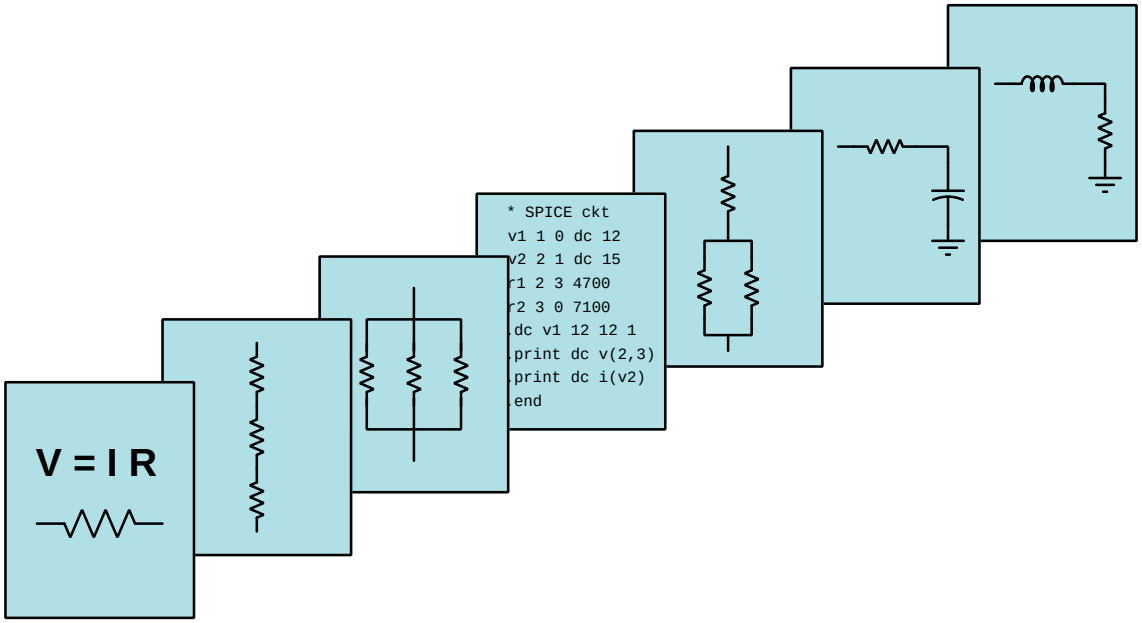
Modular Electronics Learning (ModEL) project



High-Frequency Amplifiers

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Last update = 15 October 2025

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Chapter 1

Introduction

1.1 Recommendations for students

Electronic amplifier circuits designed to operate at high signal frequencies differ substantially from those designed for low-frequency and DC signals. For high-frequency applications we must compensate for parasitic effects such inter-electrode capacitance within the devices themselves that would otherwise limit the circuit's gain and/or generate unwanted oscillations. High-frequency amplifiers may be broadly divided into categories according to their output power, the highest-output circuits generally used as final amplifiers in radio transmitter systems and the lowest-output circuits generally used to amplify the very weak signals intercepted by a receiving antenna.

Important concepts related to high-frequency amplifier circuits include **electromagnetic radiation**, **resonance**, **tank circuits**, **filter** networks, **mixers**, frequency **conversion**, **BJT** behavior, basic amplifier **configurations**, **classes** of operation, energy **efficiency**, capacitive and inductive **reactance**, **impedance matching**, **oscillation**, **feedback**, **neutralization**, **transformers**, **distortion**, and amplifier **alignment**.

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

- How might an experiment be designed and conducted to measure the gain of an amplifier circuit? What hypotheses (i.e. predictions) might you pose for that experiment, and what result(s) would either support or disprove those hypotheses?
- How is electromagnetic radiation produced?
- How is electromagnetic radiation detected and perceived by a circuit?
- Why is amplification necessary in radio systems?
- What purpose may a *mixer* serve in a radio system?
- Why are mixer circuits often followed by filter networks?
- What are some of the advantages and disadvantages of the common-emitter amplifier configuration?

- What are some of the advantages and disadvantages of the common-collector amplifier configuration?
- What are some of the advantages and disadvantages of the common-base amplifier configuration?
- What purpose is served by an *RFC*?
- Where are coupling capacitors used in amplifier circuits, and for what purpose?
- Where are decoupling capacitors used in amplifier circuits, and for what purpose?
- How does a tank circuit function?
- Why must some RF amplifiers be *neutralized*?
- What distinguishes the different "classes" of amplifier operation from one another?
- Why is it important that an LNA exhibit minimal distortion?
- Where might we find IF amplifiers in a radio system?

1.2 Challenging concepts related to high-frequency amplifiers

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

- **Common terminals in amplifier configurations** – BJT amplifier circuits are often categorized as being "common-emitter", "common-collector", or "common-base", and it is usually unclear why this is so. One approach is to simplify these circuits to show them as *grounded-emitter*, *grounded-collector*, and *grounded-base*, respectively.

- **Gain calculations** – gain for any amplifier is most properly calculated as the ratio of output *change* to input *change*, not necessarily the ratio of output to input. For example, voltage gain is calculated as $A_V = \frac{\Delta V_{out}}{\Delta V_{in}}$, the "Delta" ($\Delta$) symbols representing "change in" the designated variable(s). $\frac{\Delta V_{out}}{\Delta V_{in}}$ is equivalent to $\frac{V_{out}}{V_{in}}$ if and only if the amplifier in question outputs zero when the input is zero (i.e. when the transfer function is *purely linear* rather than merely being *affine*), which for simple one-transistor amplifiers is almost never true.

- **Decibels** – "decibels" are an attempt to express power ratios (i.e. power gains or attenuation factors) logarithmically rather than linearly, and as such they tend to generate confusion for students less familiar (or unfamiliar) with exponential and logarithmic functions.

- **Frequency-shifting or Heterodyning** – the fact that multiplying two sinusoidal signals in the time domain results in adding/subtracting those signals in the frequency domain is not intuitive at all, and is based on trigonometric identities. A section contained in the *Derivations and Technical References* chapter explains how the mathematics of this works.

1.3 Recommendations for instructors

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

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

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

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

- **Outcome** – Identify component functions within a high-frequency amplifier circuit

  Assessment – Identify the function of each component within an RF power amplifier circuit; e.g. pose problems in the form of the "Solid-state PA component functions" Conceptual Reasoning question.

  Assessment – Identify the effects of given component faults within an RF power amplifier circuit; e.g. pose problems in the form of the "Faults in a low-power CW transmitter" Diagnostic Reasoning question.

- **Outcome** – Calculate resonant frequencies for different LC networks

  Assessment – Calculate the frequency at which an LC network should resonate; e.g. pose problems in the form of the "Tank circuit calculations" Quantitative Reasoning question.

- **Outcome** – Independent research

  Assessment – Locate an RF amplifier manual and properly interpret some of the information contained in that document including power specifications, schematic diagram, etc.

Chapter 2

Case Tutorial

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

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

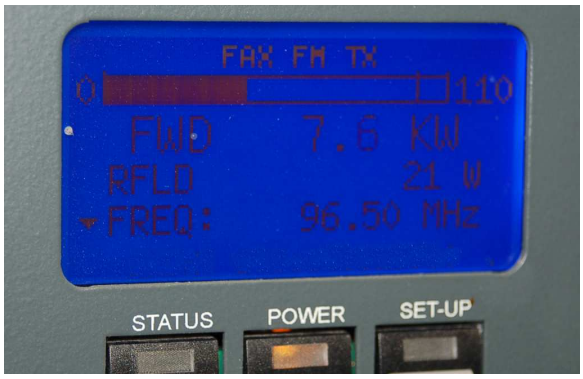
2.1 Example: broadcast FM transmitter

In the following photograph we see a Gates Air model FAX 20K broadcast FM transmitter in two parts: the exciter (upper) and the RF power amplifier (lower). An exciter consists of the RF oscillator and modulation circuitry to generate a proper RF signal at a low power level, typically just a few Watts. An RF power amplifier takes the signal from the exciter and amplifies the power to a level suitable for radiation at an antenna:

In this particular case the amplifier is rated for 20 kiloWatts of continuous RF power but typically operates at about 17 kW. The antenna array for this transmitter consists of three circular-polarized dipole antenna elements fed through a semi-rigid coaxial transmission line atop a tower approximately 100 meters in height.

Digital displays on both the exciter and the power amplifier show relevant information about their operation. On the exciter's display we see a forward power output of 1.3 Watts with zero[1] reflected power at a carrier frequency of 96.50 MHz:

The power amplifier takes the exciter's signal and boosts its power to 7.6 kW, with only 21 Watts of reflected power coming back from the antennas. Normally the power output is 17 kW, but was turned down for this photographic opportunity to limit RF exposure while in the transmitter shack:

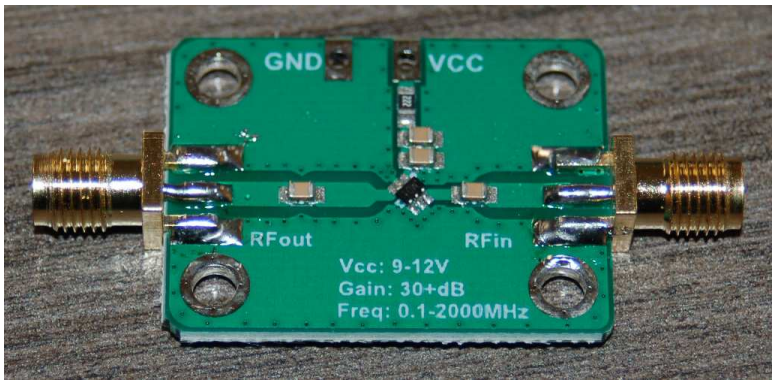


[1] One would expect a perfect standing wave ratio in a case like this because the exciter couples to the power amplifier using a short piece of coaxial cable through perfectly-matched input and output ports.

A modern design philosophy for high-power RF amplifiers is to build them in modular form, with multiple power amplifier modules operating in parallel. These small amplifier modules may be individually replaced and serviced, allowing for continuous broadcasting operation even while repairs are underway. Here we see the cabinet door opened on the Gates power amplifier to show sixteen of these modules with cooling fins exposed, the entire assembly standing less than 2 meters in height:

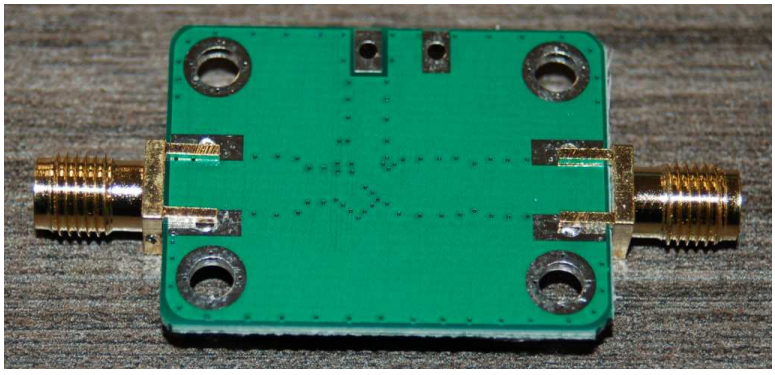
2.2 Example: broadband low-noise amplifier PCB

The following photographs show an inexpensive broadband low-noise amplifier (LNA) intended for hobbyist use in preamplifying RF signals captured by an antenna before being received by a receiver circuit. Signal input and output connections take place via SMA-style threaded coaxial connectors, while DC power enters the board by means of wires which must be soldered to two pads (V_{CC} and Ground):



Amplification is provided by the black-colored integrated circuit (IC) in the center of the board, with DC power entering at the top. Note the two decoupling capacitors soldered between the V_{CC} trace and the ground plane. Note also the coupling capacitors on both the input and output traces to prevent the amplifier IC from seeing DC in the incoming signal or to output DC to the outgoing SMA connector.

The bottom of this printed circuit board consists of a solid copper ground plane with an abundance of vias[2] "stitching" the upper and lower ground planes together. In RF circuitry we find that a multitude of connections are necessary to force two or more relatively large conductors to be electrically common with each other, since lengths of copper may behave as transmission lines:

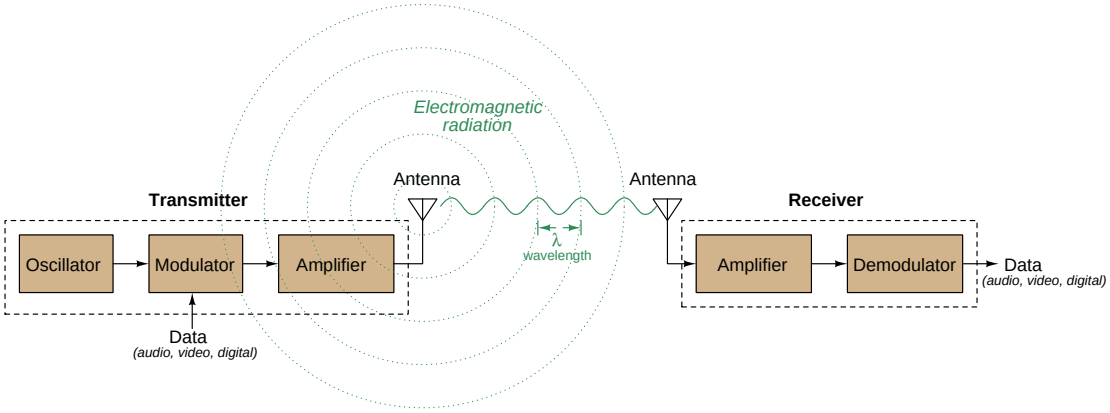


[2] In PCB layout terminology, a *via* is a metal-plated hole designed to electrically connect copper traces or planes on different layers of the printed circuit board.

Chapter 3

Tutorial

Radio transmitters and receivers alike require amplifier circuits to boost the power level of high-frequency signals:

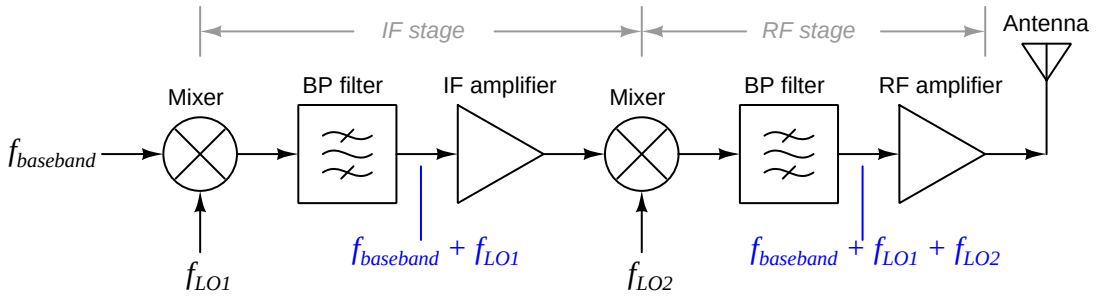


In the block diagram shown above, the two amplifiers operate at the same frequency but at radically disparate power levels. The transmitter's RF amplifier must output fairly high power to effectively radiate electromagnetic waves from its antenna. The receiver's RF amplifier must amplify the incredibly weak RF signal captured by its antenna without contributing much noise to that signal.

