will suffer -15 dB over 100 feet, and -150 dB over 1000 feet. To illustrate how decibels may be used to calculate power delivered to a load in such a system, accounting for various gains and losses along the way using decibel figures:

$21.8 \mathrm{dBm}+(-0.17 \mathrm{~dB} / \mathrm{ft})(6 \mathrm{ft})+45 \mathrm{~dB}+(-0.17 \mathrm{~dB} / \mathrm{ft})(20 \mathrm{ft})$ $21.8 \mathrm{dBm}-1.02 \mathrm{~dB}+45 \mathrm{~dB}-3.4 \mathrm{~dB}$

A similar application of decibels is found in multi-stage amplifier circuits, where one stage amplifies a signal to be fed into a successive stage to be amplified more. The power gains of these stages, each expressed as a ratio, multiply to make the over-all amplifier's power gain (ratio). The power gains of those same stages, each expressed as a decibel figure, add to make the over-all amplifier's power gain (dB):


[^9]Another common application of decibels is to express ratios of voltage and/or current rather than power. However, since the unit of the Bel has been defined as an expression of a power ratio, we cannot simply substitute $V$ or $I$ for $P$ in any of the formulae we've seen so far.

Suppose an amplifier has a voltage gain of 2 (i.e. $V_{\text {out }}$ is twice as large as $V_{i n}$ ), and we would like to express this gain in decibels. Since decibels are intended to express power gain and not voltage gain, we must figure out how much power gain is equivalent to a voltage gain of two. Obviously, voltage and power are fundamentally different quantities, but if we imagine ourselves connecting a fixed load resistance to the input signal, and then to the output signal, we will realize that load's power dissipation will be more than double when energized by a voltage twice as large. Joule's Law is helpful to determine the exact ratio of power dissipation:

$$
P=\frac{V^{2}}{R}
$$

Doubling voltage for any given load resistance results in power quadrupling because power is proportional to the square of the voltage applied to a fixed resistance. Using this as the basis for applying decibels to a voltage ratio. Knowing that Joule's Law also declares power is proportional to the square of the current applied to a fixed resistance $\left(P=I^{2} R\right)$ means this same mathematical relationship will apply to current gains and reductions as well as voltage gains and reductions:

$$
\mathrm{dB}=10 \log \left(\frac{P_{\text {out }}}{P_{\text {in }}}\right)=10 \log \left(\frac{V_{\text {out }}}{V_{\text {in }}}\right)^{2}=10 \log \left(\frac{I_{\text {out }}}{I_{\text {in }}}\right)^{2}
$$

An algebraic identity of logarithms is that the logarithm of any quantity raised to a power is equal to that power multiplied by the logarithm of the quantity. Expressed in general terms:

$$
\log x^{y}=y \log x
$$

Therefore, we may simplify the decibel formula for voltage gain by removing the " 2 " power and making it a multiplier:

$$
\begin{aligned}
& 10 \log \left(\frac{V_{\text {out }}}{V_{\text {in }}}\right)^{2}=(2)(10) \log \left(\frac{V_{\text {out }}}{V_{\text {in }}}\right)=20 \log \left(\frac{V_{\text {out }}}{V_{\text {in }}}\right) \\
& 10 \log \left(\frac{I_{\text {out }}}{I_{\text {in }}}\right)^{2}=(2)(10) \log \left(\frac{I_{\text {out }}}{I_{\text {in }}}\right)=20 \log \left(\frac{I_{\text {out }}}{I_{\text {in }}}\right)
\end{aligned}
$$

Thus, we may use decibels to express voltage or current ratios if we simply substitute 20 instead of 10 as the multiplier.

We can see the practicality of using decibels to represent something other than electrical power by examining this analog meter face, belonging to a Simpson model 260 VOM (Volt-OhmMilliammeter). Note the bottom scale on this meter's face, calibrated in decibels (DB):


Pay attention to the note on decibels written in the lower-left corner of the meter face, where 0 dB is defined as 0.001 Watt dissipated by 600 Ohms. The fact that 0 dB is defined as 1 milliWatt means it should (properly) be labeled dBm rather than $\mathrm{dB}^{4}$. A load resistance value is necessary as part of this definition for dB because this meter cannot measure power directly but must infer signal power from measurements of AC voltage. Without a specific load resistance, there is no clear relation between voltage and power. 600 Ohms is an old telecommunications standard for audiofrequency AC signals, and continues to be used today for voltage-based decibel measurements of audio-frequency AC signals.

The meter as shown is connected to nothing at all, and so registers 0 Volts AC. This, of course, corresponds to zero power, and it has no corresponding decibel value because the logarithm of zero is mathematically undefined ${ }^{5}$. Practically, it means $-\infty \mathrm{dB}$, which is why the needle at the 0 Volt position "falls off" the left-hand end of the dB scale.

Close inspection of the dB scale on this meter face reveals another interesting property of decibels, and that is the nonlinear nature of the dB scale. This contrasts starkly against all the voltage and current scales on this meter face which are linear. This nonlinearity is a fundamental property of decibels because it is based on the logarithm function which is nonlinear.

