INTRODUCTION TO RF

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LAST UPDATE = 26 APRIL 2022

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Chapter 1

Introduction
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: near-field probing inside a PC

This first set of images shows the signal spectrum (left) and photograph (right) of an E-field probe held near a pair of wires connecting to a video processing PCB inside of a personal computer, picking up a spread of frequencies centered around 260 kHz:

Next we see the same E-field probe held over the hub of a cooling fan motor, intercepting the electric field from a square-wave voltage signal with a fundamental frequency of approximately 27 kHz (and its associated odd harmonics):
2.1. EXAMPLE: NEAR-FIELD PROBING INSIDE A PC

Switching to an H-field probe, the following two examples illustrate the polarization of this probe. In the first set of images we see the spectrum detected by placing the probe with its loop parallel to the current-carrying trace on the PC’s motherboard, detecting a cluster of signals centered around 4.25 MHz with maximum sensitivity because parallel conductors ensure mutually perpendicularity with the magnetic field lines:

In the second image set we see the cluster of frequencies all but gone with the probe loop rotated to be perpendicular with the offending PCB trace. The pulsed current still flows through the PCB trace, but because the probe’s loop is now perpendicular to that trace it means the magnetic field lines are now parallel to the probe loop, and therefore induction (from that signal) no longer occurs:
2.2 Example: SDR as a probe analyzer

A spectrum analyzer is an ideal instrument to display signals intercepted by E-field and H-field probes, but spectrum analyzers are typically quite expensive. While even inexpensive digital oscilloscopes come equipped with Fast Fourier Transform (FFT) capability to display signal spectra, the bandwidth of an entry-level oscilloscope may be insufficient to reliably show frequencies of interest in near-field probing.

However, a viable alternative exists for affordable near-field probing, and that is the use of a Software-Defined Radio (SDR) receiver unit. An SDR receiver, paired with appropriate software to display the spectrum of any received signals, works quite well as a broadband spectrum analyzer, especially when precise measurement of signal amplitude is unimportant. When probing for electric and/or magnetic fields, we care about the frequencies of the intercepted signals and their relative amplitudes, but are generally uninterested in determining precisely how strong each signal is because the signal strength varies so much depending on how we hold the probe.

The first image here is of an AirSpy brand SDR receiving a signal from an E-field probe:

![Image of E-field probe spectrum](image1)

Next, we see the spectrum from an H-field probe:

![Image of H-field probe spectrum](image2)

Both spectra were detected outside the case of an uninterruptible power supply (UPS) unit for a personal computer.
Chapter 3

Tutorial
3.1 Characteristics of RF

The term \( RF \) refers to radio frequency, and simply means any AC power or signal frequency great enough to permit radiation of energy in the form of electromagnetic waves, which are oscillating electric (\( \vec{E} \)) and magnetic (\( \vec{H} \)) fields propagating through space\(^1\). The threshold where electromagnetic radiation becomes significant enough to be of any concern is where the length of the conductors involved approach the AC’s wavelength (\( \lambda \)):

\[
\lambda = t_p c = \frac{c}{f}
\]

Where,
- \( \lambda \) = Wavelength, in meters
- \( t_p \) = Period of oscillation, in seconds
- \( c \) = Speed of light in a vacuum, \( 2.99792458 \times 10^8 \) meters per second
- \( f \) = Frequency of oscillation, in Hertz

Typical frequencies associated with “RF” span from hundreds of kiloHertz to hundreds of GigaHertz. Frequencies below this range radiate very ineffectively for circuits of modest physical size. The frequency range of infrared light begins in the hundreds of GigaHertz. It is worth noting that electromagnetic waves comprise much more than just radio waves, but also constitute infrared light, visible light, ultraviolet light, X-rays, Gamma rays, and cosmic rays at progressively higher frequencies and shorter wavelengths.

The spectrum of frequencies comprising “RF” is quite broad, and commonly subdivided into different categories. Note that none of these categorical definitions is strict, and that the following ranges and lettered designations should be considered approximate only:

<table>
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<tr>
<th>Frequency range</th>
<th>Wavelength range</th>
<th>RF subcategory designation</th>
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<td>3 GHz to 30 GHz</td>
<td>10 cm to 1 cm</td>
<td>Super High Frequency (SHF)</td>
</tr>
<tr>
<td>300 MHz to 3 GHz</td>
<td>1 m to 10 cm</td>
<td>Ultra High Frequency (UHF)</td>
</tr>
<tr>
<td>30 MHz to 300 MHz</td>
<td>10 m to 1 m</td>
<td>Very High Frequency (VHF)</td>
</tr>
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<td>3 MHz to 30 MHz</td>
<td>100 m to 1 m</td>
<td>High Frequency (HF)</td>
</tr>
<tr>
<td>300 kHz to 3 MHz</td>
<td>1 km to 100 m</td>
<td>Medium Frequency (MF)</td>
</tr>
<tr>
<td>30 kHz to 300 kHz</td>
<td>10 km to 1 km</td>
<td>Low Frequency (LF)</td>
</tr>
<tr>
<td>3 kHz to 30 kHz</td>
<td>100 km to 10 km</td>
<td>Very Low Frequency (VLF)</td>
</tr>
</tbody>
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\(^1\)The cross-product of perpendicular electric field and magnetic field vectors results in another vector called the Poynting vector (\( \vec{S} \)) representing the direction of radiated power and measured in Watts per square meter.
3.1. CHARACTERISTICS OF RF

RF is an important topic for any electronics student or professional for several reasons:

- RF is necessary to create radio and radar systems, built for the express purpose of radiating electromagnetic energy and/or receiving electromagnetic energy

- Electromagnetic “emissions” accompany any circuit operating at sufficiently high frequency, thereby posing potential interference for any nearby radio receiver systems

- Parasitic effects such as capacitance and inductance become problematic at these high frequencies

- Many standard cabling and construction techniques suitable for DC and low-frequency AC circuitry fail miserably if operated at radio frequencies

- RF poses unique safety hazards unknown to low-frequency and DC circuitry
3.2 Signal coupling and transmission lines

All conductors separated by an insulating medium exhibit capacitance, the ability to store energy in an electric field (related to voltage). All conductors exhibit inductance, the ability to store energy in a magnetic field (related to current). For single wires or collections of wires within a cable, the amount of capacitance and inductance per unit length is very small, negligible for many applications such as DC and line-frequency AC power circuits. However, for signals having high frequency (also, signals with rapid rise/fall times), these parasitic effects can no longer be ignored.

The ability for one conductor to influence another via these effects is referred to as coupling or crosstalk. Often the conductor exerting influence is deemed the aggressor while the conductor receiving this influence is called the victim:

\[ V = k \frac{d\Phi}{dt} \]  
\[ I = \frac{\varepsilon}{\mu} \frac{d\Phi}{dt} \]

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

Varying current in one conductor causes voltage to appear across another conductor. Varying potential on one conductor causes current to appear through load connected to another conductor.

Note how both of these effects are proportional to the rate of change of either current (inductive coupling) or voltage (capacitive coupling). For a sinusoidal waveshape, maximum rate of change is a direct function of that signal’s frequency. For other waveshapes such as square waves, maximum rate-of-change is distinct from the signal’s fundamental frequency. However, by Fourier’s Theorem we know that any non-sinusoidal waveshape is actually equivalent to a superposition of sinusoids at different frequencies (called harmonics), with steeper rise/fall times associated with higher-frequency harmonics. Thus, it is fair to say that rapid rise/fall times and high frequency values are really just two different ways to express the same state of affairs, rise/fall times referencing the time domain and harmonic frequencies referencing the frequency domain.