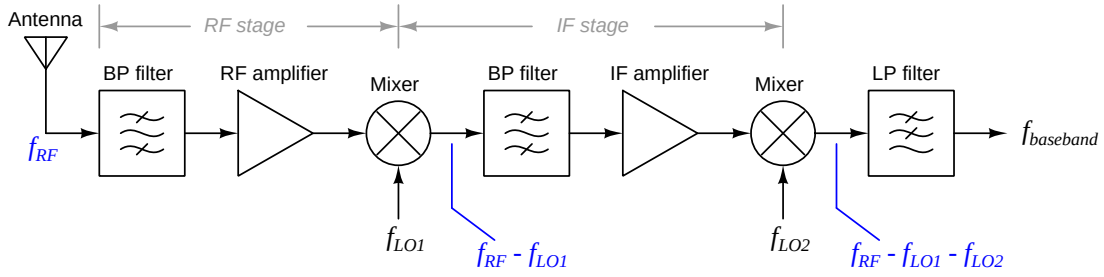
Such high-frequency amplifiers differ substantially from the circuits used to amplify low-frequency (audio-range) or DC signals. Differences include compensation for debilitating effects of high-frequency operation on the active components, optimizations for narrow ranges of frequency, and in some cases very high voltage levels (e.g. for high-power radio transmitters) or very low noise specifications (e.g. for sensitive radio receivers). For some applications such as microwave RF transmission, specialized active devices such as *klystron* tubes and *traveling wave* tubes have been invented which simply cannot be used at lower frequencies.

Furthermore, many radio systems use mixers to upconvert and/or downconvert signal frequency bands, with separate amplification stages in-between the mixer stages in order to optimize each amplifier's performance[1]. Note the following block diagrams, where mixers separate the radio-frequency (RF) amplifiers from the intermediate-frequency (IF) amplifiers:

Transmitter system:



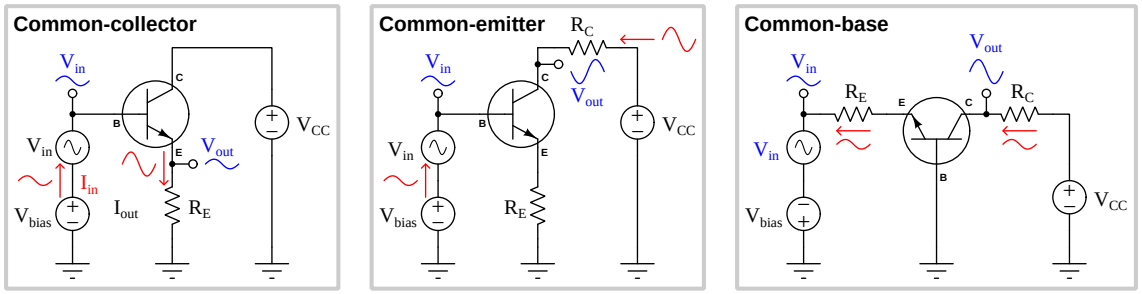
Receiver system:



[1] Optimizing amplifier noise, linearity, and efficiency simplified if that amplifier need only function over a limited frequency range. Therefore, it makes more sense to have multiple amplifier stages with each one operating on a different band of frequencies than to have a multi-stage amplifier operating on one band only.

3.1 Amplifier review

The three different BJT amplifier configurations are shown here side-by-side, with ground-referenced voltage waveforms represented in blue and current waveforms represented in red:



Amplifier configuration	AC voltage gain	AC current gain
Common-collector	≈ 1 maximum	$\beta + 1$ maximum
Common-emitter	$\approx -\frac{R_C}{R_E}$ maximum	β maximum
Common-base	$\approx \frac{R_C}{R_E}$ maximum	≈ 1 maximum

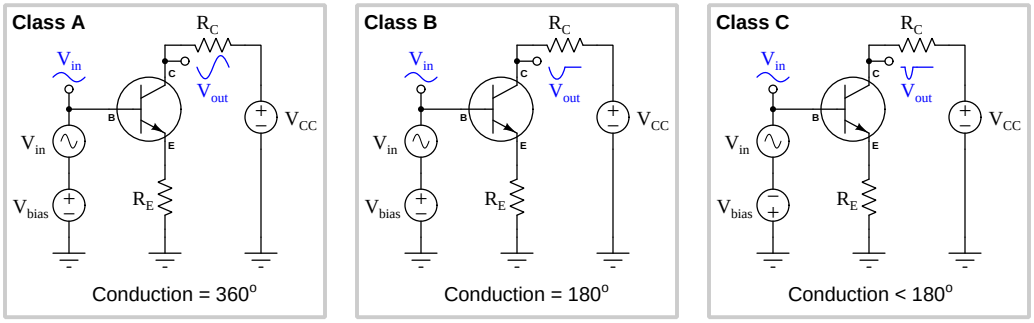
Note how the common-emitter configuration is the only amplifier circuit with a "negative" or "inverting" voltage gain. This means the output voltage signal will be phase-shifted by 180^o from the input voltage signal. For the other two amplifier configurations, there is no phase shift between V_{out} and V_{in} and as such they have "positive" voltage gains.

Gain values are shown as "maximum" because the practical gain depends on the load resistance connected between the output terminal and ground. Values and formulae specified in the table are valid only for cases where the load is one of the circuit resistances (e.g. R_C for the common-emitter and common-base, R_E for the common-collector) and nothing else is connected to the output terminal. Any connected load resistance will tend to drive voltage gain and current gain to lower values. A noteworthy exception to this rule is voltage gain for the common-collector amplifier, which remains very nearly 1 with or without external load resistance.

Of notable utility to RF amplifiers is the common-base topology[2], which is superior to the other two configurations in terms of high-frequency performance. The *cascode* amplifier is a two-transistor topology consisting of a common-emitter stage feeding a common-base stage – the common-emitter providing current gain and the common-base providing voltage gain – known as well for its excellent high-frequency performance.

[2]The term "topology" when applied to technology refers to the shape or configuration of something. In this case, the particular arrangement of components that comprise a transistor amplifier circuit.

Three common modes of operation for amplifiers are *Class A*, *Class B*, and *Class C*, referring to progressively lower angles of conduction. This complicated-sounding phrase simply means that with each successive class of operation the transistor spends less time (i.e. fewer degrees of the waveform's cycle) in the "on" or conducting state. Representing each of these classes of operation for a simple common-emitter topology:



Of these three classes, only class A is able to faithfully reproduce the entire waveshape with just a single transistor. Class B amplifiers require two transistors working in "push-pull" tandem fashion, each one amplifying one-half of the waveform. Class C amplifiers require an additional LC "tank circuit" to sustain complete output oscillations during the time the transistor is off. From the perspective of energy efficiency, though, class C is better than class B, and class B is better than class A. The less time the transistor spends in the "on" state, the less power it dissipates in the form of heat.

Radio receiver amplifiers generally operate in class A mode, where the design priority is maintaining the integrity of the very weak signal captured by the antenna. Class A operation yields the most faithful reproduction of the signal's waveshape, which is equivalent to saying it introduces the least amount of harmonic distortion. Energy efficiency is not as important here because the power levels handled by a receiver's amplifier are very low. Radio transmitters, by contrast, benefit from classes other than class A because energy efficiency is far more important for a transmitter amplifier than it is for a receiver amplifier. If a transmitter amplifier exhibits distortion, that may be handled by proper filtering on the output[3]. Any attenuation of the output signal by this filtering may be overcome simply by driving more power to the output.

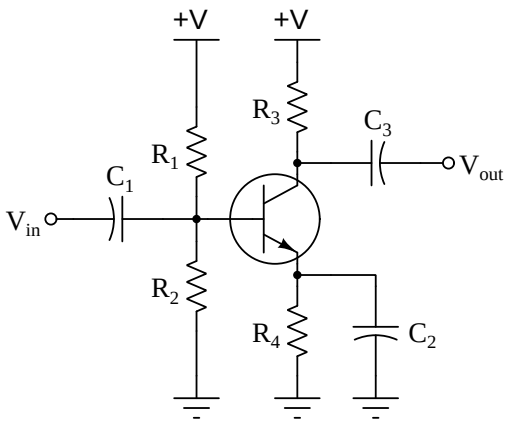
[3] Anything that acts to distort what is otherwise a pure sinusoidal wave introduces *harmonic frequencies* to that signal. These are integer-multiple sinusoidal frequencies of the fundamental. For example, if the fundamental RF signal to be broadcast is 1000 kHz and the power amplifier adds harmonics to this 1000 kHz signal, those harmonic frequencies will be integer-multiples of that fundamental: e.g. 2000 kHz, 3000 kHz, 4000 kHz, 5000 kHz, etc. The magnitude of each harmonic depends on the nature of the distortion.

3.2 RF power amplifiers

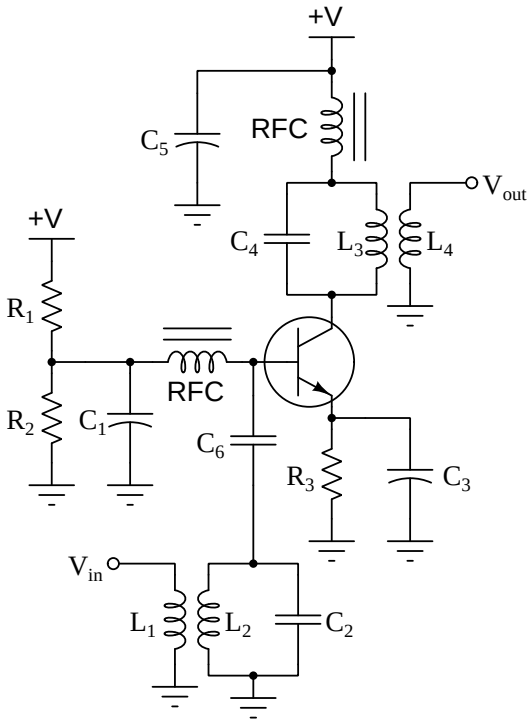
The purpose of an RF power amplifier (often labeled *PA*) is to boost the power of a modulated RF signal to a level appropriate for antenna broadcast. Either transistors or vacuum tubes may be used, with vacuum tubes still finding contemporary use in high-power transmitter applications.

When we examine the schematic diagram of an RF power amplifier and compare it to an audio-frequency amplifier design (both common-emitter using NPN transistors), we notice some interesting differences:

Typical low-frequency CE amplifier



Typical high-frequency CE amplifier

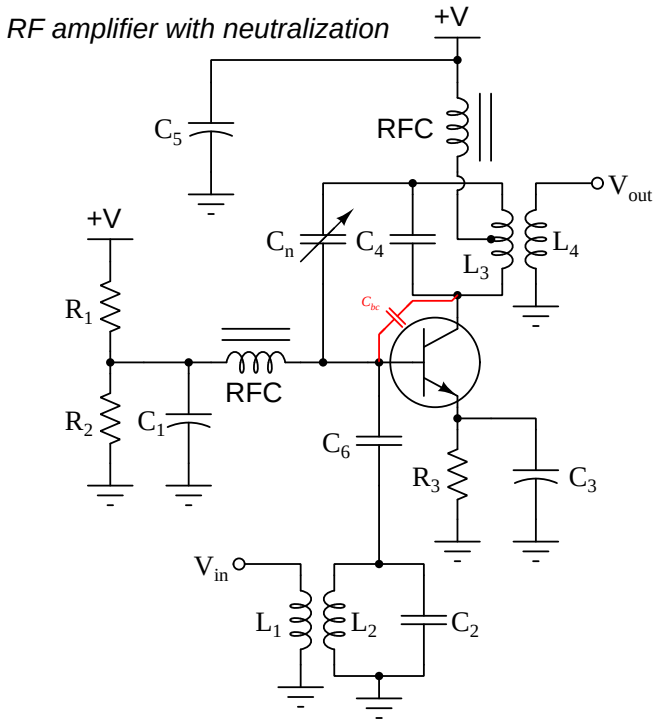


In the low-frequency amplifier circuit, C_1 and C_3 are coupling capacitors acting as high-pass filters for the input and output AC signals, allowing them to pass through to or from the transistor while blocking DC bias voltage. Capacitor C_2 is an emitter-bypass intended to boost the amplifier's voltage gain. Resistors R_1 and R_2 set the base's bias voltage while resistor R_3 establishes the amplifier's voltage gain and resistor R_4 helps stabilize the transistor's biasing over a range of operating conditions.

In the high-frequency amplifier circuit, we cannot help but notice the presence of several inductors, two of them paired with nonpolarized capacitors to form *tank circuits*. These parallel LC networks form band-pass filters tuned to the expected operating frequency of the RF carrier signal. We also see iron-core inductors marked "RFC" which stands for *radio-frequency choke*, acting as low-pass filters in conjunction with bypass capacitors C_1 and C_5 to block RF signal from

reaching the DC power supply rails while passing DC. Also unique is the inductive coupling for the input and output signals, with the possibility of different turns ratios to help match the input and output impedances of the amplifier to the high-frequency source and load, respectively.

A potential problem for all amplifier circuits including high-frequency amplifiers is *self-oscillation*. This is where the output signal couples to the input in such a manner as to create positive feedback. In common-emitter transistor amplifiers this feedback naturally occurs by means of the parasitic base-collector capacitance inside the transistor, and for high-frequency amplifier circuits with tuned inputs (i.e. a tank circuit connected to the base) this capacitance invites regenerative oscillations in that tuned network. One way to combat this problem is to intentionally incorporate feedback of the opposite phase so as to cancel out the parasitic feedback effect. In the field of RF amplification this technique is called *neutralization*.

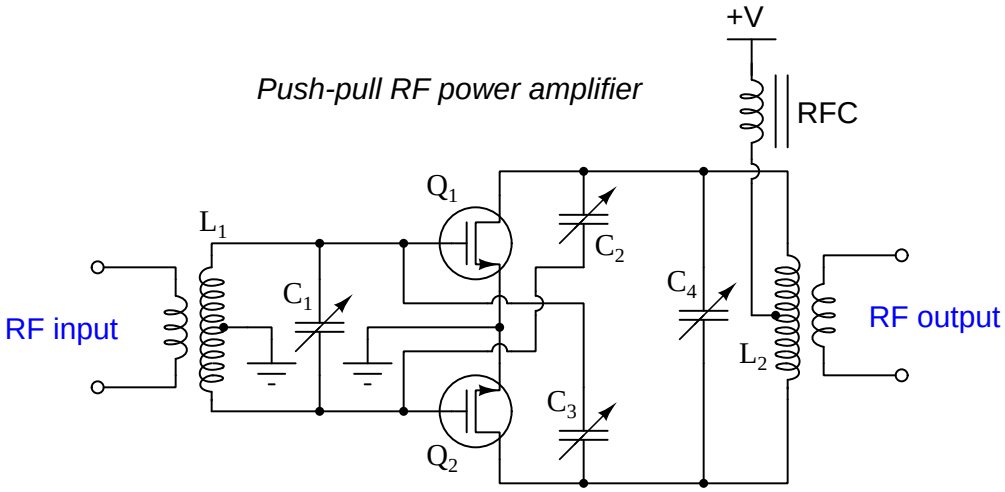


By center-tapping inductor L_3, the top and bottom terminals of the C_4/L_3 tank circuit become opposite in polarity with reference to the center-tap point (which is AC-grounded through capacitor C_5). Therefore, if the bottom terminal of that tank circuit sends the wrong type of feedback signal to the transistor's base, the top terminal of the same tank circuit (being opposite in polarity) will send just the right type of feedback to cancel out (or *neutralize*) that parasitic capacitance's effect.