[^10]Now, we will explore what is necessary to make this meter register 0 dBm (i.e. 1 milliWatt) with an applied AC voltage. 1 milliWatt of power dissipated by 600 Ohms is equivalent to:

$$
V=\sqrt{P R}=\sqrt{(0.001)(600)}=0.7746 \text { Volts }
$$

Setting the VOM to the 2.5 VAC range and applying just enough AC voltage to bring the needle to the 0 dB mark allows us to verify that this is indeed equivalent to just under 0.8 Volts (read on the 2.5 VAC scale):


In the lower-right corner of the meter face we see some notes regarding correction values for decibel measurements when using different AC voltage ranges. The dB scale is read directly when the meter is set on the 2.5 VAC range. When set on the 10 VAC range (i.e. a range four times as great), the meter's needle will experience a deflection one-fourth as much as when set to the 2.5 VAC range, and therefore it will point to a lesser (or even negative) value on the dB scale. Converting a voltage ratio of 0.25 into a decibel figure shows us how much less the needle will register on the dB scale when the voltage range is quadrupled:

$$
20 \log \left(\frac{2.5}{10}\right)=-12.04 \mathrm{~dB}
$$

Therefore, when using the 10 VAC range instead of the 2.5 VAC range, one must add 12 dB to the reading. Likewise, we may prove each of the printed correction factors for the alternative voltage-measurement ranges listed ( 50 Volt AC range and 250 Volt AC range):

$$
\begin{aligned}
& 20 \log \left(\frac{2.5}{50}\right)=-26.02 \mathrm{~dB} \\
& 20 \log \left(\frac{2.5}{250}\right)=-40.0 \mathrm{~dB}
\end{aligned}
$$

### 4.2 Near-field versus far-field regions

An electric field exists wherever voltage exists (i.e. wherever an imbalance exists between positive and negative electrical charges), parallel to the axis of that voltage. A magnetic field exists wherever an electric charge moves, perpendicular to the axis of that charge's motion. These phenomena exist for DC (direct) as well as AC (alternating) electricity, and are shown in the two following illustrations:


Electric and magnetic fields, however, are not simply manifestations of voltage and current, respectively. Mathematical discoveries made by the Scottish physicist James Clerk Maxwell (and later simplified by Oliver Heaviside) also relate electric fields and magnetic fields directly to each other. Consider two ${ }^{6}$ of Maxwell's equations shown below:

$$
\begin{gathered}
\oint \vec{E} \cdot d \mathbf{s}=-\frac{d \Phi_{B}}{d t} \\
\oint \vec{B} \cdot d \mathbf{s}=\mu_{0} I+\mu_{0} \epsilon_{0} \frac{d \Phi_{E}}{d t}
\end{gathered}
$$

The first equation describes how an electric field $(\vec{E})$ is created by a varying magnetic flux $\left(\frac{d \Phi_{B}}{d t}\right)$, which is otherwise known as Faraday's Law of Electromagnetic Induction. This is the law exploited in the function of electro-mechanical generators whereby coils of wire are subjected to changing magnetic fields, creating voltage between the coils' end-points. The negative sign in this equation is an embodiment of Lenz's Law, which states that any current resulting from the induced voltage will produce its own magnetic field opposing the first magnetic field's direction of change.

The second equation shown here describes two different ways to produce a magnetic field $(\vec{B})$. One way is to use a moving stream of electric charges known as a current $(I)$, a fact also known as Ampère's Law. This is the law exploited in the function of electromagnets, where we produce a magnetic field by connecting a coil of wire to an electrical source. The second way is to vary an electric flux $\left(\frac{d \Phi_{E}}{d t}\right)$ in empty space with surrounding magnetic permeability $\mu_{0}$ and electric permittivity $\epsilon_{0}$.

[^11]Maxwell's equations suggest that in pulsed DC and AC circuits, where the resulting electric and/or magnetic fields vary over time $\left(\frac{d}{d t}\right)$ rather than holding steady, those time-varying fields will mutually support one another over space and time. That is, a varying electric field will eventually produce a varying magnetic field, and vice-versa, those fields propagating one another as an electromagnetic wave radiating away from the circuit through space at the speed of light ${ }^{7}$.

At close range, immediately adjacent to the circuit conductors, electric and magnetic fields are strictly functions of those conductors' voltages and currents, respectively. These fields' shapes follow the basic forms shown in the previous illustrations: magnetic field lines circling current-carrying conductors and electric field lines stretching between conductive surfaces. We generally refer to this region of space around an energized circuit as the near-field region, where electric and magnetic fields are distinct from one another in form and in relative magnitude.

At farther distances from the energized circuit, the electric and magnetic fields are found in pairs oscillating at right angles to one another in space, forming a single electromagnetic wave radiating away from the source circuit spherically in all directions. This form of wave is a direct consequence of Maxwell's equations describing how the rate-of-change of one field creates the other field, and vice-versa. Below we see a crude representation of an electromagnetic wave, with an electric $\vec{E}$ field, a magnetic $\vec{H}$ field, and the vector of propagation $\vec{S}$ called the Poynting vector:

Electromagnetic wave


This region where the electric and magnetic fields exist as coupled pairs comprising a well-formed wave is referred to as the far-field region. In this region the electric and magnetic fields are always perpendicular to one another and their relative magnitudes are in a fixed proportion governed by the permeability and permittivity of free space.

The demarcation between near- and far-field regions depends on the physical dimensions of the radiating circuit as well as the wavelength of the signal $(\lambda)$, wavelength being calculated by dividing the speed of light $\left(2.9979 \times 10^{8}\right.$ meters per second in empty space) by the signal frequency in Hertz. There is no simple rule for predicting where the near-field region ends and the far-field region begins, and in fact there is a gradual morphing of one to the other, but one may reliably consider any distance from the circuit in excess of multiple wavelengths to be far-field.

[^12]The following list compares and contrasts several near-field versus far-field characteristics:

- In the near-field region electric and magnetic field strengths depend greatly on the geometry of the energized circuit's conductors as well as on the specific voltage and current levels existing at each location. In the far-field region, however, the electric and magnetic field strengths are always in fixed proportion to one another.
- Far-field effects may be ignored for low-frequency AC circuits because these circuits' wavelengths are so long. At 60 Hz , for example, the wavelength is nearly 5 million meters. If we consider the far-field region of a circuit to begin at least multiple wavelengths from the source, this puts the far-field region of a 60 Hz circuit at least one-quarter of the Earth's circumference away from the circuit in question!
- In the near-field region the proportionality between electric and magnetic field strengths is a function of circuit impedance: high-impedance circuits will have stronger electric fields than magnetic fields, and low-impedance circuits will have stronger magnetic fields than electric fields, all other factors being equal. This is due to Ohm's Law establishing the relationship between voltage and current $\left(Z=\frac{V}{I}\right)$, and how electric fields originate in a circuit from potential differences while magnetic fields originate in a circuit from currents. In the far-field region, however, where the electric and magnetic fields exist only through mutual support, their strengths are always in the same (fixed) proportion defined as the characteristic impedance of free space which is approximately 377 Ohms. This value is equal to the square root of the ratio of magnetic permeability to electric permittivity for free space $\left(Z_{0}=\sqrt{\frac{\mu_{0}}{\epsilon_{0}}}\right)$ because these parameters of space dictate just how strongly a varying electric field creates a magnetic field.
- The relationship between field strength and physical distance from the circuit is a very complex one within the near-field region, as this depends greatly on the geometry of the circuit conductors. In the far-field region, however, we find the Inverse-Square Law always holds true: as distance from the circuit increases, electromagnetic wave strength simply and reliably diminishes with the square of that distance as if the wave were radiating away in a spherical fashion from a point-source ${ }^{8}$. For example, if we double the distance from the radiating circuit (from a point in the far-field region to another point in the far-field region twice as far away in empty space), the power conveyed by the electromagnetic radiation will always be four times less. Tripling the far-field distance always weakens the wave's power by a factor of nine. This is simply because the area over which the radiated energy spreads increases with the square of the distance from any point-source, viewing that point-source as the center of a sphere.
- In the far-field region every radiating circuit has a definite radiation pattern where the strength of the radiated electromagnetic wave as a function of the angle from the geometric centerline follows a consistent pattern regardless of distance. This is a very important feature of antennas, where different antenna designs feature unique far-field radiation patterns. By contrast, in the near-field region of an antenna the radiation pattern varies significantly with distance.

[^13]- The spatial polarization of the electromagnetic wave (i.e. the orientation of its perpendicular electric and magnetic fields) is always well-defined in the far-field region but often ill-defined in the near-field region. This means, among other things, that two or more antennas will exchange electromagnetic energy efficiently only if they are appropriately oriented to one another over far-field distances, but may exchange energy fairly well regardless of orientation over near-field distances.
- Any "gain" specifications for an antenna structure apply only to apparent gains in signal power over the far-field range, because they refer to the degree to which an antenna focuses its energy in one direction more than another (i.e. its directionality), implying a distance over which the electromagnetic wave has become well-formed and the antenna's radiation pattern is reliably established. At near-field distances these "gain" figures are meaningless.


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

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

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

[^14]
## 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 ${ }^{3}$. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

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

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

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

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

[^15]
### 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 problemsolving, 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.
$\sqrt{ }$ 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.
$\sqrt{ }$ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

### 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

Conservation of Energy

Simplification as a problem-solving strategy

Graphing as a problem-solving strategy

Algebraic substitution

Electromagnetic wave

Antenna

Frequency

Wavelength

Directionality

Dipole

Decibels

Isotropic

Gain

Margin

ERP

Noise

Frequency domain

Signal-to-noise ratio

BER

Path loss

Inverse square law

Fade loss

Site test

Fresnel zone

Line-of-sight

### 5.1.3 Link budget graph

Show where the following parameters (or parameters associated with these components) fit into the following link budget graph. Note that this is a generic graph, and is not necessarily tailored to this particular application:

- BER (bit error rate) $=10^{-6}$
- Distance $=3$ miles
- EAN2400NR $1 / 2$ wave whip transmitting antenna
- ASC0032SF transmitting cable (3 feet long)
- EAN2414CR Corner Reflector receiving antenna
- ASC0102SN receiving cable (10 feet long)



## Challenges

- Explain why the bit error rate is an important factor in this calculation. If we desire a lower (smaller) bit error rate, what must change?
- Define "sensitivity" for a radio receiver unit.
- Explain why one should always incorporate some fade loss into the minimum transmitter power calculation for any realistic radio application.
- After calculating the minimum transmitter power for this application, calculate the amount of margin (for fade and other losses) based on this particular transmitter's rated power output.


### 5.1.4 Cable loss and frequency

Why do RF signal cables experience energy dissipation (in the form of heat) when conducting RF signals? What is/are the fundamental principle(s) at work here?

What effect, if any, does a change in signal frequency have on power dissipation for a coaxial cable? Why?

## Challenges

- What differences in cable design mitigate these losses?


### 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 problemsolving 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 ${ }^{5}$ on an answer key!

[^16]
### 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, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6} \mathrm{H} / \mathrm{m}$ represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number $\left(N_{A}\right)=\mathbf{6 . 0 2 2 1 4 0 7 6} \times 10^{23}$ per mole $\left(\mathrm{mol}^{-1}\right)$
Boltzmann's constant $(k)=1.380649 \times 10^{-23}$ Joules per Kelvin $(\mathrm{J} / \mathrm{K})$
Electronic charge $(e)=\mathbf{1 . 6 0 2 1 7 6 6 3 4} \times 10^{-19}$ Coulomb (C)
Faraday constant $(F)=\mathbf{9 6}, \mathbf{4 8 5 . 3 3 2 1 2} \ldots \times 10^{4}$ Coulombs per mole $(\mathrm{C} / \mathrm{mol})$
Magnetic permeability of free space $\left(\mu_{0}\right)=1.25663706212(19) \times 10^{-6}$ Henrys per meter $(\mathrm{H} / \mathrm{m})$
Electric permittivity of free space $\left(\epsilon_{0}\right)=8.8541878128(13) \times 10^{-12}$ Farads per meter $(\mathrm{F} / \mathrm{m})$
Characteristic impedance of free space $\left(Z_{0}\right)=376.730313668(57)$ Ohms $(\Omega)$
Gravitational constant $(G)=6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ( $\mathrm{m}^{3} / \mathrm{kg}-\mathrm{s}^{2}$ )

Molar gas constant $(R)=8.314462618 \ldots$. Joules per mole-Kelvin $(\mathrm{J} / \mathrm{mol}-\mathrm{K})=0.08205746(14)$ liters-atmospheres per mole-Kelvin