All this is to say that RF experiences greater levels of signal coupling (“crosstalk”) than low-frequency and DC. This becomes quite apparent if we calculate reactance at different frequencies. For example, the amount of capacitive reactance between a pair of conductors exhibiting 0.1 pF of capacitance between them is 26.53 GigaOhms – high enough that the two conductors may be considered un-coupled (i.e. isolated) for all practical purposes. However, at a frequency of 5 GHz this capacitive reactance value falls all the way down to a mere 318.3 Ohms.
Even if crosstalk were of no concern, there would still be the issue of a cable’s intrinsic inductance and capacitance bearing on the signal. The combined effect of this $L$ and $C$ within a cable results in the cable being able to store and release energy in its own right, as shown by the following *lumped-parameter model*:

A lumped-parameter model of a two-conductor cable

When a pulse signal is applied at one end of this cable, the reactive elements of that cable (i.e. capacitance between the conductors, inductance along the cable length) begin to store energy. This translates to a current drawn by the cable from the source of the pulse, as though the cable were acting as a (momentarily) resistive load. If the cable under test were infinitely long, this charging effect would never end, and the cable would indeed behave exactly like a resistor from the perspective of the signal source. However, real cables (having finite length) do stop “charging” after some time following the application of a voltage signal at one end, the length of that time being a function of the cable’s physical length and the speed of light. If we remove the electrical source prior to the pulse reaching the cable’s end, the pulse continues to propagate down the cable’s length all on its own, because the Law of Energy Conservation means the energy embodied by that pulse cannot simply disappear!

In honor of the cable’s capacity to absorb energy and propagate pulses, we typically refer to it as a *transmission line*\(^2\). All electrical cables act as transmission lines, but the effects just mentioned are so brief in duration that we only notice them when the cable is exceptionally long and/or the pulse durations are exceptionally short (i.e. high-frequency signals). With RF, practically every pair of conductors must be treated as a transmission line, and this includes traces on printed circuit boards (PCBs).

The “resistance” exhibited by a transmission line during the “charging” period is called its *characteristic impedance* or *surge impedance* ($Z_0$), and is a function of the conductors’ spacing from each other as well as the permittivity of the insulation separating them. All other factors being equal, greater spacing between conductors results in greater $Z_0$. Interestingly, this impedance has absolutely nothing to do with the line’s physical length.

If a transmission line is not terminated by a load having the same resistance as the line’s characteristic impedance ($Z_0$), some portion of every pulse’s energy will reflect back to the source after reaching the cable’s end. These reflected pulses are of great concern in RF systems because they represent poor energy transfer to the load, can create interference with subsequent pulses coming from the RF source, and in some cases can even cause cable and/or equipment damage! Therefore, in RF systems we generally take care to ensure cable impedance matches impedances found at both ends of the cable so that these reflections do not occur\(^3\). For example, in a radio transmitter system we would be sure to connect a transmission line to the transmitter’s output connector having a characteristic impedance equal to the transmitter’s output impedance, and at the other end of that cable.

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\(^2\)This use of the term is entirely different from the same term’s use in the electric power industry, where a “transmission line” is a set of conductors used to send large amounts of electrical energy over long distances.

\(^3\)From the traveling signal’s perspective, encountering a resistance equal to the cable’s own characteristic impedance at the end of that cable is akin to encountering an infinite length of that same cable.
line we would be sure to connect an antenna having an impedance also equal to (or nearly equal to) the line’s impedance.

Another cause of reflected signals in a transmission line is any discontinuity (i.e. sudden change in dimension) in that line. For example, bending a cable around too small of a radius, pinching a cable with a clamp, a sharply-angled corner on a PCB trace, etc. will cause the characteristic impedance of that localized region to differ somewhat from the characteristic impedance of the rest of the transmission line. Since reflections are caused fundamentally by sudden changes in characteristic impedance encountered by the traveling signal, such discontinuities will degrade transmission line performance.

\footnote{An anecdotal example of this is a colleague of mine who decided (wisely) to install 75-Ohm RG-59 coaxial cable throughout the new house he was building so that every room could have convenient cable television (or cable internet) service. Being unfamiliar with proper cable installation standards, however, he used electrical staples to anchor the RG-59 cable to the wall stud boards just as he was accustomed to doing for regular type-NM 60 Hz AC electrical cables. After the wall paneling was installed he tried connecting televisions to these new cable receptacles and was sorely disappointed in the “noisy” video quality the units displayed. All of those staples pinching the coaxial cable caused signal reflections, resulting in signal power attenuation at the receivers as well as corrupted signals due to the interference caused between the incident and reflected signal waves. Unwilling as he was at that point to tear down all the paneling and wallboard to replace the now-useless RG-59 cabling, he simply abandoned it and routed other cables to points of use in more conventional fashion (i.e. under the floors, through the crawlspace of the house).}
3.3  Skin effect

An interesting AC-only phenomenon called skin effect is where most of the electric current oscillating through a conductor travels near the periphery (the “skin”) of that conductor while the center of the conductor carries very little current\(^5\). This effect becomes more pronounced as frequency increases, and at RF frequencies is severe enough that the surface area of a conductor is a better gauge of its ampacity than its cross-sectional area. The following formula gives an approximation of skin depth for a given material (\(\rho\) and \(\mu\)) and frequency (\(f\)):

\[
\delta \approx \sqrt{\frac{2\rho}{2\pi f \mu}}
\]

Where,

- \(\delta\) = Skin depth, in meters
- \(\rho\) = Resistivity of conductor material, in Ohm-meters
- \(f\) = Frequency of AC current
- \(\mu\) = Absolute permeability of material, in Henrys per meter

“Skin depth” is a measure of how deep into a conductor the current falls off to \(e^{-1}\) times the intensity of the current at the conductor’s surface. For example, at 60 Hz the skin depth of a pure copper conductor (\(\rho = 1.68 \times 10^{-8}\) Ohm-meters, \(\mu = 1.26 \times 10^{-6}\) Henrys per meter) is approximately 8.4 millimeters. For comparison, the radius of a 0000 AWG wire is 5.84 millimeters, which means at 60 Hz the skin effect for even that large of a copper conductor is negligible: the 60 Hz AC current is able to freely occupy the entire cross-sectional area of that conductor. If we re-calculate for a much higher frequency, however – say, 10 kHz instead of 60 Hz – the skin depth falls to approximately 0.65 millimeters, which means most of a 0000 AWG copper conductor’s cross-sectional area would be effectively unused. Increasing frequency into VHF territory (say, 200 MHz) decreases skin depth to a mere 0.0046 millimeters for copper. At higher frequency, it is as if the conductor were much smaller-gauge than it physically measures, with a correspondingly decreased ampacity rating.

Power conductors used for RF are always hollow rather than solid for this reason: it would be a waste of metal to make a solid conductor when the vast majority of the current would not pass through its center anyway.