With the neutralization method shown here, perfect neutralization occurs when $C_n = C_{bc}$.

Push-pull amplifier topologies are also useful as RF power amplifiers, especially for applications where we require a *balanced* RF output signal such as directly driving a dipole-style antenna. Recall that *unbalanced* signals are where the signal voltage is measured between one signal conductor and ground (typically Earth ground in RF systems), whereas *balanced* signal voltages appear between two un-grounded signal conductors, ideally with the ground-referenced potential of each always equal in magnitude and opposite in polarity. Antennas utilizing dipole elements require balanced driving signals in order to produce symmetrical radiation patterns.

The following push-pull amplifier design makes use of N-channel MOSFETs[4] rather than BJTs:

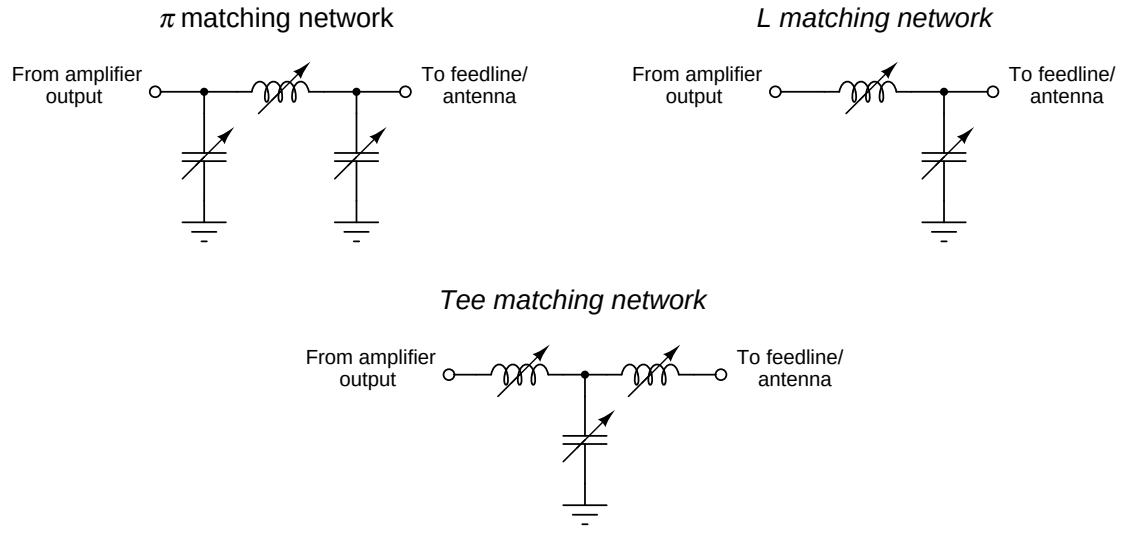


Tank circuit C_1/L_1 tunes the input of the amplifier while C_4/L_2 tunes the output and helps to suppress unwanted harmonics (especially when operated in class B or class C modes). Capacitors C_2 and C_3 serve to neutralize the amplifier, helping to prevent self-oscillation. Note how the input signal for this amplifier happens to be balanced as well (i.e. two un-grounded terminals).

[4] If the MOSFET symbols look unfamiliar, it's because they are alternative to the symbols I typically use. The source terminal of each is identified by the presence of the arrowhead, which points in the direction of quiescent source current. For N-channel MOSFETs this means conventional flow exiting the source terminal (and entering the drain).

While many RF power amplifiers have parallel-LC "tank circuits" for filtering and harmonic reduction, it is also customary to find combinations of inductors and/or capacitors on both the input and/or output for the purpose of *impedance matching*. On the input side of an RF power amplifier, there may be a need to match the amplifier's input impedance to the output impedance of the oscillator/modulator feeding it for the purpose of transferring the maximum amount of power from one to the other. On the output side of an RF power amplifier, similar LC networks will serve to match the antenna and feedline impedance to that of the amplifier, also for maximum transfer of power from the amplifier to the antenna (load).

Tank circuits always consist of inductance and capacitance connected directly in parallel with each other, so that they may freely exchange energy back and forth in resonance. By contrast, impedance-matching networks tend to be L-shaped or π-shaped or T-shaped for unbalanced-signal circuits:



Adjustable capacitance and/or inductance is useful to precisely site-match the antenna and feedline to the transmitter's output, but if the parameters are well-known in advance you may find fixed-value components used in matching networks. Since this method of matching impedances only works for fixed frequency values, adjustable L/C combinations allow for re-alignment when switching transmission frequencies. For more information on impedance matching using LC networks, refer to section 4.2 beginning on page 38.

It is worth noting that RF power amplifiers are generally tested for proper operation with a suitable load resistor connected in lieu of an antenna. By doing this, the amplifier's performance may be thoroughly investigated under the same loading conditions that an antenna would ordinarily provide without actually broadcasting any electromagnetic radiation.

The following photograph shows a 50 Ohm resistor specifically designed for transmitter testing, this one with a power rating of 150 Watts maximum. As it so happens, 50 Ohms is a widely-recognized standard for RF power amplifier output impedance:

One should *never* operate an RF power amplifier without a suitable load connected to its output, whether that be a proper antenna or a "dummy" load of proper resistance. Failure to do so may actually cause damage to the amplifier's internal circuitry! Even Citizen's Band (CB) radio transceivers rated at just 5 Watts of output power come with warnings not to transmit without the output connected to a proper load.

3.3 Low-noise amplifiers

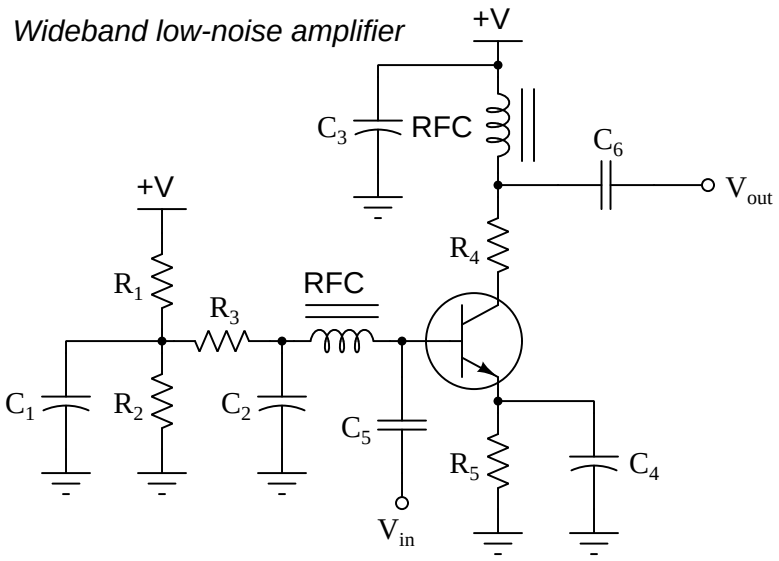
An RF amplifier intended to amplify the signal captured by an antenna is commonly referred to as a *low-noise amplifier* or *LNA*. These amplifiers are designed for the very challenging task of amplifying an extremely weak electrical signal without contributing substantial distortion or noise[5] to that signal, hence the name. Energy efficiency is not very important for a low-noise amplifier because the output power is generally quite low, just high enough to provide a signal with enough strength to properly drive the mixer, filtering, and/or demodulator circuitry. It is far more important for an LNA to faithfully reproduce the signal than to be energy-efficient, and so class A operation is standard.

Linearity is important for any low-noise amplifier because we do not want the amplifier to add artifact frequencies to the received signal. If the amplifier receiving an RF signal distorts it in any way, the result will be that the band of frequencies constituting the input signal will mix with each other, causing new frequencies to emerge in the signal spectrum called *intermodulation products*. A standard test for amplifier linearity is to feed it an input signal consisting of two different sinusoidal AC voltages summed together, and then use a spectrum analyzer to check for the presence of any additional frequencies in the output signal. A perfectly linear amplifier will exactly reproduce the input spectrum at the output and not introduce any new frequencies.

Low-noise amplifiers may be broadly divided into *narrowband* and *wideband* (also called *broadband*) categories. For radio receivers designed to operate over a narrow range of frequencies, it is customary to equip the input amplifier(s) with tuned LC networks to better filter out any out-of-band signals. Some radio receivers and RF test equipment, however, must be able to effectively sample a wide range of signals, and the amplifiers used in those applications generally lack such tuning networks.

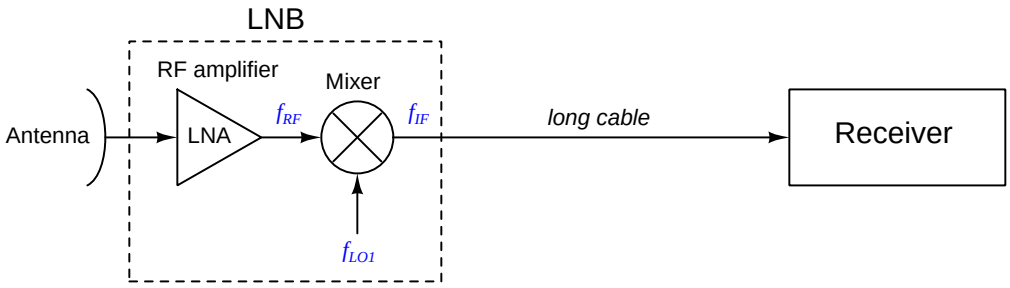
[5] "Noise" is simply defined as any unwanted alteration of an electrical signal, which includes cross-coupling of physically adjacent signals, drifting of signal bias or amplitude over time, etc. All amplifiers *generate* noise to some extent, with high-gain amplifiers being worse in this regard.

An example of a wideband low-noise amplifier appears below:



Decoupling capacitors C_1, C_2, and C_3 provide stable AC ground points in the circuit while working in conjunction with the radio-frequency chokes (RFC) to prevent any RF signal from reaching the power supply rails. Capacitors C_5 and C_6 act as high-pass filters to allow the RF signal into and out of the amplifier while blocking all DC bias from those same input and output terminals. Capacitance values are chosen so as to not resonate with the RFCs at any point within the amplifier's design bandwidth, which means this circuit is *untuned* and should exhibit a relatively "flat" gain over that range of signal frequencies.

In microwave receiver applications where the antenna may be located a substantial distance from the rest of the receiver circuitry, it makes sense to locate the low-noise amplifier and downconverting mixer directly at the focal point of the antenna dish, so that the cable connecting the antenna system to the rest of the receiver need only handle intermediate frequency (IF) signals rather than the full RF intercepted by the antenna. In such installations the LNA, mixer, and local oscillator are enclosed in the same module, commonly called a *low-noise block downconverter* or *LNB*:

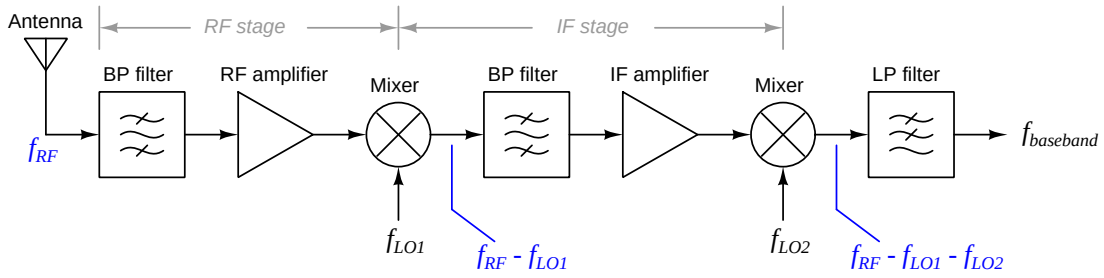


A photograph of a typical satellite-television receiver antenna with a three-element LNB appears in the following photograph:

The rationale for having three LNBs offset from one another is to be able to receive signals from three different satellites in geosynchronous orbit without re-positioning the directional dish antenna.

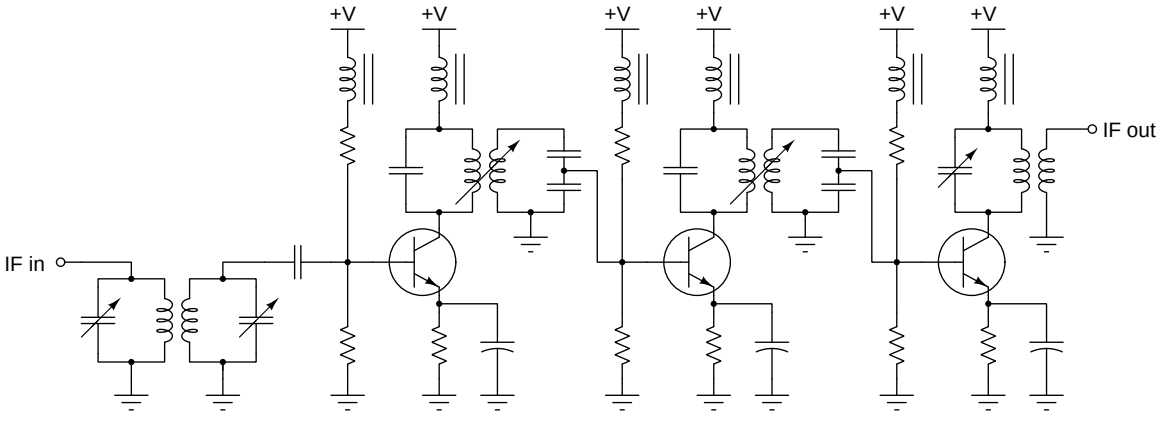
3.4 IF amplifiers

Many RF systems, particularly radio receivers, use mixers to downconvert the RF signal received by the antenna into a lower frequency called *IF* (intermediate frequency) that is still far greater than the baseband. This IF signal must be amplified for further processing (e.g. additional mixer stages to downconvert to the baseband frequency range), as shown in the following receiver block diagram:



Amplifier design becomes more complicated as frequency increases, which is good design rationale for the existence of IF signals and IF amplifiers: downconvert the RF signal into a more manageable frequency range, then amplify it there rather than try to do so at the extremely high frequencies of RF.