Planck constant $(h)=\mathbf{6 . 6 2 6 0 7 0 1 5} \times 10^{-34}$ joule-seconds $(\mathrm{J}-\mathrm{s})$
Stefan-Boltzmann constant $(\sigma)=\mathbf{5 . 6 7 0 3 7 4 4 1 9} \ldots \times 10^{-8}$ Watts per square meter-Kelvin ${ }^{4}$ (W/m ${ }^{2} \cdot \mathrm{~K}^{4}$ )

Speed of light in a vacuum $(c)=\mathbf{2 9 9}, \mathbf{7 9 2}, 458$ meters per $\operatorname{second}(\mathrm{m} / \mathrm{s})=186282.4$ miles per second ( $\mathrm{mi} / \mathrm{s}$ )

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

### 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:

|  | $\mathbf{A}$ | $\mathbf{B}$ | $\mathbf{C}$ | $\mathbf{D}$ |
| :--- | :--- | :---: | :---: | :---: |
| $\mathbf{1}$ | Distance traveled | 46.9 | Kilometers |  |
| $\mathbf{2}$ | Time elapsed | 1.18 | Hours |  |
| $\mathbf{3}$ | Average speed | $=B 1 / \mathrm{B} 2$ | $\mathrm{~km} / \mathrm{h}$ |  |
| $\mathbf{4}$ |  |  |  |  |
| $\mathbf{5}$ |  |  |  |  |

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

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

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

[^17]Common ${ }^{7}$ arithmetic operations available for your use in a spreadsheet include the following:

- Addition (+)
- Subtraction (-)
- Multiplication (*)
- Division (/)
- Powers ( ${ }^{\wedge}$ )
- Square roots (sqrt())
- Logarithms (ln(), $\log 10())$

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

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

|  | $\mathbf{A}$ | $\mathbf{B}$ |
| :---: | :---: | :---: |
| $\mathbf{1}$ | $\mathrm{x} \_1$ | $=(-B 4+\operatorname{sqrt}((B 4 \wedge 2)-(4 * B 3 * B 5))) /\left(2 \star_{B 3}\right)$ |
| $\mathbf{2}$ | $\mathrm{x}-2$ | $=(-B 4-\operatorname{sqrt}((B 4 \wedge 2)-(4 * B 3 * B 5))) /\left(2 \star^{2} 3\right)$ |
| $\mathbf{3}$ | $\mathrm{a}=$ | 9 |
| $\mathbf{4}$ | $\mathrm{~b}=$ | 5 |
| $\mathbf{5}$ | $\mathrm{c}=$ | -2 |

This example is configured to compute roots ${ }^{9}$ of the polynomial $9 x^{2}+5 x-2$ 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.

[^18]Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$
\begin{gathered}
y=\sqrt{b^{2}-4 a c} \quad z=2 a \\
x=\frac{-b \pm y}{z}
\end{gathered}
$$

|  | $\mathbf{A}$ | $\mathbf{B}$ | $\mathbf{C}$ |
| :--- | :---: | :---: | :--- |
| $\mathbf{1}$ | $\mathrm{x} \_1$ | $=(-B 4+C 1) / C 2$ | $=\operatorname{sqrt}((B 4 \wedge 2)-(4 * B 3 * B 5))$ |
| $\mathbf{2}$ | $\mathrm{x} \_2$ | $=(-B 4-C 1) / C 2$ | $=2 * B 3$ |
| $\mathbf{3}$ | $\mathrm{a}=$ | 9 |  |
| $\mathbf{4}$ | $\mathrm{~b}=$ | 5 |  |
| $\mathbf{5}$ | $\mathrm{c}=$ | -2 |  |

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

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

[^19]
### 5.2.3 Power ratio and dB conversions

Convert between the following power ratio and decibel values:

- $-21 \mathrm{~dB}=$ power ratio gain of
- Power ratio gain of $20=$
- $+50 \mathrm{~dB}=$ power ratio gain of
- Power ratio reduction of $\frac{1}{40}=$
- Power ratio gain of $1600=$
- $+26 \mathrm{~dB}=$ power ratio gain of
- Power ratio reduction of $\frac{1}{800}=$
- $-33 \mathrm{~dB}=$ power ratio gain of


## Challenges

- What advantage(s) is/are there to using decibels to express power gains/losses?
- Estimate some of these answers using mental math, knowing that $+10 \mathrm{~dB}=\times 10$ ratio, -10 $\mathrm{dB}=\times \frac{1}{10}$ ratio, $+3 \mathrm{~dB}=\times 2$ ratio, and $-3 \mathrm{~dB}=\times \frac{1}{2}$ ratio.
- What would it mean if any of the dB figures had an " m " or a "W" suffix attached?


### 5.2.4 Power and loss calculations

Suppose a radio transmitter unit outputs 25 Watts of RF power at a frequency of 900 MHz , into a half-wave dipole antenna. The radio energy radiates outward from the transmitting antenna, and is received by another antenna to send a signal of 1.8 microWatts into a radio receiver:


Calculate the transmitter's output power $\left(P_{t x}\right)$ in both dBm and dBW , and also the receiver's input signal power $\left(P_{r x}\right)$ in dBm and dBW . Then, calculate the total power loss between transmitter and receiver ( $P_{\text {loss }}$ ), in dB.
$P_{t x}=$ $\qquad$ $\mathrm{dBm}=$ $\qquad$ dBW
$P_{r x}=$ $\qquad$ $\mathrm{dBm}=$ $\qquad$ dBW
$P_{\text {loss }}=$ $\qquad$ dB

Explain in your own words the meaning of the following units: $d B m, d B W$, and $d B$. Also, explain why it is appropriate to use dBm or dBW to represent $P_{t x}$ and/or $P_{r x}$, but not for $P_{\text {loss }}$ (instead, $P_{\text {loss }}$ must be represented in plain dB ).