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\(^5\)This is an inductive effect, where the interior regions of a solid conductor experience more mutual induction from current traveling through the exterior region, and as a consequence of this any current in the conductor’s center finds itself opposed by the magnetic fields of the peripheral currents, such that more current travels near the surface of the conductor than through its center.
An impedance-matching network for a 50 kW AM broadcast transmitter operating at 550 kHz is shown in the following photograph, the inductors made of hollow (silver-coated) metal tubes. The entire network is housed inside of a small shielded room, visible through the open door:

Bare-metal grounding conductors used in RF applications are typically of braided-strand construction or consist of thin strips of sheet metal rather than being conventional circular wire. The idea here is much the same as with the hollow tubes seen in the above photograph: maximize the conductor’s surface area while using the least amount of metal mass.
3.4 Balanced versus unbalanced signals

Although not unique to RF applications, the distinction between balanced and unbalanced electrical signals is an important one in RF circuits. Simply defined, a balanced signal is where the voltage in question is measured between two ungrounded conductors. This is also known as a differential signal. By contrast, an unbalanced signal is where the voltage in question is measured between a specific conductor and ground. This is also known as a ground-referenced or single-ended signal.

Balanced signals tend to be more resistant to the effects of induced noise than unbalanced signals, as illustrated by the following diagrams showing the transmission of digital pulse signals. Note that the same advantage of noise immunity applies to balanced analog signals as well as digital:
One important application of these two different signal types relates to radio antennas. Single-wire “whip” or monopole antennas are inherently unbalanced devices, using Earth ground as the point of reference. Double-element (dipole) antennas, however, are inherently balanced devices:

Mis-matching antenna and signal types results in poor performance. For example, if we attempt to drive a dipole antenna from an unbalanced (single-ended) RF source, the result will be an attenuated and mis-shapen radiation pattern from the antenna.
3.4. BALANCED VERSUS UNBALANCED SIGNALS

A device useful for translating between balanced and unbalanced signals is a transformer called a balun\(^6\). The following balun transformer examples are known as voltage baluns because the energization of each winding is proportional to the applied signal voltage:

![Voltage Balun Diagram]

A different style of balun called a current balun places the windings in series with the load rather than parallel, such that winding energization is proportional to signal current rather than signal voltage:

![Current Balun Diagram]

The high frequency values of RF makes possible transformers having little or no iron in their cores\(^7\). A balun rated for 3 kW of RF power, for example, may be easily held in one hand. A 3 kVA power transformer rated for 50 Hz or 60 Hz service, by contrast, weighs over 30 kilograms due mostly to the iron core’s mass.

\(^6\)As you might guess, the name “balun” is a portmanteau of the words balanced and unbalanced.

\(^7\)Faraday’s Law of Electromagnetic Induction informs us that induced voltage is proportional to the rate-of-change of magnetic flux. At high frequency, the peak value for magnetic flux does not have to be very great in order to have huge rates-of-change. However, as frequency decreases, the peak value of an oscillating magnetic flux must grow larger and larger to maintain the same maximum rate of rise or fall. Larger quantities of magnetic flux translate to iron cores with greater cross-sectional area, in order to distribute that magnetic flux over a greater area to keep the flux density below the iron’s saturation limit. Therefore, low-frequency transformers have more massive cores than high-frequency transformers, all other factors being equal.
3.5 RF cabling

In RF applications we very rarely find single conductors used to convey signals as we might in DC or low-frequency AC circuits. Instead, a popular alternative is coaxial cable where one conductor rests in the center of a hollow conductor sharing the same centerline, or twinaxial cable where two conductors rest side-by-side within a hollow conductor. The outer conductor is often a metal-foil wrapping or braided-metal sheath entirely covering the center conductor:

![Coaxial cable](Image1.png)  ![Twinaxial cable](Image2.png)

For both types of cables it is common practice to connect the outer (hollow) conductor to Earth ground at one far end of the cable to electrostatically shield the inner conductor(s) from external electric fields, and also to reduce electromagnetic emissions from the cable. This makes coaxial cables well-suited to unbalanced signals, and twinaxial cables to balanced signals.

Industry-standardized RF cables often bear RG (“Radio-Grade”) designations, for example RG-6, RG-59, RG-11, etc. Each numbered “RG” type defines a set of basic electrical characteristics including impedance and physical diameter. There seems to be no logical association between the RG-number and any specific property of the cable, as these were arbitrary designators assigned to different cable designs over many years. Some of these characteristics may vary somewhat by manufacturer, which means it’s always prudent to check the detailed specifications before purchasing or using any RG-type cable for a critical application.

The United States military has abandoned the RG designators in favor of “M17” classifications referencing the MIL-DTL-17 standard. Since these designations are defined and enforced by the US military for exacting tolerances and punishing applications, variance between manufacturers tends to be less than with RG-designated cables.

In addition to flexible coaxial cabling, formable, semi-rigid, and rigid coaxial lines also exist. As their names imply, these coaxial transmission line options are stiffer than regular cables. Formable coaxial cables use a “metal-filled” braided outer conductor which allows them to be hand-formed and re-formed as needed. Semi-rigid coaxial line uses solid-metal tube for the outer conductor and often must be formed using special tools. Rigid coaxial line is for high-power applications, using metal tube for the outer conductor and usually smaller-diameter metal tube for the inner conductor. The benefit of using a solid-metal outer conductor rather than foil wrap or metal braid is superior shielding even at extremely high signal frequencies.

Semi-rigid and rigid coaxial lines commonly utilize plastic or ceramic spacers at set intervals along the length of the line to support the inner conductor and keep it a constant distance from the outer conductor, rather than a solid plastic fill material as is standard in flexible coaxial cable. The use of occasional spacers means most of the insulation between outer and inner conductors is air (or nitrogen fill gas) rather than plastic, which gives these coaxial lines lower losses and higher bandwidth capability.
3.5. RF CABBING

Rigid coaxial lines resemble copper pipe when viewed from the outside, and typically come with flanges pre-installed at the ends so that they may be easily joined to form longer lengths, or to take corners using special elbow fittings. A photograph of some rigid coaxial lines appear below, as part of the installation for a 50 kW AM radio broadcast transmitter:

At microwave frequencies it becomes possible to convey RF energy using an entirely different structure called a waveguide. A “waveguide” is a completely hollow metal tube lacking any center conductor(s), usually rectangular in cross-section and filled with either air or some other dry gas. Electromagnetic waves propagate through the tube’s interior, with the tube walls functioning as both inductors (length) and capacitor plates (width). At extremely high frequencies, waveguides are far more effective than coaxial lines in terms of shielding and signal attenuation (i.e. power loss).

Below we see an illustration of a waveguide section (left), and a photograph of a waveguide network (right) connecting multiple microwave transceivers to antennas:
Like coaxial lines, waveguides are also available in rigid and semi-rigid forms. The following photograph shows three different types of waveguide joined together, rigid (bottom-left), rectangular semi-rigid (right), and circular semi-rigid (upper-left):

If you closely examine the rigid waveguide section, you will notice an SMA connector at its far end which is how this waveguide connects to the microwave transceiver hardware. The SMA connector leads to a small wire “stub” inside the waveguide which is essentially an antenna for transmitting and receiving RF energy inside the waveguide tube. A short coaxial cable with SMA connectors at either end makes the final connection between the microwave transceiver and the waveguide, the waveguide then leading all the way up to the dish-style antenna at the top of a tall tower.