IF amplifiers typically operate on a fixed signal frequency, it being the responsibility of the downconverting mixer to decrease the RF signal's frequency to the narrow range expected by the IF amplifier. It is not uncommon, especially in legacy radio receiver designs, for IF amplifiers to have *double-tuning* networks on both input and output, each consisting of a transformer with a tuning capacitor on both primary and secondary windings. An example of a double-tuned, three-stage IF amplifier appears below:



The procedure to adjust all these double-tuned tank circuits for optimum IF amplifier performance is called *alignment*, or sometimes *peaking*[6].

[6] A simple technique for IF alignment consists of sending a constant-amplitude AM-modulated signal into the front

end of the IF amplifier and carefully adjusting each double-tuned tank for maximum ("peak") output signal, hence the term *peaking*.

Chapter 4

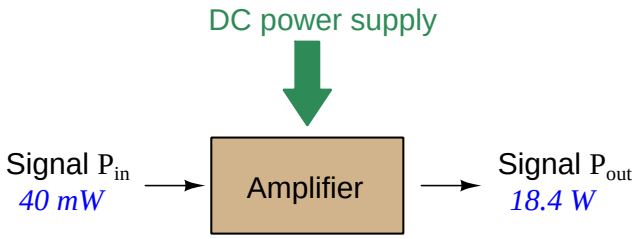
Derivations and Technical References

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:



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

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:

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

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

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

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

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):

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

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

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:

$$\text{Ratio} = 10^{\frac{26.6276 \text{ dB}}{10}}$$

$$\text{Ratio} = 10^{2.66276 \text{ B}}$$

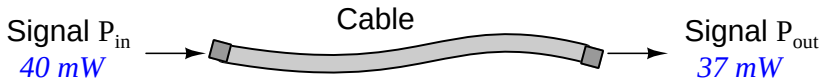
$$\text{Ratio} = 460$$

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:



$$\text{Gain} = \frac{P_{out}}{P_{in}} = \frac{37\ mW}{40\ mW} = 0.925$$

$$10 \log \left(\frac{P_{out}}{P_{in}} \right) = 10 \log \left(\frac{37 \text{ mW}}{40 \text{ mW}} \right) = -0.3386 \text{ dB}$$

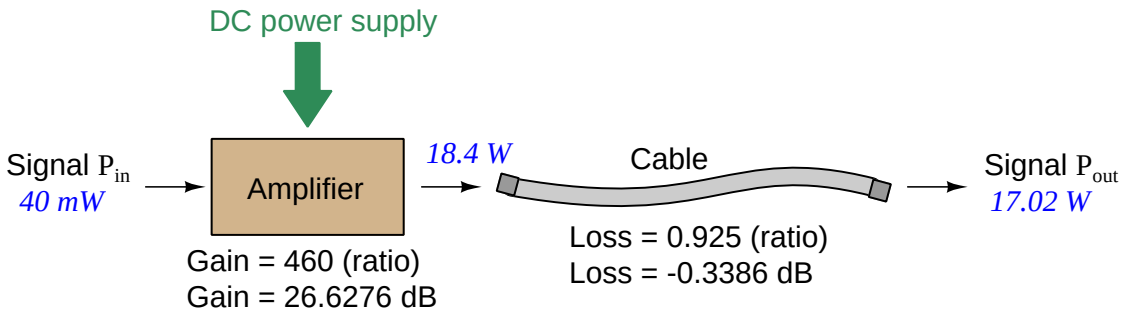
Contrasting this result against the previous result (with the amplifier) we see a very important property of decibel figures: any power *gain* is expressed as a *positive* decibel value, while any power *loss* is expressed as a *negative* decibel value. Any component outputting the exact same power as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

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

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

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



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

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

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.

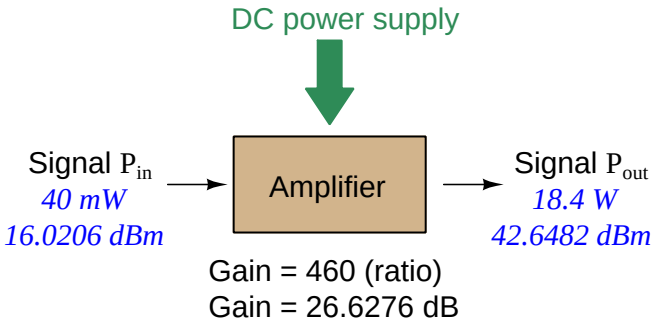
Decibels always represent comparisons of power, but that comparison need not always be P_{out}/P_{in} for a system component. We may also use decibels to express an amount of power compared to some standard reference. If, for example, we wished to express the input power to our hypothetical amplifier (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 *m*illiWatt 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 *adding* the amplifier's gain factor yields the amplifier's output power in dBm:

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

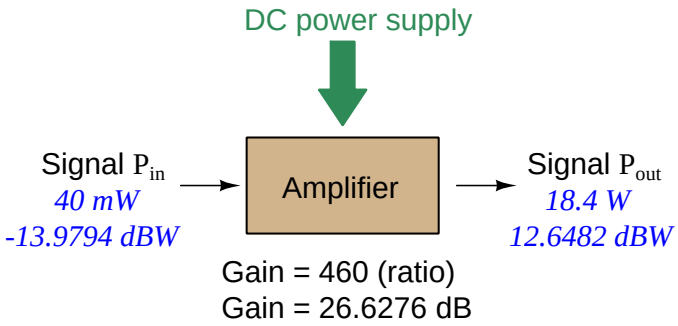
$$16.0206 \text{ dBm} + 26.6276 \text{ dB} = 42.6482 \text{ dBm}$$

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.

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:

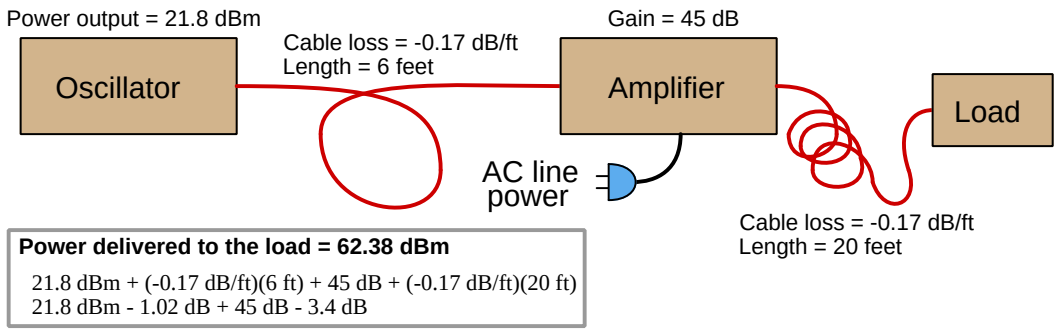
$$P_{in}(\text{dB}) + P_{gain}(\text{dB}) = P_{out}(\text{dB})$$

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

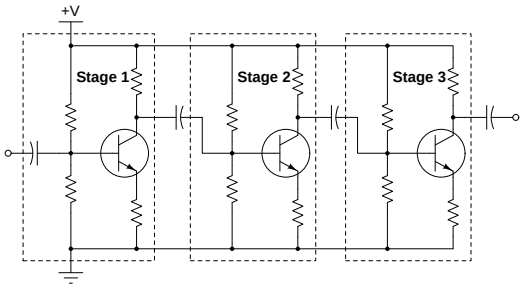
An electronic signal that begins 13.9794 dB less than 1 Watt, when boosted by an amplifier gain of 26.6276 dB, will become 12.6482 dB greater than the original reference power of 1 Watt.

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[3]" one type of problem into a simpler type: in this case, a problem of multiplying ratios into a (simpler) problem of adding decibel figures.

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



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):



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

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:

$$\log x^y = y \log x$$

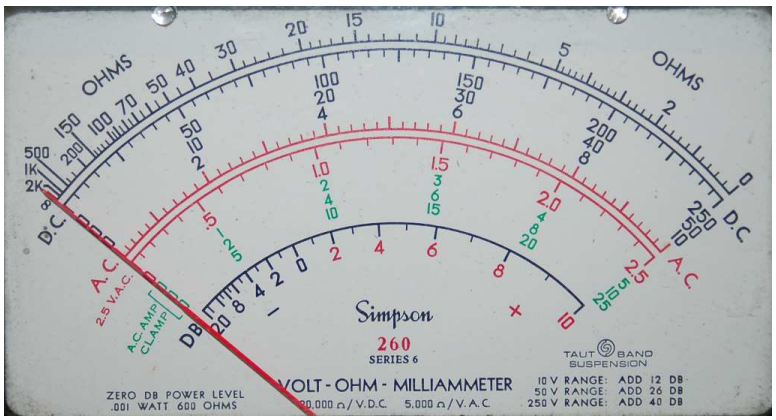
Therefore, we may simplify the decibel formula for voltage gain by removing the "2" power and making it a multiplier:

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

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

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[4]. A load resistance value is necessary as part of this definition for dB because this meter cannot measure power directly but must infer signal power from measurements of AC *voltage*. Without a specific load resistance, there is no clear relation between voltage and power. 600 Ohms is an old telecommunications standard for 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*[5]. 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.

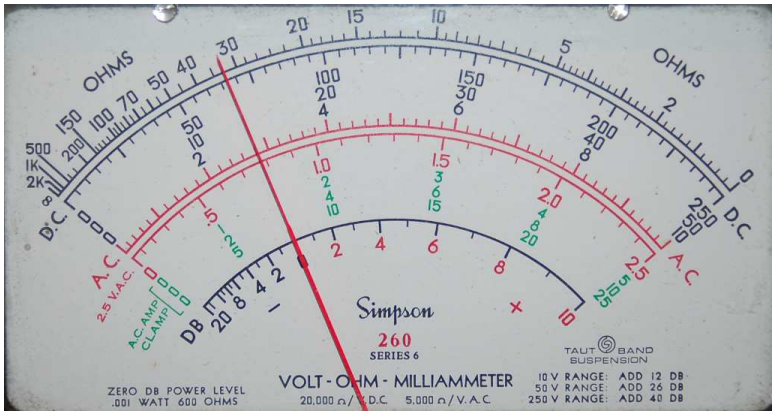
[4] Such mis-labeling is not that uncommon in the profession, the expectation being that the technician or engineer working with the instrument ought to be familiar enough with the concept of decibels to know when dB really means dBm, or dBW, etc.

[5] Your electronic calculator will complain if you attempt to take the logarithm of zero!

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



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

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

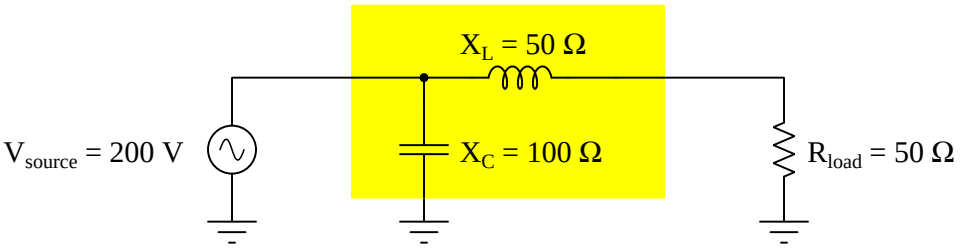
Therefore, when using the 10 VAC range instead of the 2.5 VAC range, one must add 12 dB to the reading. Likewise, we may prove each of the printed correction factors for the alternative voltage-measurement ranges listed (50 Volt AC range and 250 Volt AC range):

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

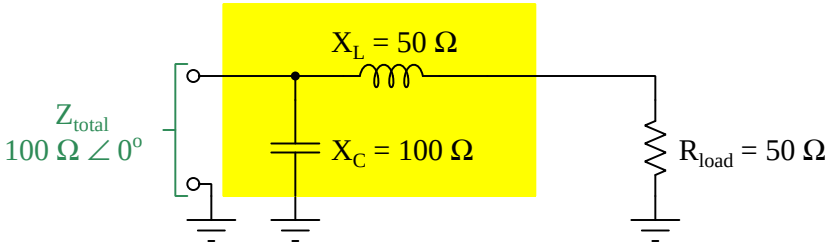
$$20 \log \left(\frac{2.5}{250} \right) = -40.0 \text{ dB}$$

4.2 LC impedance-transformation networks

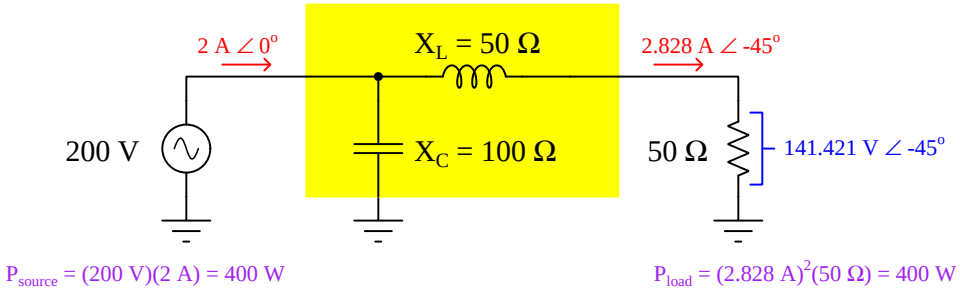
An interesting and useful property of inductor-capacitor networks is their ability to make the impedance of a load "look" different to a connected source. As an example of this, consider the following network connected between a 200 Volt AC source and a 50 Ohm resistive load. In order to keep this example as simple as possible, we specify reactance values for the inductor and capacitor rather than actual inductance and capacitance values (along with a specified source frequency):



If we perform the necessary series-parallel impedance calculations for the LC network and resistive load, we find that the total impedance (as calculated from the perspective of the input terminal where the source would connect) is precisely 100 Ohms resistive (i.e. $100\ \Omega \angle\ 0^o$ or $100 + j0$) which is twice the impedance of the load with the same phase angle.

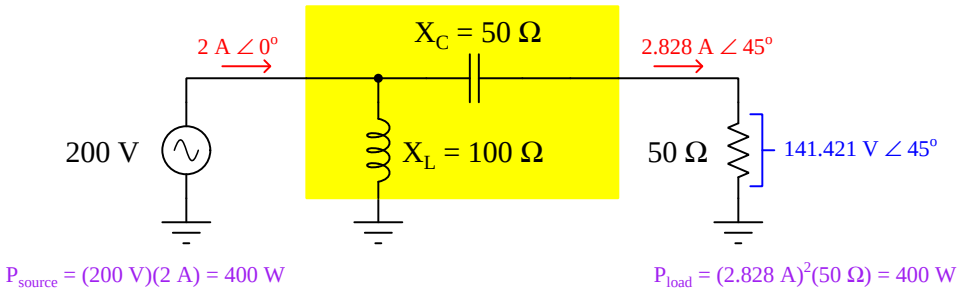


Therefore, when this circuit is energized we find the following voltage, currents, and powers at the source and load:



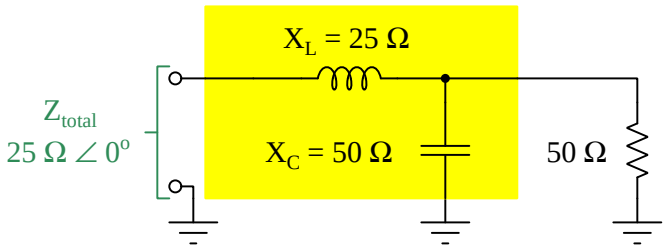
Note how with the simple LC network the source "sees" a 100 Ohm load impedance even though the actual load is 50 Ohms, and also how load power and source power are precisely equal (at least given an ideal inductor and an ideal capacitor having no dissipative losses).