## Challenges

- Explain why the "decibel" is such a commonly used unit for power, and also for power gains and losses, in RF communications work.
- Does it matter if $P_{\text {loss }}$ is calculated from the transmit and receive powers in units of Watts, dBm , or dBW ? Why or why not?
- If we wished to reduce the power loss from transmitter and receiver, how could we do so? Note: there are many different solutions to this problem!
- If the transmitting and receiving antennas were spaced farther apart, would $P_{\text {loss }}$ increase, decrease, or remain the same?
- If the transmitting and receiving antennas were both located closer to ground level (i.e. not as high off the ground), would $P_{\text {loss }}$ increase, decrease, or remain the same?
- Estimate these decibel values by first rounding the power ratio to the nearest product of 10 and/or 2, then applying the equivalence of 10 dB to a 10 -fold ratio and 3 dB to a two-fold ratio.


### 5.2.5 Waveguide power loss

In many microwave radio systems, hollow rectangular tubes known as waveguides are often used in lieu of cables to serve as transmission lines between the transceiver and the antenna. These hollow metal tubes acts as "pipes" to convey GHz-range electromagnetic waves with great efficiency, far exceeding the efficiency of coaxial cables:


The following table shows a comparison between RG-49/U waveguide and RG-9/U flexible cable:

| Parameter | RG-49/U waveguide | RG-9/U coaxial cable |
| :---: | :---: | :---: |
| External dimensions | 2 inch $\times 1$ inch | 0.420 inch diameter |
| Dielectric | Air | Polystyrene plastic |
| Weight | 1.4 pounds per foot | 0.15 pound per foot |
| Attenuation at $f=5 \mathrm{GHz}$ | 0.011 dB per foot | 0.23 dB per foot |
| Maximum power rating | 1.2 MW | 66 W |

Suppose an RG-49/U waveguide is used to transfer RF energy from a 300 Watt radar transceiver to a dish antenna. Calculate the RF power (in Watts) available at the antenna, assuming the waveguide is 8 feet long and that there are no other power losses between the transceiver and the antenna.

Now suppose that radar transceiver's power is increased to 800 Watts. Calculate the RF power (in Watts) available at the antenna, assuming the same waveguide length.

Now suppose that radar transceiver's power is increased to 3 kiloWatts. Calculate the RF power (in Watts) available at the antenna, assuming the same waveguide length.

Does the waveguide power loss remain constant as transmitter power increases, or does it change with the amount of transmitted power? How does the "lost" RF energy manifest itself through the waveguide (given that the Law of Energy Conservation tells us energy cannot be created or destroyed)?

## Challenges

- Explain why the waveguide shown has such a greater power rating than the coaxial cable, based on their respective $\mathrm{dB} /$ foot loss ratings.
- Why aren't waveguides used for all GHz-frequency radio applications, given that their power losses are so much less than the losses exhibited by coaxial cable?
- For those who have studied level measurement technologies, explain how the concept of a waveguide relates to guided-wave radar (GWR) level transmitters.
- Is is possible for a waveguide to experience reflected signals as in the case of improperly terminated transmission line cables? Why or why not?


### 5.2.6 Path loss estimation

Suppose a radio transmitting antenna radiates 120 kW of RF power into space, and that only 30 milliWatts of this power reaches a receiving antenna some distance away. Calculate the path loss in decibels without using a calculator. Note that an addition or subtraction of 10 dB is exactly equal to a 10 -fold multiplication or division ratio (respectively), and that an addition or subtraction of 3 dB is approximately equal to a two-fold multiplication or division ratio.

## Challenges

- Explain what creates path loss. Is this something that can be overcome or at least mitigated by applying the correct technology? Why or why not?
- Explain what fade loss is, what creates it, and how it differs from path loss.
- Is path loss affected by the type of antenna used to transmit the RF energy? Explain why or why not.
- Is path loss affected by the type of antenna used to receive the RF energy? Explain why or why not.
- Is path loss affected by the frequency of the RF energy transmitted?


### 5.2.7 Fresnel zone interference

Calculate the necessary height the radio antennas (assume the same height for each) in order that the first Fresnel zone will have no interference. Assume a signal frequency of 900 MHz , and that the two objects shown lie exactly along the line-of-site path between the two antennas:


## Challenges

- If you were the one designing this antenna system, what other concerns might you have about the antenna height in relation to objects possibly infringing on the Fresnel zone?
- Suppose zoning regulations prohibited you from installing an antenna tower any higher than 20 feet. Devise appropriate solution(s) for the radio link given this limitation.


### 5.2.8 Fresnel zone ground contact

Suppose two radio antennas are located on 12 -foot towers, with free and open space in between. If their operating frequency is 900 MHz , calculate the distance between these towers where the first Fresnel zone contacts the ground in between. Is this tower-to-tower distance a minimum or a maximum value for practical radio operation?


## Challenges

- Identify at least one practical factor which would change the distance value allowable between the two antennas. For example, what could change in the system to permit a longer distance between antennas?


### 5.2.9 Minimum transmitter power

Calculate the minimum required transmitter power for an FM radio broadcast station, assuming we wish an FM radio receiver with a sensitivity of -90 dBm be able to receive the signal. Assume the following gains, losses and other parameters in the system:

- Frequency $=104.5 \mathrm{MHz}$
- Distance $=120 \mathrm{~km}$
- Transmitter antenna gain $=6 \mathrm{dBi}$
- Receiver antenna gain $=0 \mathrm{dBi}$
- Transmitter cable loss $=0.09 \mathrm{~dB}$ per foot
- Receiver cable loss $=0.12 \mathrm{~dB}$ per foot
- Transmitter cable length $=300$ feet
- Receiver cable length $=3$ feet long

After calculating the required (minimum) transmitter power, re-calculate to include a fade margin of 20 dB for good measure. Explain what "fade margin" is, and why it might be a good idea to include it in an RF link budget calculation.

## Challenges

- Identify at least one alteration to any of the given parameters that would result in more power required at the transmitter.