### 3.6 RF connectors

A variety of special connectors exist to terminate coaxial cable. The following subsections showcase just a few of these.
3.6. RF CONNECTORS

3.6.1 BNC connectors

This twist-lock style of coaxial connector is extremely common on test instruments capable of high frequency operation, such as signal generators, oscilloscopes, and spectrum analyzers. Photographs below show male (left) and female (right) BNC connectors:

Here we see an oscilloscope probe cable with a male BNC connector on its end, engaged with the female BNC connector on the front panel of an oscilloscope. The quarter-turn twist-lock design of the BNC connector type is evident in this photograph:

3.6.2 TNC connectors

TNC is nothing more than a threaded version of BNC; instead of a quarter-turn locking mechanism, we have a threaded barrel requiring multiple turns to fully engage. Here we see a male TNC connector at the end of a coaxial cable:
3.6.3 SMA and ST connectors

A much smaller connector format than BNC/TNC is SMA (threaded) and its quarter-turn twist-lock counterpart ST. Below we see photographs of a male SMA connector on the end of a cable (left) and a female “bulkhead” SMA connector designed to mount to an instrument panel (right):

Next we see an SMA “cap” with a built-in 50 Ohm termination resistor:

ST connectors are quite popular for fiber-optic cabling. The SMA/ST counterparts are analogous to TNC/BNC, the former being threaded and the latter twist-lock.

It should be noted that other styles of small-diameter threaded RF connectors exist which are very similar to SMA but have slightly different dimensions. These include the 2.4 mm, 2.92 mm, and 3.5 mm connectors. Just to make matters confusing, while SMA connectors will physically join with 3.5 mm and with 2.92 mm connectors, these are actually different connector designs and should not be intermixed.
3.6. RF CONNECTORS

3.6.4 PL-259 connectors

Another threaded RF connector standard is PL-259, commonly seen on high-frequency (HF) radio equipment for antenna connectors. Below we see female (left) and male (right) PL-259 connectors on cable ends:

3.6.5 N connectors

Yet another threaded RF connector standard is the N-type. Below we see a female N connector on a test instrument (left) and a male N connector at the end of a cable:
3.6.6 Reverse-polarity connectors

Threaded RF connectors may have either external or internal threads, and also have either male or female inner-conductor contact points. Typically a internally-threaded connector has a male pin which engages with the female socket of an externally-threaded connector. Below are some photographs of standard SMA-type connectors showing a “male” connector on the left and a “female” connector on the right:

A variation on these connector types is something known as a *reverse-polarity connector*. With these, the thread type remains the same but the center-conductor contact points change. Below we have a “reverse polarity male” connector on the left and a “reverse polarity female” connector on the right:

Having standard-polarity and reverse-polarity variations of each connector gender makes sense if the purpose is to prevent an end-user from attaching a cable to the wrong connector.

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8If you find these conventions illogical, you are not alone. From the standard connectors one might assume that the connector’s gender is a function of the center conductor, with “male” having the pin and “female” having the socket. However, with reverse polarity connectors it is this “defining” characteristic that swaps while the *thread types* remain the same! Anyone accustomed to pipe threads will likely find themselves wanting to call a “male” connector “female” instead because the threads are internal to the connector, and vice-versa. However, if you are familiar with industrial compression-style tube fittings the gender designations make a little more sense.
3.7 PCB layout

Traces laid out on printed circuit boards (PCBs) act like transmission lines just like cables and individual wires at radio frequencies. That being the case, careful layout is important for good circuit performance. Below we see a PCB for a personal computer Wi-Fi radio network adapter. Note the female SMA connector on the left-hand edge of this PCB, awaiting connection to an antenna:

![PCB Image]

Several features of this PCB are worth noting for their high-frequency qualities. First, the curved trace connecting the center-pin of the SMA connector to the RF amplifier (housed under the metal cover) is a good example of careful trace routing intended to maintain a consistent characteristic impedance along its length. Not only does the trace avoid any sharp turns, but the consistent clearance between the trace and the surrounding copper “pours”\(^9\) ensures the traveling signals experience consistent parasitic capacitance and inductance between those conductors. A sharply-angled trace here would have presented a discontinuity to any signals traveling along it, and thereby caused signal reflections; inconsistent clearance between the trace and surrounding ground plans would have also given the line different characteristic impedance values at different locations. Second, we see a differential (balanced) signal pathway in the form of two traces extending from two of the card-edge connector pads, ending in a pair of vias\(^10\). Third, it is impossible not to notice

\(^{9}\)A copper pour on a PCB is simply an otherwise unused area of a board layer that is filled with copper instead of being left bare. This stands in contrast to a copper plane which is an unbroken layer of copper covering the entire area of one board layer.

\(^{10}\)In PCB design, a via is a metal-plated hole passing between two or more copper layers on the board, intended to connect a trace on one layer to a trace on another layer. These differ from through-hole component pads in their lack
the abundance of vias connecting large copper areas on the top side of the board to corresponding copper areas on the bottom side. This next photograph shows the underside of this same Wi-Fi PCB, where the vias connecting top and bottom copper planes appear as tiny holes:

In DC and low-frequency AC applications, such an abundance of vias would serve no purpose other than for high-current applications. Ordinarily, just a single via would be necessary to make two copper surfaces electrically common to each other, but here we must “stitch together” those opposing copper layers far more frequently. A good practice is to space these “stitching” vias no farther apart from each other than one-twentieth of a wavelength \( \lambda/20 \) for the highest anticipated signal frequency, with even closer spacing being better.

Concern over via spacing is rooted in transmission line theory, particularly in the phenomenon of standing waves. When two conductive surfaces are electrically joined at two locations, the area between those joints has the ability to resonate like a transmission line shorted at both ends. The short-circuit (via) at either end ensures voltage nodes (zero) and current anti-nodes (maximum), with the lowest-frequency standing wave being a half-cycle. Therefore, vias placed at \( \lambda/2 \) intervals invite resonance, which in turn will degrade the performance of adjacent RF circuitry:

A maximum spacing recommendation of \( \lambda/20 \) comes from the time-honored engineering practice of designing things at least one order of magnitude \( (10^1) \) more conservative than some critical limit in order to render that critical effect inconsequential. Placing vias closer together means the resonant frequency for any standing wave must increase (i.e. higher \( f = \) shorter \( \lambda \)), and so choosing to of bare copper areas to solder, since vias are nothing more than inter-layer connectors and not intended as termination points for components.
space vias closer together means resonance is possible only at frequencies greater than the circuit is designed to operate.

Below are top- and bottom-layer photographs of another RF board, this one being a low-noise amplifier for boosting the strength of RF signals prior to the input of a radio receiver. The top side of this PCB (left) hosts all the components and is rather simple in layout, having three distinct copper “pour” areas surrounding traces. This board’s bottom side (right) is nothing but a solid copper ground plane, with vias “stitching” the bottom-layer ground plane to all three of the top-layer pours:

Rows of vias “stitching” top-layer ground areas to the bottom-layer ground plane are plentiful on this PCB, and as you can see they are necessary around the circumference of each pour.

The reason for the close spacing of “stitching” vias on a PCB is exactly the same as the reason why metal cover plates on RF devices are fastened by a seemingly over-abundance of screws: to ensure the distance between connection points is significantly shorter than a half-wavelength of the RF signal in question. The following photograph is a good example of this, there being far more screws fastening each cover plate to the metal chassis than mechanical considerations alone would require:
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3.8 Near-field testing

The fact that every conductor acts as an antenna for RF permits a novel form of diagnostic testing based on the detection of high-frequency electric and/or magnetic fields in RF circuits. If we equip an RF measuring instrument such as a spectrum analyzer with a special antenna probe, and then place that probe in close proximity to suspected radiating conductors within an energized circuit, we may determine where these fields are strongest and which component(s) in the circuit are most responsible for unwanted RF emissions.