We may achieve the same load impedance transformation by exchanging the placement of the inductor and capacitor, but maintaining the original reactance values (50 Ohms in series, 100 Ohms in parallel). The only difference is in the phase shift of current and voltage at the 50 Ohm resistive load:

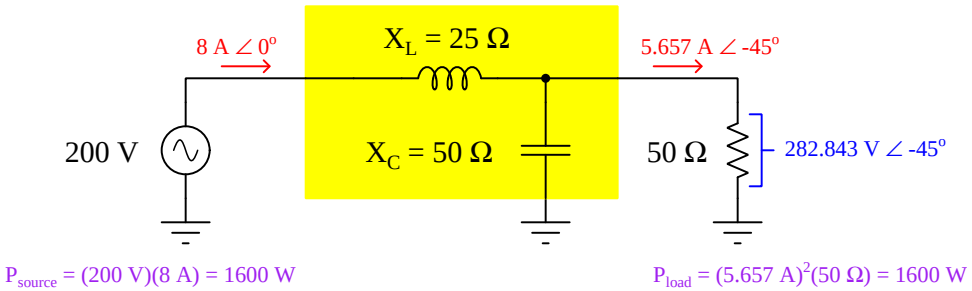


One way to view these LC impedance-transformation networks conceptually is to view the series-connected component (with the load) as adding to the load's impedance, and the parallel-connected component (with the source) correcting that increased impedance to become purely resistive as seen by the source.

It is also possible to transform a resistive load's impedance *down* rather than up, by altering the series-parallel relationship of the reactive components and suitably altering their reactance values. In this case, the LC network transforms the 50 Ohm resistive load into 25 Ohms as "seen" by the AC source:



Therefore, when this circuit is energized we find the following voltage, currents, and powers at the source and load:

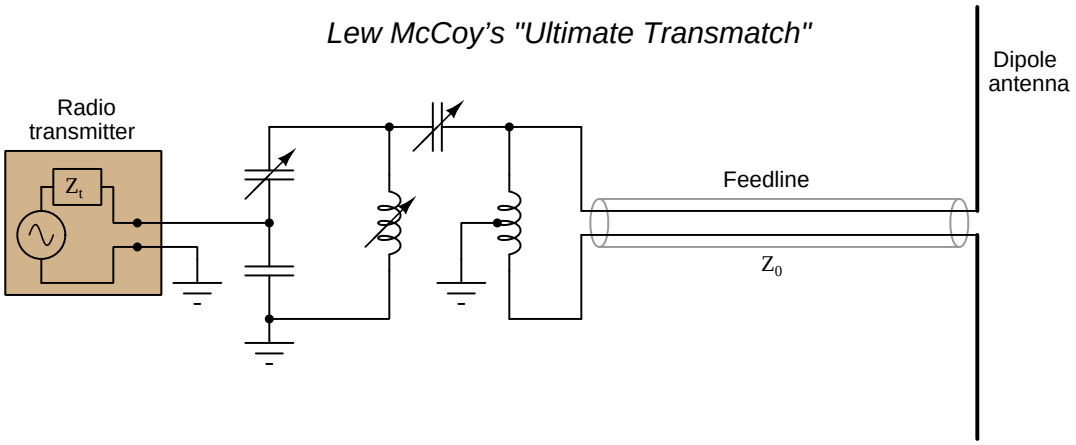


Again, we may conceptually understand these LC impedance-transformation networks by considering the parallel-connected component as a means to diminish the load's apparent impedance, and considering the series-connected component as a means to cancel out any remaining reactance so that the source sees a purely resistive load. The reason this network decreases the load's apparent impedance is because the component connected directly to the load is in *parallel*, while the former network increased the load's apparent impedance because the component connected directly to the load was in *series*.

As before with the impedance-boosting network, we may swap the positions of L and C and achieve the same effect if the reactance values remain the same (i.e. 50 Ohm inductive reactance in parallel with the 50 Ohm load resistance and 25 Ohm capacitive reactance in series with the source).

Impedance transformation occurs because capacitors and inductors are (ideally) non-dissipative components. Stacking inductance and capacitance in a series-parallel network with a load obviously alters the total impedance value, thus making the load "appear" to have a different impedance than it does from the perspective of the source, but the non-dissipative nature of the LC network means no energy is "wasted" therein and the resistive load must receive all of the source's power. Just as a transformer with a turns ratio other than 1:1 clearly presents a different voltage to the load than what the source supplies, and given the non-dissipative nature of the transformer and the Law of Energy Conservation this *must* mean current gets transformed in the inverse ratio.

A common application of this impedance-transformation method is matching the impedance of an antenna and feedline system to the output impedance of a radio-frequency power amplifier, such as that found in a radio transmitter system. The principle involved here is the Maximum Power Transfer Theorem, which states the amount of power delivered to a load from a source is maximized when the load's impedance is adjusted to equal that of the source[6]. Proper impedance-matching between load and source is also necessary to minimize signal reflections and *standing waves* along transmission lines such as the feedlines connecting radio transceivers to their respective antennas. Often referred to as *transmatch* networks, an example of impedance transformation by an LC network[7] is found in Lew McCoy's "ultimate transmatch" designed for amateur radio operations:



Adjustable capacitors and inductors are typically provided in transmatch networks so that the radio operator may "align" the unit to the operating frequency of the transmitter as well as to the exact impedances of the amplifier and antenna/feedline system. McCoy's general instructions for using this particular network (as written in his July 1970 *QST* magazine article "The Ultimate Transmatch") include setting both variable capacitors to maximum capacitance, adjusting the variable inductor until minimum reflected power is obtained (i.e. as close to a perfect standing wave ratio as possible), and then adjusting variable capacitors C_1 and C_2 by trial-and-error until the best match is obtained, as indicated by the SWR reaching unity or reflected power decreasing

[6] This would be the source's equivalent Thévenin or Norton impedance.

[7] In fairness, McCoy's design also incorporates a wideband transformer at its output, accounting for a 1:4 impedance transformation of its own.

to zero. Although multiple combinations of C and L values are possible for matching any given transmitter to its line and antenna at a particular frequency, McCoy recommends optimizing for a solution using maximum capacitance[8].

A photograph of an impedance-matching network for a 50 kW AM broadcast transmitter operating at 550 kHz is shown in the following photograph, with silver-coated inductor tubes to minimize resistance at high frequencies[9]. The entire network is housed inside of a small shielded room, visible through the open door:

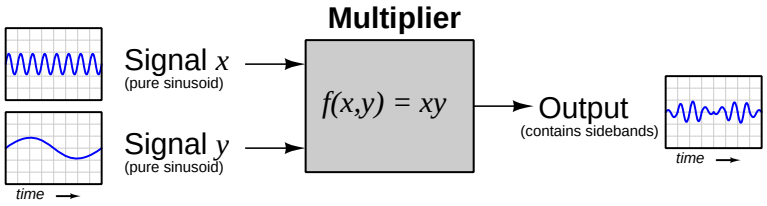
A caveat to this method of impedance transformation is that it only functions properly at (or near) one frequency value. Other impedance-transformation techniques such as *transformers* and *amplifiers* work over much broader frequency ranges.

[8] For example if a combination of high L and low C results in a good match, but another combination consisting of low L and high C also happens to result in a good match, the latter combination is preferable.

[9] At radio frequencies, the *skin effect* causes the majority of the current to travel on the outside surface of the conductor rather than the interior. Therefore, the electrical conductivity of the conductor's surface material matters more than its interior bulk. This is also why most RF conductors are hollow rather than solid metal: having a solid RF conductor would just be a waste of metal since nearly all of the current travels along the exterior surface.

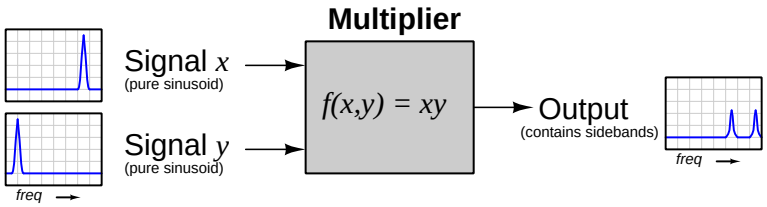
4.3 Mathematics of signal mixing

A common method for modulating signals is to multiply them together using a device constructed for that purpose. The amplitude of the lower-frequency signal serves to boost or attenuate the amplitude of the higher-frequency signal, so that the result is an *amplitude-modulated* signal where the signal's "envelope" follows the amplitude of the lower-frequency signal. A device constructed for the purpose of amplitude-modulating sinusoidal signals is commonly called a *mixer*[10].



A mixer's function as an amplitude modulator is easy enough to grasp when we view the signals from the perspective of the time domain, as shown by the blue-colored waveforms in the above illustration: in this example, signal y modulates the amplitude of signal x. What is far less intuitive to grasp is how these signals appear in the *frequency domain*, viewed as independent sine (or cosine) waves at different frequencies superimposed upon each other to comprise waveforms more complex than simple sinusoids.

When two sinusoidal signals are multiplied (i.e. "mixed" in the modulation sense of the word), the result is the production of additional frequencies called *sidebands*. The lower sideband signal's frequency is the difference between the two input signal frequencies, and the upper sideband signal's frequency is the sum of the two input signal frequencies. The mixer illustration will now be shown with signals represented in the frequency domain rather than in the time domain:



Proving just why sidebands are produced requires the application of some mathematics, specifically *trigonometry*.

[10] This terminology may be confusing for anyone accustomed to working with professional-grade audio equipment, where a "mixer" is a very different sort of electronic device, used to sum a set of audio-frequency signals to make a single (or multiple) channel of audio information.

We will begin our derivation by representing the mixer's two input signals as cosine functions, each with its own frequency (ω_x and ω_y). Since the value passed to a cosine function must be an angle and not a frequency, we will represent the two input signals as $\cos \omega_x t$ and $\cos \omega_y t$, respectively[11]. We may express the output signal as a time-based function, as follows:

$$f(x, y) = (\cos \omega_x t)(\cos \omega_y t)$$

Among the various mathematical identities in trigonometry is this one, relating the product of two cosine functions with cosines of the angular sum and difference:

$$\cos x \cos y = \frac{\cos(x - y) + \cos(x + y)}{2}$$

Substituting $\omega_x t$ for x and $\omega_y t$ for y yields the following result:

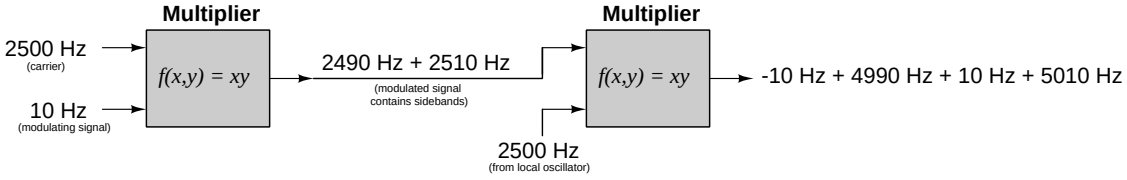
$$\cos(\omega_x t) \cos(\omega_y t) = \frac{\cos(\omega_x t - \omega_y t) + \cos(\omega_x t + \omega_y t)}{2}$$

Factoring out t in the angle terms on the right-hand side of this equation:

$$\cos(\omega_x t) \cos(\omega_y t) = \frac{\cos[(\omega_x - \omega_y)t] + \cos[(\omega_x + \omega_y)t]}{2}$$

This proves the multiplier's output signal consists of two sidebands. Given two sinusoidal input signals of differing frequency ($\cos(\omega_x t)$) and ($\cos(\omega_y t)$), the result is a *lower sideband* sinusoid having a frequency equal to the difference of the two input frequencies ($\cos[(\omega_x - \omega_y)t]$) and an *upper sideband* sinusoid having a frequency equal to the sum of the two input frequencies ($\cos[(\omega_x + \omega_y)t]$). The divisor of 2 merely means these sidebands will be weaker (i.e. less amplitude) than the input signals, and is irrelevant from the perspective of frequency.

For example, if signal x has a frequency of 2500 Hz and signal y has a frequency of 10 Hz, the two sidebands will have frequencies of 2490 Hz and 2510 Hz, respectively. This is what happens when a 2500 Hz *carrier* wave is amplitude-modulated by a 10 Hz *modulating* wave. If these modulated sideband signals happen to be fed into another multiplier along with a 2500 Hz *local oscillator* signal, the lower sideband wave of 2490 Hz will generate two sidebands of its own (−10 Hz and 4990 Hz) while the upper sideband wave will generate two sidebands of its own (10 Hz and 5010 Hz).



The two low-frequency signals (10 Hz and −10 Hz) carry the information embodied by the original modulating signal. In fact, these two signals are really identical to each other, since the

[11] ω represents frequency in angular units per second, typically radians per second. Time (t), of course, is typically measured in seconds. The product of radians per second and seconds is simply radians: an angle.

cosine function is an *even*[12] mathematical function and therefore $\cos(-10t) = \cos(10t)$. The two high-frequency signals (4990 Hz and 5010 Hz) are irrelevant to our purposes here and may be easily filtered out using a low-pass filter, if they aren't already severely attenuated by the bandwidth limitations of the circuitry.

Thus, we see how a multiplying function may be used to *amplitude-modulate* a signal onto a higher-frequency carrier, and how the same type of function may be used to *demodulate* that modulated signal to obtain the original signal's information. Another way of describing this is to say the first multiplier *upconverts* the 10 Hz signal into sidebands of much greater frequency, and then the second multiplier *downconverts* those sidebands to recover the original 10 Hz signal frequency.

The use of a multiplier to "downconvert" the frequency of a signal by mixing it with another signal of differing frequency is called *heterodyning*. This is the same phenomenon you hear with two audio tones of nearly-identical pitch played simultaneously[13]: the result as heard by your ears is a low-frequency "beat" pattern representing the difference in frequency between the two original tones. Heterodyning was first applied to radio technology as a means to impart an audible tone to an inaudible (radio-frequency) signal, in order to construct a radio receiver circuit capable of indicating the presence or absence of a carrier-wave signal broadcast by a transmitter using a keyswitch to switch on and off.