### 5.2.10 Link budget margin

Perform a link budget analysis of the following radio communication system, using a FreeWave FGR2 industrial data radio ( 900 MHz ) transmitting at 5 mW with the following components and parameters:

- Receiver sensitivity $=-110 \mathrm{dBm}$ at $\operatorname{BER}$ of $10^{-4}$
- Distance $=8.5$ miles
- EAN0900YC Yagi transmitting antenna gain $=+12.15 \mathrm{dBi}$
- ASC0202SN transmitting cable ( 20 feet long) $=-1.7 \mathrm{~dB}$
- EAN0906YA Yagi receiving antenna gain $=+8 \mathrm{dBi}$
- ASC0302SN receiving cable (30 feet long) $=-2.5 \mathrm{~dB}$

Specifically, calculate the amount of margin (i.e. safety factor) between the 5 mW transmitter power and the bare-minimum transmitter power you calculate from the link budget.

## Challenges

- Explain the purpose for having a budget or margin of difference between the minimum required transmitting power and the actual transmitting power. Why should we need more than what is minimally calculated, especially when considering that excess transmitting power may cause problems for neighboring electronic systems?


### 5.2.11 Maximum distance between antennas

Suppose two radio transceivers must communicate with each other over a long distance. Each one uses a half-wave "whip" antenna with 6 dBi gain, a lightning arrestor at the transceiver $(-0.5 \mathrm{~dB}$ loss at each transceiver), and each one has 25 feet of coaxial cable connecting the transceiver to the antenna ( -0.2 dB loss per foot). Each transceiver transmits 350 mW of RF power, and has a receiving sensitivity of -103 dBm .

Assuming a 900 MHz signal frequency, no fade loss, and absolutely clear line-of-sight between the two antennas, how far away may these transceivers be separated and still fall within the RF budget for good communication?

## Challenges

- If the signal frequency were higher, how would this affect the maximum distance?


### 5.2.12 Using $C$ to calculate receiver power

Examine the following program written in the C programming language, for calculating the amount of RF power available at the input of a receiver:

```
#include <stdio.h>
#include <math.h>
int main (void)
{
    float dist, tgain, rgain, tcable, rcable, f, tpower, Lp, lambda,
            rpower, margin;
    printf("Enter xmtr power (W): "); scanf("%f", &tpower);
    printf("Enter frequency (Hz): "); scanf("%f", &f);
    printf("Enter xmtr feed losses (dB): "); scanf("%f", &tcable);
    printf("Enter xmtr antenna gain (dB): "); scanf("%f", &tgain);
    printf("Enter distance (m): "); scanf("%f", &dist);
    printf("Enter rcvr antenna gain (dB): "); scanf("%f", &rgain);
    printf("Enter rcvr feed losses (dB): "); scanf("%f", &rcable);
    printf("Enter fade margin (dB): "); scanf("%f", &margin);
    tpower = 10 * log10(tpower/1e-3);
    lambda = 2.99792458e8 / f;
    Lp = -20 * log10(4 * M_PI * dist / lambda);
    rpower = tpower + tgain + rgain + Lp + tcable + rcable - margin;
    printf("RF power at receiver input = %f dBm = %e Watts\n",
            rpower, pow(10,rpower/10)/1000);
    return 0;
}
```

Explain how this program calculates receiver power, and also verify its accuracy by simulating one of the link budget examples given in this module.

## Challenges

- Add lines of code to ensure that even if the user mistakenly enters positive values for feed losses, the result will still be correct.
- How would the user enter feed losses for a receiver with a built-in antenna?


### 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 Possible faults in radio SCADA system

In this SCADA system, multiple Programmable Logic Controllers (PLCs) in remote locations communicate to a centralized "master" PLC. This Master Terminal Unit (MTU) communicates with multiple "slave" Remote Terminal Units (RTUs) via radio using Modbus protocol. Each PLC communicates with its radio transceiver via a short RS-232 serial cable:


Unfortunately, there is a problem with this system. RTU number 4 does not communicate with the MTU. Upon inspection, you see that the "Tx" and "Rx" LED indicators are blinking on all the RTU radio transceivers except for RTU \#4: there, only the "Rx" LED blinks.

Identify the likelihood of each specified fault for this system. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault is compatible with all measurements and symptoms in this SCADA network.

- Damaged antenna on MTU
- Damaged antenna on RTU \#4
- PLC halted (not running) RTU \#4
- Radio transceiver powered down on RTU \#4
- "TD" conductor broken inside RS-232 cable on RTU \#4
- "RD" conductor broken inside RS-232 cable on RTU \#4
- PLC baud rate set incorrectly on RTU \#4
- PLC baud rate set incorrectly on MTU
- Modbus mode (RTU/ASCII) set incorrectly on RTU \#4
- Modbus mode (RTU/ASCII) set incorrectly on MTU
- Fresnel zone interference between MTU and RTU \#4


## Challenges

- A powerful troubleshooting technique is to swap identical components between elements of a system to see if and where the problem moves. Explain how this simple test could be applied to this SCADA system in order to diagnose the fault.
- An important question to answer is whether the "Tx" and "Rx" LED indicators on the radio transceivers refer to transmission and reception over the wireless network or over the RS-232 serial network. Explain how we may conclusively answer this question based on the information given and our knowledge of serial Modbus networks.


## 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 ${ }^{1}$ 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 ${ }^{2}$ 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 ${ }^{3}$ 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

[^20]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, videorecordings showing the demonstration are acceptable. All relevant safety precautions must be followed, all test equipment must be used correctly, and the student must be able to properly explain all results. The student must also successfully answer all Challenges presented by the instructor for that experiment or project.