This is known as near-field testing, the name referring to the detection of either an electric or a magnetic field in close proximity to a conductor. When electromagnetic waves propagate through empty space, the oscillating electric and magnetic field strengths relate to one another by the physical constant called the characteristic impedance of free space. Just as impedance is generally defined as the ratio of voltage to current \( Z = \frac{V}{I} \), impedance for an electromagnetic wave is defined as the ratio of electric field to magnetic field magnitudes \( Z = \frac{E}{H} \), where \( E \) is expressed in Volts per meter, \( H \) in Amperes per meter, and \( Z \) (as always) in Ohms. For empty space this impedance ratio is fixed by the magnetic permeability and electric permittivity of a vacuum, \( \sqrt{\mu_0 \varepsilon_0} \), which happens to be approximately 377 Ohms. This means that for any region of empty space where there is an electromagnetic wave, the electric field value in Volts per meter must be 377 times greater than the magnetic field value in Amperes per meter.

However, when we measure these fields in close proximity to an energized RF circuit, we often find different ratios between \( E \) and \( H \), the ratios dominated by circuit impedances more than the impedance of free space. Near high-impedance networks, for example, we find \( E \) fields that are more than 377 times stronger than corresponding \( H \) fields; near low-impedance networks we find \( E \) fields less than 377 times as strong as the accompanying magnetic fields.

![Diagram of RF sources and impedance ratios](image)

An important principle in antenna theory is reciprocity, which simply means a structure that is optimum for radiating a certain signal will likewise be optimum for intercepting that same signal. In
other words, good transmitting antennas make good receiving antennas. If we desire to preferentially
detect an electric field, we need an open-wire antenna; if we wish to sense a magnetic field, we need
a loop antenna.

The following illustrations show E-field probe versus H-field probe designs:

Single-electrode E-field probes work equally well in all physical orientations, but dual-electrode
(dipole) E-field probes and H-field probes (which are always loops) exhibit polarization in that they
are maximally sensitive when oriented parallel to the emitting conductors.

Since electric fields and electrical potential (voltage) are associated with one another, and
similarly magnetic fields are associated with electrical currents, we find E-field probes most useful
near points in a circuit with high potential relative to ground while H-field probes are most useful
near conductors carrying high current.
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Here are two commercial E-field probes, both consisting of single electrodes covered in a layer of black plastic to prevent metal-to-metal contact with the circuit under test. The larger-tipped probe is more sensitive to electric fields, but less precise in locating the position of the source:

![E-field probes](image1)

Here are two commercial H-field probes, both consisting of wire loops (with electrostatic shielding to prevent detection of electric fields) covered in black plastic. Again, the larger probe has greater sensitivity to weak fields, but is less useful for pinpointing the exact location of its source:

![H-field probes](image2)

All of these near-field probes have BNC connectors for attachment to coaxial cable, to route the detected signal to the input of a suitable measuring instrument. Spectrum analyzers work very well as near-field probe indicators because they show a wide range of signal frequencies at once and are able to very intuitively represent the strength of each of those signals by their relative peak heights. Near-field probing is very much a qualitative art, where relative signal strength matters far more than absolute amplitude.
3.9 RF safety

Electromagnetic radiation conveys energy, and as such may pose a physical hazard to living bodies. The following warning sign, found near the base of an FM broadcast transmitting antenna, implies as much:

We will explore some of the hazards of RF exposure, beginning from the most severe and progressing to the least harmful.
At very high levels of RF power – on the order of tens of kiloWatts and more – the electromagnetic energy has a similar effect on the human body to direct electric shock: overriding muscle control. There are cases where RF technicians were accidentally exposed to such levels while working on radio transmitting towers, and actually lost their grip on the tower as a result\textsuperscript{11}.

High-power RF exposure also carries direct thermal hazards: the electromagnetic energy has the ability heat up living tissue, to the point of inducing deep tissue burns in extreme scenarios. This, in fact, is how microwave cooking ovens work: the RF causes water molecules in the food to rotate, and in so doing translates that energy into heat. This is also the principle at work in diathermy, a therapeutic treatment for certain muscular injuries and to induce coagulation of certain tissues where the patient is exposed to localized RF by a qualified medical professional.

At power levels too low to cause muscular paralysis or immediately burn tissue, RF can still be hazardous. Documented cases of RF technicians exposed to high levels of electromagnetic energy from broadcasting antennas reveal symptoms including headaches, blurred vision, paresthesia (strange skin sensations), back pain, diarrhea, physical weakness, insomnia, and general discomfort, in some cases symptoms persisting for years following the exposure.

Hazards resulting from much lower levels of exposure to RF are an area of active research and dispute. In 2011 the International Agency for Research on Cancer (IARC) classified RF electromagnetic fields as Group 2B carcinogens, which means “possibly carcinogenic to humans”. This designation was based on provisional data showing an increase in gliomas (a type of malignant brain tumor) and acoustic neuromas (an often benign tumor affecting the auditory nerve) associated with cellular telephone usage.

The Chairperson of this Working Group, Dr. Jonathan Samet, made the following statement recorded in Press Release 208 from the IARC on 31 March 2011:

“The evidence, while still accumulating, is strong enough to support a conclusion and the 2B classification. The conclusion means that there could be some risk, and therefore we need to keep a close watch for a link between cell phones and cancer risk.”

The Group found limited evidence for cellular telephone use contributing to gliomas and acoustic neuromas, and inadequate evidence for other types of cancer. “Limited evidence” is defined as a positive correlation deemed credible by the Group, but one weak enough that other factors such as bias and chance cannot be eliminated. In other words, the 2B carcinogen classification simply says it’s possible low-level RF exposure could cause certain types of cancer. The IARC has other classifications appropriate for definitive causal associations.

Similar uncertainties plague other efforts to discern causal links between RF exposure and a range of possible health problems, including cataracts, male sterility, leukemia. Also, the current lack of a plausible mechanism explaining how electromagnetic waves could cause some of these maladies (i.e. a general theory of RF hazards) makes the research more difficult. However, it seems prudent to

\textsuperscript{11}I have personally met people who had this happen to them. One individual testified that his limbs began to flail about uncontrollably as soon as the antenna became energized, causing him to fall off the tower entirely! Fortunately for him, the fall was less injurious than he expected, and in fact his rapid descent removed him from RF exposure faster than if he had been able to climb down, which at the power level he was experiencing would have severely burned him in a very short amount of time.
apply what is commonly referred to as the Precautionary Principle, where we exercise caution even if we are not sure something causes harm.

Occupational and general exposure limits established by governmental regulating bodies such as the FCC are largely based on the well-established thermal effects of high-power RF emissions. Mitigations when working around RF sources include lock-out, tag-out (LOTO) and intentionally reducing output power during the exposure period.
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:

\[
\text{Gain} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{18.4 \text{ W}}{40 \text{ mW}} = 460
\]

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:

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

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 \( (1 \text{ dB} = \frac{1}{10} \text{ of a Bel}) \). Therefore, this is the form of formula you will commonly see for expressing electrical signal power gains or losses:

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

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\(^1\).