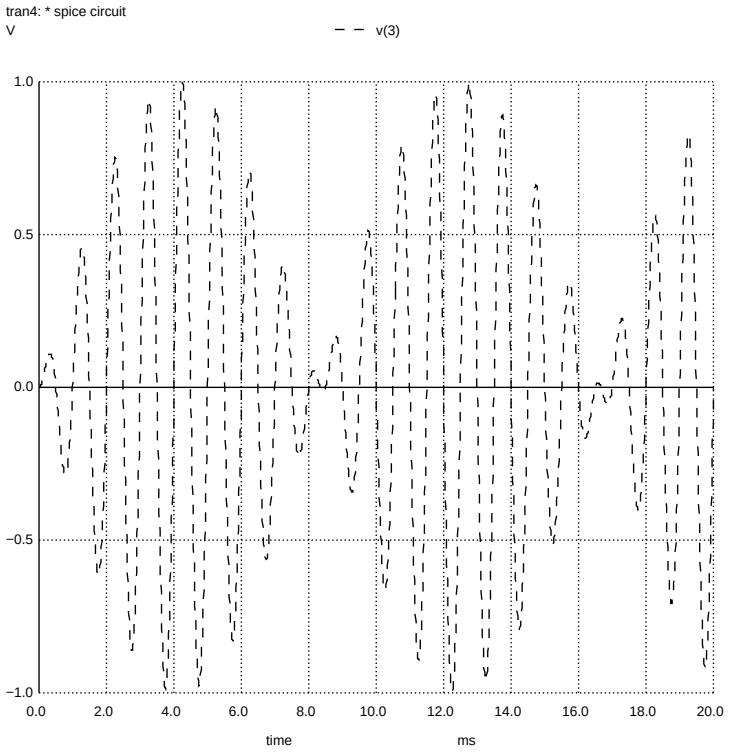
[12] Any mathematical function $f(x)$ is considered *odd* if $f(-x) = -f(x)$, as is the case with polynomial functions having only odd degree terms (e.g. $2x^7 + 8x^5 - x^3 + 9x$). Conversely, any mathematical function is considered *even* if $f(-x) = f(x)$, as with polynomial functions having only even (or zero) degree terms (e.g. $x^6 - 6x^4 + 3x^2 - 8$). The sine function is considered odd while the cosine function is even: for example, $\sin(-10) = -\sin(10)$ while $\cos(-10) = \cos(10)$.

[13] This is also the same phenomenon responsible for the perception of musical *harmony*: two or more tones played simultaneously that give rise to the impression of even more tones. This is why two or three tones of appropriate frequency played with each other sound so much richer than those same tones played one at a time: your auditory senses "mix" them together in such a way that you hear not only the original tones but also their respective sidebands. When mixed by a nonlinear system (in this case, your sense of hearing provides the nonlinearity necessary for true mixing to occur) the whole actually is greater than the sum of its parts.

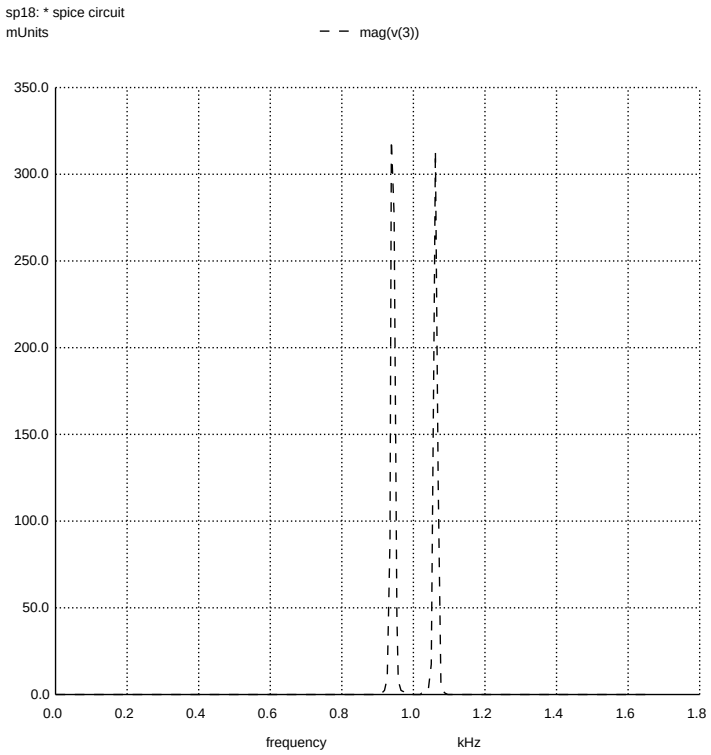
The following computer simulation (run in NGSPICE) shows a 60 Hz sinusoidal voltage (`v1`) and a 1 kHz sinusoidal voltage (`v2`) being mixed by a nonlinear dependent voltage source `b1` in the spice netlist. The three 5 kΩ resistors do nothing but satisfy SPICE's need for complete circuit loops:

```
* Mixer circuit
v1 1 0 sin (0 1 60 0 0)
v2 2 0 sin (0 1 1000 0 0)
b1 3 0 v=(v(1)*v(2))
r1 1 0 5000
r2 2 0 5000
r3 3 0 5000
.tran 0.01m 20m
.plot tran v(3)
.end
```

Plotted over a range of 0 to 20 milliseconds, the mixed signal (voltage between node 3 and ground) appears as a standard amplitude-modulated waveform:



A spectrum plot (generated using NGSPICE's `fft` command[14] shows the two sidebands at 940 Hz and 1060 Hz:



[14] In order to obtain a crisp plot of these two sidebands, the transient analysis parameters of the NGSPICE netlist had to be modified from the values giving a clean time-domain plot. Instead of analyzing over 0.01 millisecond intervals from 0 milliseconds to 20 milliseconds, the time values were shifted to 0.3 millisecond intervals from 0 milliseconds to 150 milliseconds. The interval shift from 0.01 ms to 0.3 ms shortened the frequency domain of the FFT plot, while the increased span from 20 ms to 150 ms made the peaks narrower and sharper. The modified "card" in the netlist file now reads `.tran 0.3m 150m`. The sequence of NGSPICE commands used to generate this FFT plot (after specifying the netlist filename and "running" the simulation with the `run` command) are as follows: `linearize v(3) ; fft v(3) ; plot mag(v(3))`.

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.

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

5.1 Conceptual reasoning

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Reductio ad absurdum

Re-drawing schematics as a problem-solving strategy

Cut-and-try problem-solving strategy

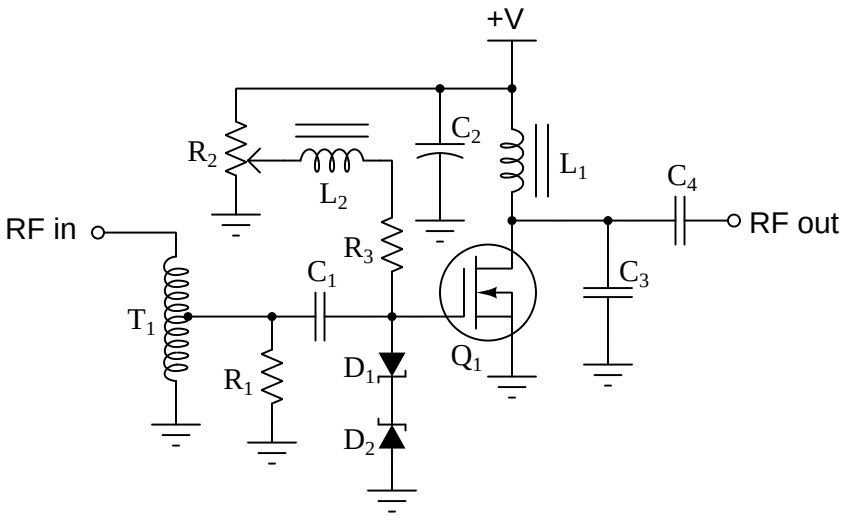
Algebraic substitution

???

5.1.3 Solid-state PA component functions

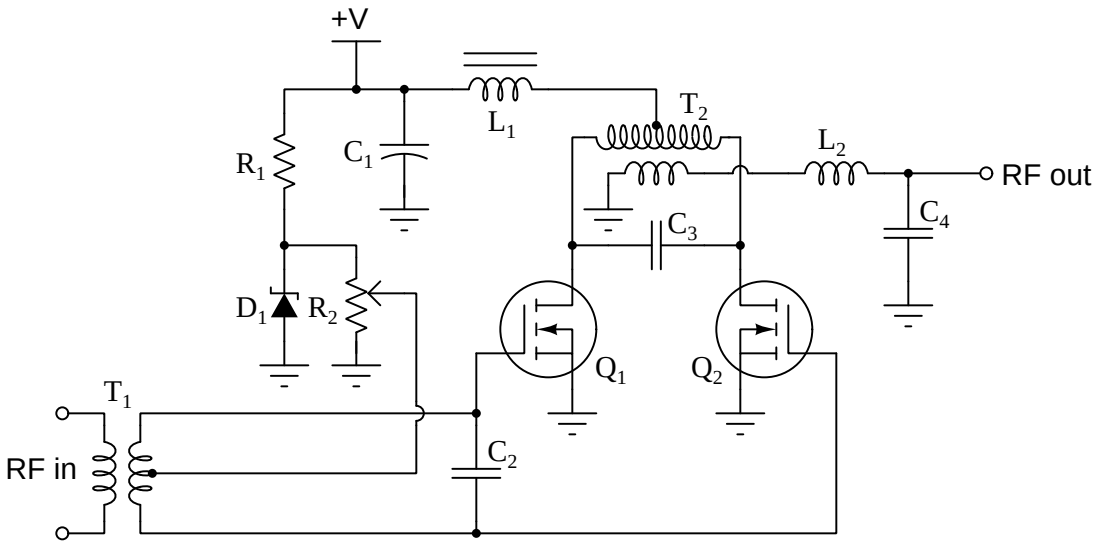
Identify the function(s) of specified components in the following RF power amplifier (PA) circuits.

Example #1



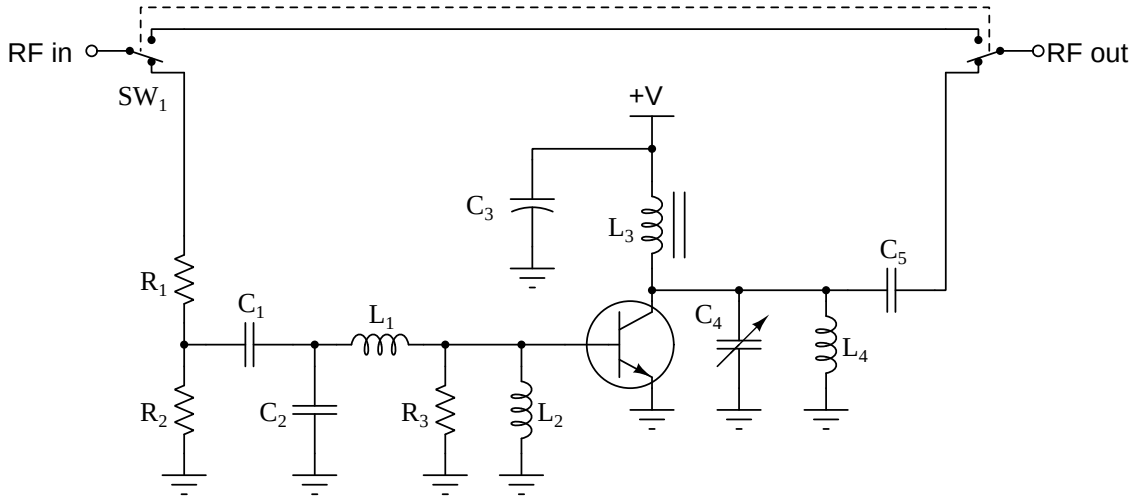
- T_1
- C_1
- C_2
- C_3
- C_4
- L_1
- L_2
- R_2
- R_3
- D_1 and D_2

Example #2



- T_1
- T_2
- C_1
- C_2
- C_3
- C_4
- L_1
- L_2
- R_2

Example #3



- C_1
- C_2
- C_3
- C_4
- C_5
- L_1
- L_2
- L_3
- L_4
- R_1
- R_2
- SW_1

Challenges

- Do either of these amplifiers employ neutralization?

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

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

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

5.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

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

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

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

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

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

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:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.2.3 Power amplifier efficiency

Suppose an RF power amplifier receives an input signal power of 2 dBm at 30 MHz and outputs a signal power of 35 dBm while drawing 5 Watts of power from the DC supply.

Calculate the energy efficiency of this amplifier.

Also, calculate this amplifier's signal power gain.

Challenges

- Which class of RF amplifier is likely to have the worst energy efficiency, class A, class B, or class C?

5.2.4 Tank circuit calculations

Calculate the resonant frequency values for a tank circuit with the following inductor and capacitor values:

- $L = 75$ μH ; $C = 30$ nF ; $f_r =$
- $L = 8$ nH ; $C = 15$ pF ; $f_r =$
- $L = 0.03$ mH ; $C = 0.01$ μF ; $f_r =$
- $L = 12$ μH ; $C = 0.022$ μF ; $f_r =$

Calculate the resonant wavelength values for a tank circuit with the following inductor and capacitor values:

- $L = 55$ μH ; $C = 7$ nF ; $\lambda_r =$
- $L = 4$ nH ; $C = 22$ pF ; $\lambda_r =$
- $L = 0.1$ nH ; $C = 0.47$ pF ; $\lambda_r =$
- $L = 33$ μH ; $C = 0.001$ μF ; $\lambda_r =$

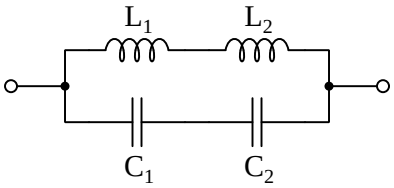
Challenges

- Identify how to increase the resonant frequency of a tank circuit.

5.2.5 Tank circuit calculator program

The following computer program (written in C) calculates the frequency of a tank circuit having two inductors and two capacitors connected as shown in the schematic diagram:

```
#include <stdio.h>
#include <math.h>

int main (void)
{
  float L[3];
  float C[3];

  printf("Enter inductance of L1 in Henrys: ");
  scanf("%f", &L[1]);

  printf("Enter inductance of L2 in Henrys: ");
  scanf("%f", &L[2]);

  printf("Enter capacitance of C1 in Farads: ");
  scanf("%f", &C[1]);

  printf("Enter capacitance of C2 in Farads: ");
  scanf("%f", &C[2]);

  printf("Resonant frequency = %f Hertz\n",
    1/(2 * M_PI * sqrt((L[1] + L[2]) * 1/(1/C[1] + 1/C[2]))));

  return 0;
}
```

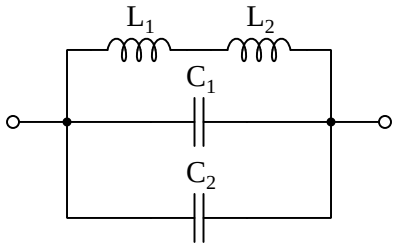


Note how this program uses *arrays*[11] of floating-point variables allowing the use of common variable names with subscripts: `L[1]` for inductance L_1 and `L[2]` for inductance L_2, etc.