Students learning from these modules would do well to abide by the following principles:

- No text should be considered fully and adequately read unless and until you can express every idea in your own words, using your own examples.
- You should always articulate your thoughts as you read the text, noting points of agreement, confusion, and epiphanies. Feel free to print the text on paper and then write your notes in the margins. Alternatively, keep a journal for your own reflections as you read. This is truly a helpful tool when digesting complicated concepts.
- Never take the easy path of highlighting or underlining important text. Instead, summarize and/or comment on the text using your own words. This actively engages your mind, allowing you to more clearly perceive points of confusion or misunderstanding on your own.
- A very helpful strategy when learning new concepts is to place yourself in the role of a teacher, if only as a mental exercise. Either explain what you have recently learned to someone else, or at least imagine yourself explaining what you have learned to someone else. The simple act of having to articulate new knowledge and skill forces you to take on a different perspective, and will help reveal weaknesses in your understanding.
- Perform each and every mathematical calculation and thought experiment shown in the text on your own, referring back to the text to see that your results agree. This may seem trivial and unnecessary, but it is critically important to ensuring you actually understand what is presented, especially when the concepts at hand are complicated and easy to misunderstand. Apply this same strategy to become proficient in the use of circuit simulation software, checking to see if your simulated results agree with the results shown in the text.
- Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied ${ }^{4}$ effort, and never give up!

Students interested in using these modules for self-study will also find them beneficial, although the onus of responsibility for thoroughly reading and answering questions will of course lie with that individual alone. If a qualified instructor is not available to challenge students, a workable alternative is for students to form study groups where they challenge ${ }^{5}$ one another.

To high standards of education,
Tony R. Kuphaldt

[^21]
## 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 $\mathrm{T}_{\mathrm{E}} \mathrm{X}$ 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. $\mathrm{T}_{\mathrm{E}} \mathrm{X}$ 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, $\mathrm{T}_{\mathrm{E}} \mathrm{X}$ is a programmer's approach to word processing. Since $\mathrm{T}_{\mathrm{E}} \mathrm{X}$ 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 $\mathrm{T}_{\mathrm{E}} \mathrm{X}$ makes it relatively easy to learn how other people have created their own $\mathrm{T}_{\mathrm{E}} \mathrm{X}$ 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 ${ }^{\mathrm{A}} \mathrm{T}_{\mathrm{E}} \mathrm{X}$ extensions to $\mathrm{T}_{\mathrm{E}} \mathrm{X}$

Like all true programming languages, $\mathrm{T}_{\mathrm{E}} \mathrm{X}$ is inherently extensible. So, years after the release of $\mathrm{T}_{\mathrm{E}} \mathrm{X}$ to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was $\mathrm{IAT}_{\mathrm{E}} \mathrm{X}$, which is the markup language used to create all ModEL module documents. You could say that $T_{E} X$ is to $I_{A} T_{E} X$ as $C$ is to $C++$. This means it is permissible to use any and all $T_{E} X$ commands within $\mathrm{AT}_{\mathrm{E}} \mathrm{X}$ source code, and it all still works. Some of the features offered by $\mathrm{LA}_{\mathrm{E}} \mathrm{X}$ that would be challenging to implement in $\mathrm{T}_{\mathrm{E}} \mathrm{X}$ 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 $\mathrm{T}_{\mathrm{E}} \mathrm{X}$ 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 2 g 6 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 $\mathrm{C} / \mathrm{C}++$ code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as Mathematica or Maple to do. It should be said that ePiX is not a Computer Algebra System like Mathematica or Maple, but merely a mathematical visualization tool. In other words, it won't determine integrals for you (you'll have to implement that in your own C/C++ code!), but it can graph the results, and it does so beautifully. What I really admire about ePiX is that it is a C++ programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a C++ library to do the same thing he accomplished something much greater.
gnuplot mathematical visualization software
Another open-source tool for mathematical visualization is gnuplot. Interestingly, this tool is not part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" not be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my gnuplot output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of Gimp to do rudimentary image editing, my use of gnuplot only scratches the surface of its capabilities, but the important points are that it's free and that it works well.

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

## Appendix D

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## Appendix E

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## Appendix F

## Version history

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

12 March 2024 - added a more instructor notes.

20 February 2024 - added a new section to the Technical References chapter on near-field versus far-field effects.

17-18 October 2023 - minor edits to image_5227, and also refined the questions (and instructor notes) in the "Power and loss calculations" Quantitative Reasoning question. Also added some instructor notes for Challenge questions, and also clarified the verbiage in the Tutorial's bit error rate example.

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.

14-15 March 2022 - corrected all instances where EIRP was expressed in relative dB rather than (absolute) dBm , and also added some more content to the Introduction chapter. Also clarified the "Link budget graph" Conceptual Reasoning question.

1-2 December 2021 - added some challenge questions to the "Power ratio and dB conversions" calculation problem, and made changes to the Case Tutorial chapter including the inclusion of a link budget graph to manage all the gains and losses of a link budget calculation problem. The graph makes it visually apparent which decibel figures must be added versus subtracted.

13 November 2021 - added "multipath-induced fading" as a synonym for "fade" loss.
6 September 2021 - added a Quantitative Reasoning question analyzing a C-language program to calculate RF power at a receiver's input given all the standard link budget parameters.

10 May 2021 - commented out or deleted empty chapters.
5 May 2021 - added several more examples to the Case Tutorial chapter.
3 May 2021 - added a Conceptual Reasoning question on the effects of frequency on cable loss.
26 April 2021 - added more examples to the Case Tutorial chapter.
20-21 April 2021 - deleted several "placeholder" lines left over from initial module development in the Questions chapter. Also added a graphic illustration to the "Power and loss calculations" Quantitative Reasoning question. Made minor edits to the Tutorial text. Added more content to the Case Tutorial and Introduction chapters.

2 December 2020 - minor edits to instructor notes.
18 November 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 made some minor edits to the Tutorial.

28 July 2020 - added questions.
27 July 2020 - document first created.

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[^0]:    ${ }^{1}$ Actual signal power is typically expressed as a decibel ratio to a reference power of either 1 milliWatt ( dBm ) or 1 Watt (dBW). Thus, 250 mW of RF power may be expressed as $10 \log \frac{250}{1}=23.98 \mathrm{dBm}$ or as $10 \log \frac{0.25}{1}=-6.02$ dBW . Power expressed in unit of dBm will always be 30 dB greater ( $1 \times 10^{3}$ greater $)$ than power expressed in dBW .