\(^1\)It is interesting to note that although the “Bel” is a metric unit, it is seldom if ever used without the metric prefix
4.1. DECIBELS

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:

\[ \text{dB} = 10 \log(\text{Ratio}) \]

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):

\[ \frac{\text{dB}}{10} = 10 \log(\text{Ratio}) \]

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:

\[ 10^{\frac{\text{dB}}{10}} = 10^{\log(\text{Ratio})} \]

\[ 10^{\frac{\text{dB}}{10}} = \text{Ratio} \]

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:

\[ \text{Ratio} = 10^{\frac{26.6276 \text{ dB}}{10}} \]

\[ \text{Ratio} = 10^{2.66276 \text{ B}} \]

\[ \text{Ratio} = 460 \]

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

“deci” (\( \frac{1}{10} \)). 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.
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:

\[
\begin{align*}
\text{Signal } P_{\text{in}} & \quad \text{Cable} \quad \text{Signal } P_{\text{out}} \\
40 \text{ mW} & \quad \text{Gain} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{37 \text{ mW}}{40 \text{ mW}} = 0.925 \\
& \quad 10 \log \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) = 10 \log \left( \frac{37 \text{ mW}}{40 \text{ mW}} \right) = -0.3386 \text{ dB}
\end{align*}
\]

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 \(\frac{1}{10} \times \frac{1}{10} = \frac{1}{100}\). 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 ±10 dB and ±3 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 \(10 \times 10 \times 2 \times 2 = 400\).

\(^{2}\)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.
4.1. DECIBELS

Observe what happens if we combine a “gain” component with a “loss” component and calculate the overall power out versus power in:

\[
\text{Gain} = 460 \text{ (ratio)} \quad \text{Loss} = -0.3386 \text{ dB}
\]

\[
\frac{18.4 \text{ W}}{40 \text{ mW}} = (460)(0.925) = 425.5
\]

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:

\[
\text{Overall gain} = \frac{17.02 \text{ W}}{40 \text{ mW}} = (460)(0.925) = 425.5
\]

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:

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

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:

\[
(10) \times (10) \times (2) \times (2) = (10 \text{ dB}) + (10 \text{ dB}) + (3 \text{ dB}) + (3 \text{ dB}) = 26 \text{ dB}
\]

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 \( P_{out}/P_{in} \) 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:

\[
P_{in} = 10 \log \left( \frac{40 \text{ mW}}{1 \text{ mW}} \right) = 16.0206 \text{ dBm}
\]

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:

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

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 \textit{adding} the amplifier’s gain factor yields the amplifier’s output power in dBm:

\[
P_{in}(\text{dB}) + P_{gain}(\text{dB}) = P_{out}(\text{dB})
\]

16.0206 dBm + 26.6276 dB = 42.6482 dBm

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.
4.1. DECIBELS

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):

\[ P_{in} = 10 \log \left( \frac{40 \text{ mW}}{1 \text{ W}} \right) = -13.9794 \text{ dBW} \]

\[ P_{out} = 10 \log \left( \frac{18.4 \text{ W}}{1 \text{ W}} \right) = 12.6482 \text{ dBW} \]

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:

\[ P_{in}(\text{dB}) + P_{gain}(\text{dB}) = P_{out}(\text{dB}) \]

\[ -13.9794 \text{ dBW} + 26.6276 \text{ dB} = 12.6482 \text{ dBW} \]

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” 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:

\[
\begin{align*}
\text{Oscillator} & : \quad \text{Power output} = 21.8 \text{ dBm} \\
\text{Cable loss} & = -0.17 \text{ dB/ft} \\
\text{Length} & = 6 \text{ feet} \\
\text{Amplifier} & : \quad \text{Gain} = 45 \text{ dB} \\
\text{Load} & : \quad \text{Cable loss} = -0.17 \text{ dB/ft} \\
\text{Length} & = 20 \text{ feet}
\end{align*}
\]

\[
\text{Power delivered to the load} = 62.38 \text{ dBm}
\]

\[
21.8 \text{ dBm} + (-0.17 \text{ dB/ft})(6 \text{ ft}) + 45 \text{ dB} + (-0.17 \text{ dB/ft})(20 \text{ ft})
\]

\[
21.8 \text{ dBm} - 1.02 \text{ dB} + 45 \text{ dB} - 3.4 \text{ dB}
\]

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):

\[\text{Stage 1} \times \text{Stage 2} \times \text{Stage 3}\]

\[\text{In fact, logarithms are one of the simplest examples of a transform function, converting one type of mathematical problem into another type. Other examples of mathematical transform functions used in engineering include the Fourier transform (converting a time-domain function into a frequency-domain function) and the Laplace transform (converting a differential equation into an algebraic equation).}\]
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. $V_{out}$ is twice as large as $V_{in}$), 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 ($P = I^2R$) means this same mathematical relationship will apply to current gains and reductions as well as voltage gains and reductions:

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

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:

$$10 \log \left( \frac{V_{out}}{V_{in}} \right)^2 = (2)(10) \log \left( \frac{V_{out}}{V_{in}} \right) = 20 \log \left( \frac{V_{out}}{V_{in}} \right)$$

$$10 \log \left( \frac{I_{out}}{I_{in}} \right)^2 = (2)(10) \log \left( \frac{I_{out}}{I_{in}} \right) = 20 \log \left( \frac{I_{out}}{I_{in}} \right)$$

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-Ohm-Milliammeter). 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 dB. 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 audio-frequency 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. Practically, it means $-\infty$ 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.

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4Such 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.

5Your electronic calculator will complain if you attempt to take the logarithm of zero!
4.1. DECIBELS

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:

\[ V = \sqrt{PR} = \sqrt{(0.001)(600)} = 0.7746 \text{ Volts} \]

Setting the VOM to the 2.5 V AC 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:

\[ 20 \log \left( \frac{2.5}{10} \right) = -12.04 \text{ dB} \]

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):

\[ 20 \log \left( \frac{2.5}{50} \right) = -26.02 \text{ dB} \]

\[ 20 \log \left( \frac{2.5}{250} \right) = -40.0 \text{ dB} \]
4.2 Electric field quantities

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

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

Where,
- \( \vec{F} \) = Force exerted on the charge (Newtons)
- \( Q \) = Charge quantity (Coulombs\(^6\))
- \( \vec{E} \) = Electric field (Newtons per Coulomb)

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

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

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

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

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\(^6\)One Coulomb of electric charge is equal to \(6.2415 \times 10^{18}\) electrons.
4.2. ELECTRIC FIELD QUANTITIES

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

$$\vec{E} = \frac{\Phi_E}{A}$$

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

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

$$\Phi_E = \frac{Q}{\epsilon}$$

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

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

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

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

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

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

Where,
- $\vec{F}$ = Force exerted on the charge (Newtons)
- $Q$ = Charge quantity (Coulombs\(^8\))
- $\vec{v}$ = Velocity of moving charge (meters per second)
- $\vec{B}$ = Magnetic field (Tesla, or Newtons per Ampere-meter)

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

---

\(^8\)One Coulomb of electric charge is equal to $6.2415 \times 10^{18}$ electrons.
Vector cross-products conveniently relate to the fingers of the right hand, which is where the “right-hand rule” originates:

\[
\vec{C} = \vec{A} \times \vec{B}
\]

When holding the index finger, middle finger, and thumb of your right hand perpendicular to each other, your index finger points in the direction of the velocity vector (\(\vec{v}\)), your middle finger in the direction of the magnetic field vector (\(\vec{B}\)), and your thumb in the direction of the force vector (\(\vec{F}\)). A simple mnemonic I use to remember these relationships of fingers to vectors is that the Index finger points in the direction of current\(^9\) (\(I\)), the Middle finger points in the direction of the magnetic field (\(B\)), and the Thumb points in the direction of the thrust (i.e. force) acting upon the moving charge.