[11] The declaration `float L[3]` creates three floating-point variables named `L[0]`, `L[1]`, and `L[2]`. Since it would be unconventional to label a component with a subscript of zero (L_0) we don't use that element of each array and instead just use the last two.

First, identify which electrical-circuit principles are applied in the source code, and specifically where.

Second, re-write this program so that it is suitable to calculate resonant frequency for a different arrangement of components:



Challenges

- Identify how to increase the resonant frequency of a tank circuit.

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.

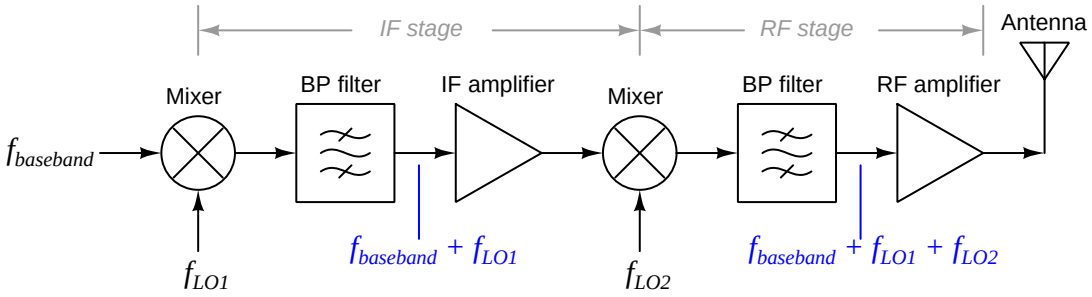
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

Identify the effects of the following faults in this block diagram of a radio transmitter:



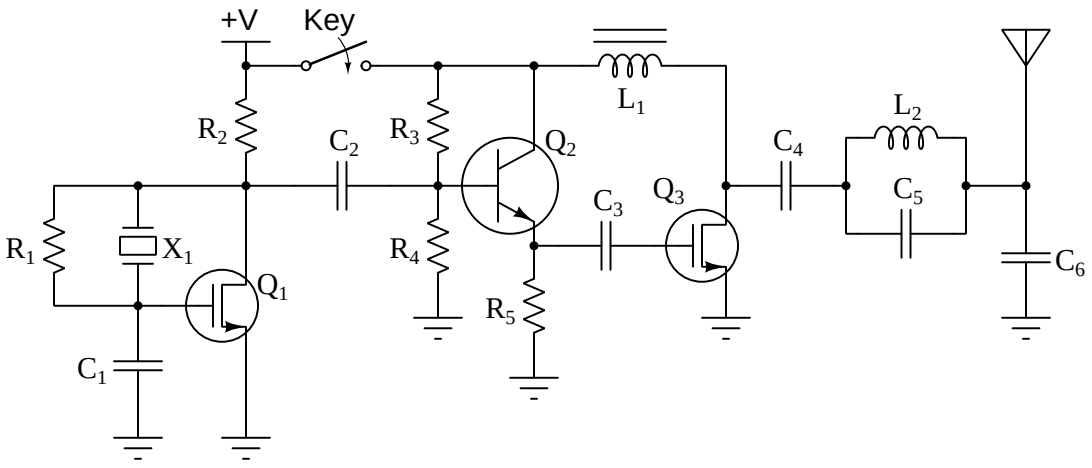
- f_{LO1} set much too low
- f_{LO2} set much too high
- Incorrect biasing in RF amplifier
- Pinched feedline between RF amplifier and antenna

Challenges

- What is the design purpose of the mixers in this radio transmitter?

5.3.2 Faults in a low-power CW transmitter

A "carrier-wave" or *CW* transmitter is one designed to transmit Morse-code (on/off) signals. These are typically much simpler than transmitters designed to handle audio (voice, music) information. An example of a simple CW transmitter appears here:



Identify the effects of the following faults in this transmitter:

- R_1 fails shorted
- R_2 fails open
- R_3 fails open
- R_4 fails open
- R_5 fails shorted
- X_1 fails open
- C_1 fails shorted
- C_2 fails open
- C_4 fails open
- L_1 fails open
- Partial short in L_2

Challenges

- What types of transistors are used in this transmitter circuit?

Chapter 6

Projects and Experiments

The following project and experiment descriptions outline things you can build to help you understand circuits. With any real-world project or experiment there exists the potential for physical harm. *Electricity can be very dangerous in certain circumstances, and you should follow proper safety precautions at all times!*

6.1 Recommended practices

This section outlines some recommended practices for all circuits you design and construct.

6.1.1 Safety first!

Electricity, when passed through the human body, causes uncomfortable sensations and in large enough measures[1] will cause muscles to involuntarily contract. The overriding of your nervous system by the passage of electrical current through your body is particularly dangerous in regard to your heart, which is a vital muscle. Very large amounts of current can produce serious internal burns in addition to all the other effects.

Cardio-pulmonary resuscitation (CPR) is the standard first-aid for any victim of electrical shock. This is a very good skill to acquire if you intend to work with others on dangerous electrical circuits. You should never perform tests or work on such circuits unless someone else is present who is proficient in CPR.

As a general rule, any voltage in excess of 30 Volts poses a definitive electric shock hazard, because beyond this level human skin does not have enough resistance to safely limit current through the body. "Live" work of any kind with circuits over 30 volts should be avoided, and if unavoidable should only be done using electrically insulated tools and other protective equipment (e.g. insulating shoes and gloves). If you are unsure of the hazards, or feel unsafe at any time, stop all work and distance yourself from the circuit!

A policy I strongly recommend for students learning about electricity is to *never come into electrical contact*[2] *with an energized conductor, no matter what the circuit's voltage*[3] *level!* Enforcing this policy may seem ridiculous when the circuit in question is powered by a single battery smaller than the palm of your hand, but it is precisely this instilled habit which will save a person from bodily harm when working with more dangerous circuits. Experience has taught me that students who learn early on to be careless with safe circuits have a tendency to be careless later with dangerous circuits!

In addition to the electrical hazards of shock and burns, the construction of projects and running of experiments often poses other hazards such as working with hand and power tools, potential

[1] Professor Charles Dalziel published a research paper in 1961 called "The Deleterious Effects of Electric Shock" detailing the results of electric shock experiments with both human and animal subjects. The threshold of perception for human subjects holding a conductor in their hand was in the range of 1 milliampere of current (less than this for alternating current, and generally less for female subjects than for male). Loss of muscular control was exhibited by half of Dalziel's subjects at less than 10 milliamperes alternating current. Extreme pain, difficulty breathing, and loss of all muscular control occurred for over 99% of his subjects at direct currents less than 100 milliamperes and alternating currents less than 30 milliamperes. In summary, it doesn't require much electric current to induce painful and even life-threatening effects in the human body! Your first and best protection against electric shock is maintaining an insulating barrier between your body and the circuit in question, such that current from that circuit will be unable to flow through your body.

[2] By "electrical contact" I mean either directly touching an energized conductor with any part of your body, or indirectly touching it through a conductive tool. The only physical contact you should ever make with an energized conductor is via an electrically insulated tool, for example a screwdriver with an electrically insulated handle, or an insulated test probe for some instrument.

[3] Another reason for consistently enforcing this policy, even on low-voltage circuits, is due to the dangers that even some low-voltage circuits harbor. A single 12 Volt automobile battery, for example, can cause a surprising amount of damage if short-circuited simply due to the high current levels (i.e. very low internal resistance) it is capable of, even though the voltage level is too low to cause a shock through the skin. Mechanics wearing metal rings, for example, are at risk from severe burns if their rings happen to short-circuit such a battery! Furthermore, even when working on circuits that are simply too low-power (low voltage and low current) to cause any bodily harm, touching them while energized can pose a threat to the circuit components themselves. In summary, it's generally wise (and *always* a good habit to build) to "power down" *any* circuit before making contact between it and your body.

contact with high temperatures, potential chemical exposure, etc. You should never proceed with a project or experiment if you are unaware of proper tool use or lack basic protective measures (e.g. personal protective equipment such as safety glasses) against such hazards.

Some other safety-related practices should be followed as well:

- All power conductors extending outward from the project must be *firmly* strain-relieved (e.g. "cord grips" used on line power cords), so that an accidental tug or drop will not compromise circuit integrity.
- All electrical connections must be sound and appropriately made (e.g. soldered wire joints rather than twisted-and-taped; terminal blocks rather than solderless breadboards for high-current or high-voltage circuits). Use "touch-safe" terminal connections with recessed metal parts to minimize risk of accidental contact.
- Always provide overcurrent protection in any circuit you build. *Always.* This may be in the form of a fuse, a circuit breaker, and/or an electronically current-limited power supply.
- Always ensure circuit conductors are rated for more current than the overcurrent protection limit. *Always.* A fuse does no good if the wire or printed circuit board trace will "blow" before it does!
- Always bond metal enclosures to Earth ground for any line-powered circuit. *Always.* Ensuring an equipotential state between the enclosure and Earth by making the enclosure electrically common with Earth ground ensures no electric shock can occur simply by one's body bridging between the Earth and the enclosure.
- Avoid building a high-energy circuit when a low-energy circuit will suffice. For example, I always recommend beginning students power their first DC resistor circuits using small batteries rather than with line-powered DC power supplies. The intrinsic energy limitations of a dry-cell battery make accidents highly unlikely.
- Use line power receptacles that are GFCI (Ground Fault Current Interrupting) to help avoid electric shock from making accidental contact with a "hot" line conductor.
- Always wear eye protection when working with tools or live systems having the potential to eject material into the air. Examples of such activities include soldering, drilling, grinding, cutting, wire stripping, working on or near energized circuits, etc.
- Always use a step-stool or stepladder to reach high places. Never stand on something not designed to support a human load.
- When in doubt, *ask an expert.* If anything even seems remotely unsafe to you, do not proceed without consulting a trusted person fully knowledgeable in electrical safety.

6.1.2 Other helpful tips

Experience has shown the following practices to be very helpful, especially when students make their own component selections, to ensure the circuits will be well-behaved:

- Avoid resistor values less than 1 kΩ or greater than 100 kΩ, unless such values are definitely necessary[4]. Resistances below 1 kΩ may draw excessive current if directly connected to a voltage source of significant magnitude, and may also complicate the task of accurately measuring current since any ammeter's non-zero resistance inserted in series with a low-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Resistances above 100 kΩ may complicate the task of measuring voltage since any voltmeter's finite resistance connected in parallel with a high-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Similarly, AC circuit impedance values should be between 1 kΩ and 100 kΩ, and for all the same reasons.

- Ensure all electrical connections are low-resistance and physically rugged. For this reason, one should avoid *compression splices* (e.g. "butt" connectors), solderless breadboards[5], and wires that are simply twisted together.

- Build your circuit with **testing** in mind. For example, provide convenient connection points for test equipment (e.g. multimeters, oscilloscopes, signal generators, logic probes).

- Design permanent projects with **maintenance** in mind. The more convenient you make maintenance tasks, the more likely they will get done.

- **Always document and save your work**. Circuits lacking schematic diagrams are more difficult to troubleshoot than documented circuits. Similarly, circuit construction is simpler when a schematic diagram precedes construction. Experimental results are easier to interpret when comprehensively recorded. Consider modern videorecording technology for this purpose where appropriate.

- **Record your steps** when troubleshooting. **Talk to yourself** when solving problems. These simple steps clarify thought and simplify identification of errors.

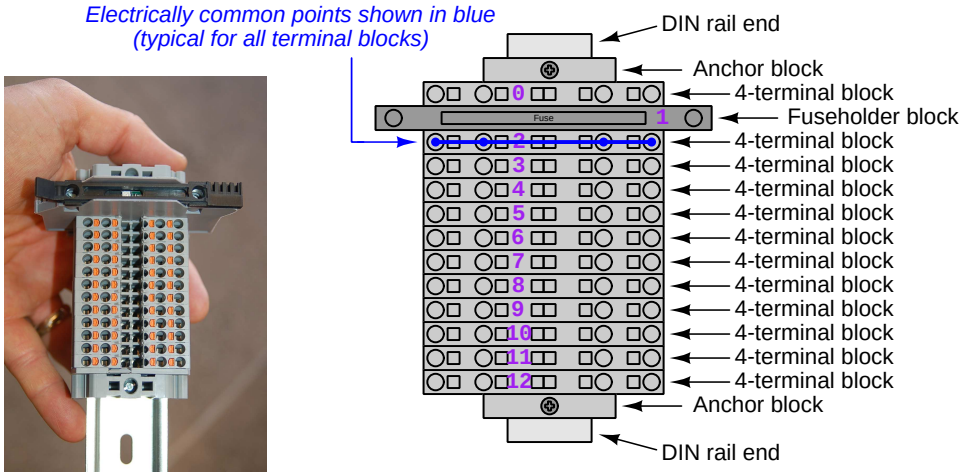
[4] An example of a necessary resistor value much less than 1 kΩ is a *shunt resistor* used to produce a small voltage drop for the purpose of sensing current in a circuit. Such shunt resistors must be low-value in order not to impose an undue load on the rest of the circuit. An example of a necessary resistor value much greater than 100 kΩ is an electrostatic *drain resistor* used to dissipate stored electric charges from body capacitance for the sake of preventing damage to sensitive semiconductor components, while also preventing a path for current that could be dangerous to the person (i.e. shock).

[5] Admittedly, solderless breadboards are very useful for constructing complex electronic circuits with many components, especially DIP-style integrated circuits (ICs), but they tend to give trouble with connection integrity after frequent use. An alternative for projects using low counts of ICs is to solder IC sockets into prototype printed circuit boards (PCBs) and run wires from the soldered pins of the IC sockets to terminal blocks where reliable temporary connections may be made.

6.1.3 Terminal blocks for circuit construction

Terminal blocks are the standard means for making electric circuit connections in industrial systems, and are also quite useful for student-built experiments, providing a robust alternative to solderless breadboards[6]. Terminal blocks provide highly reliable connections rated for significant voltage and current magnitudes, and they force the builder to think carefully about component placement which is an important mental practice. Terminal blocks designed to mount on standard 35 mm DIN rail[7] come in many types and capabilities.

Every student of electricity should build their own terminal block array consisting of several terminal blocks where each block has at least 4 connection points all electrically common to each other[8] and at least one terminal block that is a fuse holder for overcurrent protection. A pair of anchoring blocks hold all terminal blocks securely on the DIN rail, preventing them from sliding off the rail. Each of the terminals should bear a unique number starting from 0. An example is shown in the following photograph and illustration:



Screwless terminal blocks (using internal spring clips to clamp wire and component lead ends) are preferred over screw-based terminal blocks, as they reduce assembly and disassembly time, and also minimize repetitive wrist stress from twisting screwdrivers. Some screwless terminal blocks require the use of a special tool to release the spring clip, while others such as the Phoenix Contact model 3211019 blocks shown in the photograph provide buttons[9] for this task which may be pressed using the tip of any suitable tool such as a small screwdriver or multimeter test probe tip.