[^1]:    ${ }^{2}$ Noise power may be calculated using the formula $P_{n}=k T B$, where $P_{n}$ is the noise power in Watts, $k$ is Boltzmann's constant $\left(1.38 \times 10^{-23} \mathrm{~J} / \mathrm{K}\right), T$ is the absolute temperature in Kelvin, and $B$ is the bandwidth of the noise in Hertz. Noise power usually expressed in units of dBm rather than Watts, because typical noise power values for ambient temperatures on Earth are so incredibly small.

[^2]:    ${ }^{3}$ The inverse square law applies to any form of radiation that spreads from a point-source. In any such scenario, the intensity of the radiation received by an object from the point-source diminishes with the square of the distance from that source, simply because the rest of the radiated energy misses that target and goes elsewhere in space. This is why the path loss formula begins with a -20 multiplier rather than -10 as is customary for decibel calculations: given the fact that the inverse square law tells us path loss is proportional to the square of distance $\left(D^{2}\right)$, there is a "hidden" second power in the formula. Following the logarithmic identity that exponents may be moved to the front of the logarithm function as multipliers, this means what would normally be a -10 multiplier turns into -20 and we are left with $D$ rather than $D^{2}$ in the fraction.

[^3]:    4 "Margin" is the professionally accepted term to express extra allowance provided to compensate for unknowns. A more colorful phrase often used in the field to describe the same thing is fudge factor.

[^4]:    ${ }^{5}$ I am indebted to Eric McCollum, Kei Hao, Shankar V. Achanta, Jeremy Blair, and David Kechalo for presenting this form of diagram in a technical paper presented at the 45 th annual Western Protective Relay Conference in Spokane, Washington in October of 2018. I do not know if these authors are responsible for the invention of this form of graph, but it was certainly the first time I encountered one like it, and it so clearly showed all the fundamental quantities of an RF link budget that I had to include something similar in my tutorial!

[^5]:    ${ }^{6}$ The physics of Fresnel zones is highly non-intuitive, rooted in the wave-nature of electromagnetic radiation. It should be plain to see, though, that Fresnel zones cannot describe the actual electromagnetic field pattern between two antennas, because we know waves tend to spread out over space while Fresnel zones converge at each end. Likewise, Fresnel zones vary in size according to the distance between two antennas which we know radiation field patterns do not. It is more accurate to think of Fresnel zones as keep-clear areas necessary for reliable communication between two or more antennas rather than actual field patterns.

[^6]:    ${ }^{1}$ It is interesting to note that although the "Bel" is a metric unit, it is seldom if ever used without the metric prefix

[^7]:    "deci" $\left(\frac{1}{10}\right)$. One could express powers in microbels, megabels, or any other metric prefix desired, but it is never done in industry: only the decibel is used.

[^8]:    ${ }^{2}$ For high-frequency signals such as those used in radio communications, the dominant mode of energy dissipation is dielectric heating, where the AC electric field between the cable conductors excites the molecules of the conductor insulation. This energy loss manifests as heat, which explains why there is less signal energy present at the load end of the cable than is input at the source end of the cable. For DC and low-frequency AC circuits the dominant mode of energy dissipation is cable conductor resistance, which is typically very small.

[^9]:    ${ }^{3}$ In fact, logarithms are one of the simplest examples of a transform function, converting one type of mathematical problem into another type. Other examples of mathematical transform functions used in engineering include the Fourier transform (converting a time-domain function into a frequency-domain function) and the Laplace transform (converting a differential equation into an algebraic equation).

[^10]:    ${ }^{4}$ Such mis-labeling is not that uncommon in the profession, the expectation being that the technician or engineer working with the instrument ought to be familiar enough with the concept of decibels to know when dB really means dBm , or dBW, etc.
    ${ }^{5}$ Your electronic calculator will complain if you attempt to take the logarithm of zero!

[^11]:    ${ }^{6}$ Maxwell's equations of electromagnetism are typically presented as a set of four. Here we only list two of these, as the other two are not relevant to electromagnetic waves in particular.

[^12]:    ${ }^{7}$ In fact, this is precisely what light is: an electromagnetic wave of exceptionally high frequency, well beyond the frequency range of contemporary electric circuits.

[^13]:    ${ }^{8} \mathrm{~A}$ "point source" is a hypothetical point in space having no height nor width nor depth (i.e. it has zero physical dimensions) that emits radiation. Point-sources are a theoretical concept only. Real sources have spatial dimensions which makes their near-field strength/distance relationships complex, but the farther away you get from them the more their radiative behavior approaches that of a theoretical point-source.

[^14]:    ${ }^{1}$ Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding - How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.
    ${ }^{2}$ Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

[^15]:    ${ }^{3}$ Analytical thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. Synthetic thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

[^16]:    ${ }^{4}$ In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.
    ${ }^{5}$ This approach is perfectly in keeping with the instructional philosophy of these learning modules: teaching students to be self-sufficient thinkers. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

[^17]:    ${ }^{6}$ 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.

[^18]:    ${ }^{7}$ 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 $\left(9 x^{2}+5 x-2\right)$ 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.

[^19]:    ${ }^{10}$ 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.

[^20]:    ${ }^{1}$ In a traditional teaching environment, students first encounter new information via lecture from an expert, and then independently apply that information via homework. In an "inverted" course of study, students first encounter new information via homework, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply explain, but the expert's role in an inverted session is to challenge, critique, and if necessary explain where gaps in understanding still exist.
    ${ }^{2}$ Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on any topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.
    ${ }^{3}$ This rhetorical technique is known by the Latin phrase reductio ad absurdum. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply reductio ad absurdum to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

[^21]:    ${ }^{4}$ 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.