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

---

\(^9\)Some textbooks speak of a “left-hand rule” which is intended to make sense of electric charge motion (current) in terms of electron flow. As we know, electrons are the only real mobile charge carriers within metal conductors, and so technically “electron flow” notation is most physically accurate when describing the motion of electric charges in metallic circuits. However, the right-hand rule is a mathematical definition for vector cross products, the concept of the cross product arising in the late 18th century when electrical science was still in its infancy. Early explorers of electricity used the established mathematical tools of their time and applied it to their work with electric currents and magnetism. At that time, charge carriers in metal wires were assumed to be “positive” and this is how the motion of positively-charged carriers became associated with the first vector of the cross-product. As a result of this assumption which was later proven false, we have two different conventions for denoting the motion of electricity: electron-flow which is physically accurate (for metal wires, at least), and conventional flow which is mathematically accurate. This, perhaps more than any other reason, is why educational programs designed for mathematically rigorous fields (e.g. electrical engineering) exclusively use conventional flow notation rather than electron flow notation to denote the direction of current.
If the moving charge in question is not a single charged particle but rather part an electric current passing through a conductor parallel to the first, both conductors will experience a mutually-attracting force given by the following equation:

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

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

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

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

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

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

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

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

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

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

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

With parallel currents, opposite directions repel and like directions attract\(^\text{10}\).

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

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

\(^{10}\)That is, assuming it’s like charges moving in these directions! If the charges in question are opposite each other, then like directions will repel and opposite directions will attract!
The circular loops surrounding the current-carrying conductors in the previous illustrations represent the magnetic lines of \( \text{flux} \) \( (\Phi_B) \) surrounding each of those conductors. The magnetic field \( (B) \) is related to magnetic flux by area \( (A) \), the field being a measurement of how densely-packed those flux lines are per unit area:

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

Where,

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

An older unit of measurement for magnetic fields is the \textit{Gauss} which is much smaller than a Tesla, with one Tesla equivalent to 10,000 Gauss. To put things into perspective, the Earth’s natural magnetic field has a strength of approximately one-half of one Gauss\(^{11}\).

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

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

Where,

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

---

\(^{11}\)Using the online \textit{Magnetic Field Calculator} application provided by NOAA (the National Oceanic and Atmospheric Administration) at \url{https://ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm}, applying the World Magnetic Model WMM modeling algorithm for years 2019-2024, the total magnetic field strength at my home is 53,584.4 nano-Tesla (53,584.4 nT or 0.535844 Gauss), and presently (May 2020) decaying at a rate of \(-104.1\) nT per year.
The relation of magnetic flux to current through a conductor follows a similar equation:

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

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

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

Interestingly, superconducting materials forbid magnetic fields inside of their bulk, and so the permeability value of any superconductor must be zero!
4.4 The Poynting vector

We know that electric fields \((E)\) are always associated with a voltage \((V)\), and magnetic fields (field strength \(B\) and field force \(H\)) with a current \((I)\). Specifically, electric field strength is the quotient of voltage and distance between two points which is why electric fields are measured in units of \(\text{Volts per meter}\). Similarly, magnetic field force around a straight current-carrying conductor is the quotient of current and circumference of the circular magnetic path (equal to \(2\pi\) times the distance from the conductor) which is why magnetic field force is measured in units of \(\text{Amperes per meter}\).

From Joule’s Law we know that the rate of energy transfer (called power) whenever there is simultaneous voltage and current \((P = VI)\). It stands to reason, then, that just as voltage multiplied by current yields power, an electric field multiplied by a magnetic field must similarly express power transferred by those two fields through space. That is, if \(P = VI\), then the product of \(E\) and \(H\) should yield a power intensity which we shall label \(S\):

\[
P = VI \quad \text{[Watts]} = \text{[Volts][Amperes]}
\]

\[
S = EH \quad \text{[Watts/meter\(^2\)]} = \text{[Volts/meter][Amperes/meter]}
\]

Notice how the Joule’s Law equation \(P = VI\) involves scalar quantities, while the \(S = EH\) equation necessarily involves spatial dimensions of distance (meters) and area (square meters). This is because both electric and magnetic fields are vector quantities having both magnitude and spatial direction. Power intensity \((S)\) is the measure of how much power is flowing per square meter of area in open space. As it so happens, power intensity in Watts per square meter relates to electric and magnetic fields by the right-hand rule of vector cross-products, the vector expression of that power intensity being called the Poynting vector \((\vec{S})\) after its formulator, the English physicist John H. Poynting:

\[
\vec{C} = \vec{A} \times \vec{B}
\]

\[
\vec{S} = \vec{E} \times \vec{H}
\]

Poynting’s contribution to the science of electromagnetism was expressing energy conservation and energy transfer in terms of electric and magnetic fields. That is, the electric and magnetic fields associated with any electrical source result in a flow of energy away from that source through space, and the electric and magnetic fields associated with any load result in a flow of energy toward that load through space. The direction of the Poynting vector shows the direction of that energy flow,
and the Poynting vector magnitude shows how many Watts of power flow per square meter of space.

This should be a rather startling conclusion to anyone familiar with voltage, current, and power in simple DC circuits. Beginning students of electricity regard energy transfer in simple circuits as the gain and loss of potential energy in mobile electric charges, those charges gaining energy as they pass through a source and losing energy as they pass through a load:

Though this model is conceptually correct, so is Poynting’s model of energy flowing through space. In fact, if we re-draw this simple circuit illustration showing the electric and magnetic field vectors between the two wires, we can see the Poynting vector expressing that flow of energy from source to load:

\[\text{Holding your right hand such that your index finger points downward (}\vec{E}\text{) and your middle finger into the page (}\vec{H}\text{), your thumb will point to the right (}\vec{S}\text{) from source to load.}\]
If we examine the source and load separately using the right-hand rule, we see how the Poynting vector in each case shows the proper direction of energy transfer:

It is well-worth your time to apply the right-hand rule to each of the four Poynting vectors shown above, to familiarize yourself with the use of this tool as a means to determine vector cross-product directions. For example, to the left of the source we see the electric field vector pointing down which means your index finger should point downward as well. The magnetic field vector on that side is coming out of the page (middle finger pointing toward you), and holding your right hand in that manner points your thumb to the left.
For simple DC circuits and circuit elements, Poynting’s theory of power transfer may seem like a mere curiosity. It fails to explain anything we could not already explain using the model of potential energy gained and lost by mobile charge carriers, and it requires contortions of your right hand to properly align all the vectors. However, in some applications such as radio where energy radiates away from structures called antennas in the form of electromagnetic waves (oscillating electric and magnetic fields), Poynting’s theory is the only suitable explanation for power transfer because there are no wires to convey mobile electric charges from source (transmitting antenna) to load (receiving antenna). Below we see a simplified representation of an electromagnetic wave consisting of two oscillating fields (shown here as an electric field oscillating vertically and a magnetic field oscillating horizontally), and if you use the right-hand rule in each half-cycle you will find that the Poynting vector consistently points in the same direction at the speed of light:

Electromagnetic wave

Based on the direction of the Poynting vector we see in this illustration, the source (transmitting antenna) would be located somewhere above and to the left of the drawn wave. There is no definite location for a load, as electromagnetic waves spread out in all directions away from the source. Our simple illustration merely shows a “cross-section” of a wave radiating cylindrically away from the transmitting antenna. The real electromagnetic wave (of which this illustration shows just a portion) would have an electric field resembling ripples on a pond oscillating vertically while radiating away in all horizontal directions from a single point, and have a magnetic field resembling a set of concentric circles oscillating rotationally in the horizontal plane while also radiating in all directions from that same point.
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.

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

\(^2\)Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.
CHAPTER 5. QUESTIONS

GENERAL CHALLENGES FOLLOWING TUTORIAL READING

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

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

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

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

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

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

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

- Devise an experiment to disprove a plausible misconception.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

General follow-up challenges for experiments or projects

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

- Identify some of the challenges you faced in completing this experiment or project.
CHAPTER 5. QUESTIONS

• Show how thorough documentation assisted in the completion of this experiment or project.

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

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

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

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

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

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

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

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

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

\footnote{Analytical thinking involves the “disassembly” of an idea into its constituent parts, analogous to dissection. Synthetic thinking involves the “assembly” of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.}
5.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

5.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module’s full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

- Energy
- Conservation of Energy
- Simplification as a problem-solving strategy
- Thought experiments as a problem-solving strategy
- Limiting cases as a problem-solving strategy
- Annotating diagrams as a problem-solving strategy
- Interpreting intermediate results as a problem-solving strategy
- Graphing as a problem-solving strategy
- Converting a qualitative problem into a quantitative problem
- Converting a quantitative problem into a qualitative problem
- Working “backwards” to validate calculated results
5.1.3 First conceptual question

Challenges

• ???.
• ???.
• ???.

5.1.4 Second conceptual question

Challenges

• ???.
• ???.
• ???.
5.1.5 Applying foundational concepts to ???

Identify which foundational concept(s) apply to each of the declarations shown below regarding the following circuit. If a declaration is true, then identify it as such and note which concept supports that declaration; if a declaration is false, then identify it as such and note which concept is violated by that declaration:

(Under development)

- ???
- ???
- ???
- ???

Here is a list of foundational concepts for your reference: Conservation of Energy, Conservation of Electric Charge, behavior of sources vs. loads, Ohm’s Law, Joule’s Law, effects of open faults, effect of shorted faults, properties of series networks, properties of parallel networks, Kirchhoff’s Voltage Law, Kirchhoff’s Current Law. More than one of these concepts may apply to a declaration, and some concepts may not apply to any listed declaration at all. Also, feel free to include foundational concepts not listed here.

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<thead>
<tr>
<th>Challenges</th>
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<tbody>
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<tr>
<td>• ???.</td>
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<tr>
<td>• ???.</td>
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</table>

5.1.6 Explaining the meaning of calculations

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<th>Challenges</th>
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<td>• ???.</td>
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<td>• ???.</td>
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<td>• ???.</td>
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<td>• ???.</td>
</tr>
</tbody>
</table>
5.2 Quantitative reasoning

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

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

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

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

---

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

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

5.2.1 Miscellaneous physical constants

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

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

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

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

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

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

Electric permittivity of free space ($\epsilon_0$) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

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

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

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

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

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

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

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

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

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

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

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

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

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

---

\(^6\)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.
5.2. **QUANTITATIVE REASONING**

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

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

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

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

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x_1</td>
<td>(-B4 + sqrt((B4^2) - (4<em>B3</em>B5))) / (2*B3)</td>
</tr>
<tr>
<td>2</td>
<td>x_2</td>
<td>(-B4 - sqrt((B4^2) - (4<em>B3</em>B5))) / (2*B3)</td>
</tr>
<tr>
<td>3</td>
<td>a =</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>b =</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>c =</td>
<td>-2</td>
</tr>
</tbody>
</table>

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

---

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

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

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

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

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

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x_1</td>
<td>((-B4 + C1) / C2)</td>
<td>(\text{sqrt}((B4^2) - (4<em>B3</em>B5)))</td>
</tr>
<tr>
<td>2</td>
<td>x_2</td>
<td>((-B4 - C1) / C2)</td>
<td>(2*B3)</td>
</tr>
<tr>
<td>3</td>
<td>a</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>b</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>c</td>
<td>-2</td>
<td></td>
</tr>
</tbody>
</table>

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

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

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

Convert the following amplifier gains (either power, voltage, or current gain ratios) into gains expressed in the unit of decibels (dB):

- \( A_P = 25 \); \( A_P(dB) = \)
- \( A_V = 10 \); \( A_V(dB) = \)
- \( A_I = 37 \); \( A_I(dB) = \)
- \( A_P = 150 \); \( A_P(dB) = \)
- \( A_I = 41 \); \( A_I(dB) = \)
- \( A_V = 3.4 \); \( A_V(dB) = \)
- \( A_P = 18 \); \( A_P(dB) = \)
- \( A_V = 100 \); \( A_V(dB) = \)

**Challenges**

- Suppose a student mistakenly computes 10 dB for \( A_V = 10 \) (ratio). Explain what went wrong, and why the correct answer is different.
5.2.4 Decibels into gain ratios

Convert the following amplifier gains expressed in the unit of decibels (dB), to gain figures expressed as unitless ratios:

- \( A_P = 5 \) dB ; \( A_{P(ratio)} = \)
- \( A_V = 23 \) dB ; \( A_{V(ratio)} = \)
- \( A_I = 20 \) dB ; \( A_{I(ratio)} = \)
- \( A_P = 2.5 \) dB ; \( A_{P(ratio)} = \)
- \( A_I = 7.4 \) dB ; \( A_{I(ratio)} = \)
- \( A_V = 45 \) dB ; \( A_{V(ratio)} = \)
- \( A_P = 12.8 \) dB ; \( A_{P(ratio)} = \)
- \( A_V = 30 \) dB ; \( A_{V(ratio)} = \)

Challenges

- Suppose a student mistakenly computes 100 (ratio) for \( A_I = 20 \) dB. Explain what went wrong, and why the correct answer is different.

5.2.5 Amplifier gains

An amplifier has a voltage gain of 5 and a current gain of 75, both figures being ratios. Calculate the following gains:

- Power gain (as a ratio) =
- Power gain (dB) =
- Voltage gain (dB) =
- Current gain (dB) =

Challenges

- Suppose a student calculates 6.9897 dB for the voltage gain of this amplifier. Explain where they made a mistake in this calculation.
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 First diagnostic scenario

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5.3.2 Second diagnostic scenario

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<th>Challenges</th>
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| • ???.
| • ???.
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Appendix A

Problem-Solving Strategies

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

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

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

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

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

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

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

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

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

Instructional philosophy

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

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

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

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

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

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

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

• Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.
These learning modules were expressly designed to be used in an “inverted” teaching environment¹ where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic² dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student’s understanding to ensure they are truly reasoning and not just memorizing. This is why “Challenge” points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn’t been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity³ through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

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

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

Tools used

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

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

The GNU/Linux computer operating system

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

Bram Moolenaar’s Vim text editor

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

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

Leslie Lamport’s \LaTeX \ extensions to \TeX

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

Tim Edwards’ Xcircuit drafting program

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

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

**SPICE** circuit simulation program

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

Andrew D. Hwang’s **ePiX** mathematical visualization programming library

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

Python programming language

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

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Appendix E

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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.

26 April 2022 – added subsection on “reverse-polarity” RF connectors.

3 January 2022 – added comments regarding 2.4 mm, 2.92 mm, and 3.5 mm connectors. Also added information on different rigidities of coaxial cable as well as waveguides.

26-31 December 2021 – document first created.
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