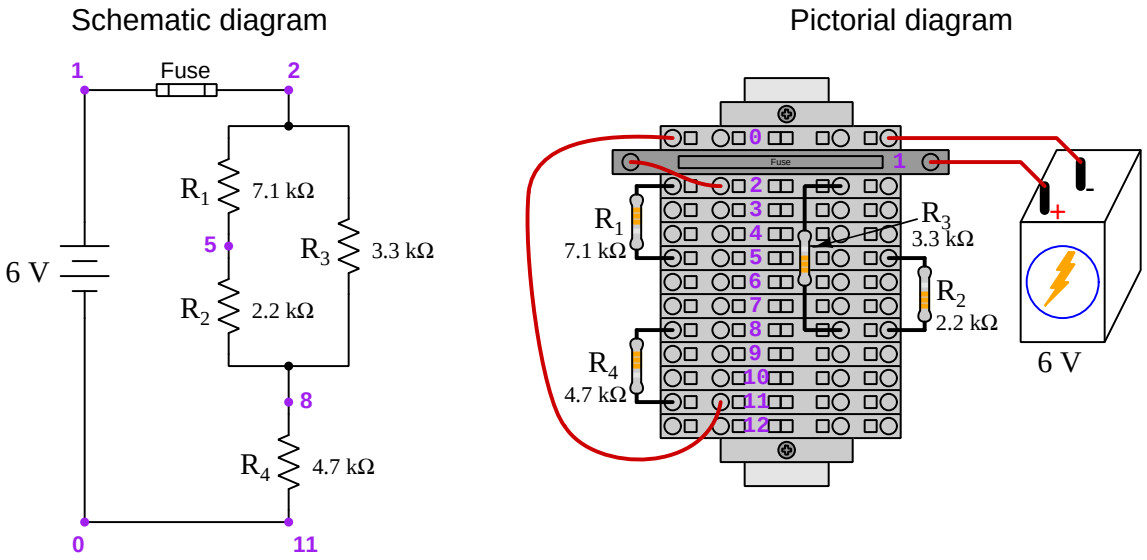
[6] Solderless breadboard are preferable for complicated electronic circuits with multiple integrated "chip" components, but for simpler circuits I find terminal blocks much more practical. An alternative to solderless breadboards for "chip" circuits is to solder chip sockets onto a PCB and then use wires to connect the socket pins to terminal blocks. This also accommodates *surface-mount* components, which solderless breadboards do not.

[7] DIN rail is a metal rail designed to serve as a mounting point for a wide range of electrical and electronic devices such as terminal blocks, fuses, circuit breakers, relay sockets, power supplies, data acquisition hardware, etc.

[8] Sometimes referred to as *equipotential*, *same-potential*, or *potential distribution* terminal blocks.

[9] The small orange-colored squares seen in the above photograph are buttons for this purpose, and may be actuated by pressing with any tool of suitable size.

The following example shows how such a terminal block array might be used to construct a series-parallel resistor circuit consisting of four resistors and a battery:



Numbering on the terminal blocks provides a very natural translation to SPICE[10] netlists, where component connections are identified by terminal number:

```
* Series-parallel resistor circuit
v1 1 0 dc 6
r1 2 5 7100
r2 5 8 2200
r3 2 8 3300
r4 8 11 4700
rfuse 1 2 0.01
rwire 0 11 0.01
.op
.end
```

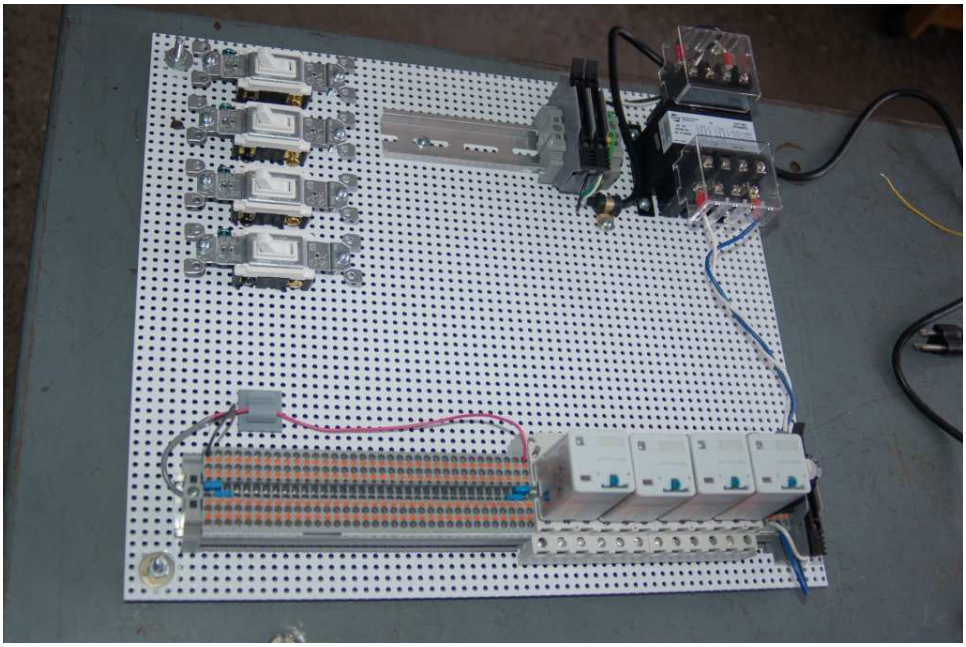
Note the use of two resistances `rfuse` and `rwire` to describe fuse resistance between terminals 1 and 2 and "jumper" wire resistance between terminals 0 and 11, respectively. Being resistances, SPICE requires a resistance value for each, and here we see they have both been set to an arbitrarily low value of 0.01 Ohm appropriate to their real-life resistance values.

Listing all components and wires along with their numbered terminals happens to be a useful documentation method for any circuit built on terminal blocks, independent of SPICE. Such a

[10] SPICE is computer software designed to analyze electrical and electronic circuits. Circuits are described for the computer in the form of *netlists* which are text files listing each component type, connection node numbers, and component values.

"wiring sequence" may be thought of as a *non-graphical description* of an electric circuit, and is exceptionally easy to follow.

An example of a more elaborate terminal block array is shown in the following photograph, with terminal blocks and "ice-cube" style electromechanical relays mounted to DIN rail, which is turn mounted to a perforated subpanel[11]. This "terminal block board" hosts an array of thirty five undedicated terminal block sections, four SPDT toggle switches, four DPDT "ice-cube" relays, a step-down control power transformer, bridge rectifier and filtering capacitor, and several fuses for overcurrent protection:



Four plastic-bottomed "feet" support the subpanel above the benchtop surface, and an unused section of DIN rail stands ready to accept other components. Safety features include electrical bonding of the AC line power cord's ground to the metal subpanel (and all metal DIN rails), mechanical strain relief for the power cord to isolate any cord tension from wire connections, clear plastic finger guards covering the transformer's screw terminals, as well as fused overcurrent protection for the 120 Volt AC line power and the transformer's 12 Volt AC output. The perforated holes happen to be on $\frac{1}{4}$ inch centers with a diameter suitable for tapping with 6-32 machine screw threads, their presence making it very easy to attach other sections of DIN rail, printed circuit boards, or specialized electrical components directly to the grounded metal subpanel. Such a "terminal block board" is an inexpensive[12] yet highly flexible means to construct physically robust circuits using industrial wiring practices.

[11] An electrical *subpanel* is a thin metal plate intended for mounting inside an electrical enclosure. Components are attached to the subpanel, and the subpanel in turn bolts inside the enclosure. Subpanels allow circuit construction outside the confines of the enclosure, which speeds assembly. In this particular usage there is no enclosure, as the subpanel is intended to be used as an open platform for the convenient construction of circuits on a benchtop by students. In essence, this is a modern version of the traditional *breadboard* which was literally a wooden board such as might be used for cutting loaves of bread, but which early electrical and electronic hobbyists used as platforms for the construction of circuits.

[12] At the time of this writing (2019) the cost to build this board is approximately $250 US dollars.

6.1.4 Conducting experiments

An *experiment* is an exploratory act, a test performed for the purpose of assessing some proposition or principle. Experiments are the foundation of the *scientific method*, a process by which careful observation helps guard against errors of speculation. All good experiments begin with an *hypothesis*, defined by the American Heritage Dictionary of the English Language as:

> An assertion subject to verification or proof, as (a) A proposition stated as a basis for argument or reasoning. (b) A premise from which a conclusion is drawn. (c) A conjecture that accounts, within a theory or ideational framework, for a set of facts and that can be used as a basis for further investigation.

Stated plainly, an hypothesis is an *educated guess* about cause and effect. The correctness of this initial guess matters little, because any well-designed experiment will reveal the truth of the matter. In fact, *incorrect* hypotheses are often the most valuable because the experiments they engender lead us to surprising discoveries. One of the beautiful aspects of science is that it is more focused on the process of *learning* than about the status of *being correct*[13]. In order for an hypothesis to be valid, it must be testable[14], which means it must be a claim possible to refute given the right data. Hypotheses impossible to critique are useless.

Once an hypothesis has been formulated, an experiment must be designed to test that hypothesis. A well-designed experiment requires careful regulation of all relevant variables, both for personal safety and for prompting the hypothesized results. If the effects of one particular variable are to be tested, the experiment must be run multiple times with different values of (only) that particular variable. The experiment set up with the "baseline" variable set is called the *control*, while the experiment set up with different value(s) is called the *test* or *experimental*.

For some hypotheses a viable alternative to a physical experiment is a *computer-simulated experiment* or even a *thought experiment*. Simulations performed on a computer test the hypothesis against the physical laws encoded within the computer simulation software, and are particularly useful for students learning new principles for which simulation software is readily available[15].

[13] Science is more about clarifying our view of the universe through a systematic process of error detection than it is about proving oneself to be right. Some scient*ists* may happen to have large egos – and this may have more to do with the ways in which large-scale scientific research is *funded* than anything else – but scientific *method* itself is devoid of ego, and if embraced as a practical philosophy is quite an effective stimulant for humility. Within the education system, scientific method is particularly valuable for helping students break free of the crippling fear of *being wrong*. So much emphasis is placed in formal education on assessing correct retention of facts that many students are fearful of saying or doing anything that might be perceived as a mistake, and of course making mistakes (i.e. having one's hypotheses disproven by experiment) is an indispensable tool for learning. Introducing science in the classroom – *real* science characterized by individuals forming actual hypotheses and testing those hypotheses by experiment – helps students become self-directed learners.

[14] This is the principle of *falsifiability*: that a scientific statement has value only insofar as it is liable to disproof given the requisite experimental evidence. Any claim that is unfalsifiable – that is, a claim which can *never* be disproven by any evidence whatsoever – could be completely wrong and we could never know it.

[15] A very pertinent example of this is learning how to analyze electric circuits using simulation software such as SPICE. A typical experimental cycle would proceed as follows: (1) Find or invent a circuit to analyze; (2) Apply your analytical knowledge to that circuit, predicting all voltages, currents, powers, etc. relevant to the concepts you are striving to master; (3) Run a simulation on that circuit, collecting "data" from the computer when complete; (4) Evaluate whether or not your hypotheses (i.e. predicted voltages, currents, etc.) agree with the computer-generated results; (5) If so, your analyses are (provisionally) correct – if not, examine your analyses and the computer simulation again to determine the source of error; (6) Repeat this process as many times as necessary until you achieve mastery.

Thought experiments are useful for detecting inconsistencies within your own understanding of some subject, rather than testing your understanding against physical reality.

Here are some general guidelines for conducting experiments:

- The clearer and more specific the hypothesis, the better. Vague or unfalsifiable hypotheses are useless because they will fit *any* experimental results, and therefore the experiment cannot teach you anything about the hypothesis.
- Collect as much data (i.e. information, measurements, sensory experiences) generated by an experiment as is practical. This includes the time and date of the experiment, too!
- *Never* discard or modify data gathered from an experiment. If you have reason to believe the data is unreliable, write notes to that effect, but never throw away data just because you think it is untrustworthy. It is quite possible that even "bad" data holds useful information, and that someone else may be able to uncover its value even if you do not.
- Prioritize *quantitative* data over *qualitative* data wherever practical. Quantitative data is more specific than qualitative, less prone to subjective interpretation on the part of the experimenter, and amenable to an arsenal of analytical methods (e.g. statistics).
- Guard against your own bias(es) by making your experimental results available to others. This allows other people to scrutinize your experimental design and collected data, for the purpose of detecting and correcting errors you may have missed. Document your experiment such that others may independently replicate it.
- Always be looking for sources of error. No physical measurement is perfect, and so it is impossible to achieve *exact* values for any variable. Quantify the amount of uncertainty (i.e. the "tolerance" of errors) whenever possible, and be sure your hypothesis does not depend on precision better than this!
- Always remember that scientific confirmation is provisional – no number of "successful" experiments will prove an hypothesis true for all time, but a single experiment can disprove it. Put into simpler terms, *truth is elusive but error is within reach.*
- Remember that scientific method is about *learning*, first and foremost. An unfortunate consequence of scientific triumph in modern society is that science is often viewed by non-practitioners as an unerring source of truth, when in fact science is an ongoing process of challenging existing ideas to probe for errors and oversights. This is why it is perfectly acceptable to have a failed hypothesis, and why the only truly failed experiment is one where nothing was learned.

The following is an example of a well-planned and executed experiment, in this case a physical experiment demonstrating Ohm's Law.

```
Planning Time/Date = 09:30 on 12 February 2019

HYPOTHESIS: the current through any resistor should be exactly proportional
to the voltage impressed across it.

PROCEDURE: connect a resistor rated 1 k Ohm and 1/4 Watt to a variable-voltage
DC power supply.  Use an ammeter in series to measure resistor current and
a voltmeter in parallel to measure resistor voltage.

RISKS AND MITIGATION: excessive power dissipation may harm the resistor and/
or pose a burn hazard, while excessive voltage poses an electric shock hazard.
30 Volts is a safe maximum voltage for laboratory practices, and according to
Joule's Law a 1000 Ohm resistor will dissipate 0.25 Watts at 15.81 Volts
(P = V^2 / R), so I will remain below 15 Volts just to be safe.

Experiment Time/Date = 10:15 on 12 February 2019

DATA COLLECTED:
  (Voltage)    (Current)         (Voltage)   (Current)
   0.000 V   =  0.000 mA          8.100    =  7.812 mA
   2.700 V   =  2.603 mA          10.00 V  =  9.643 mA
   5.400 V   =  5.206 mA          14.00 V  =  13.49 mA

Analysis Time/Date = 10:57 on 12 February 2019

ANALYSIS: current definitely increases with voltage, and although I expected
exactly one milliAmpere per Volt the actual current was usually less than
that.  The voltage/current ratios ranged from a low of 1036.87 (at 8.1 Volts)
to a high of 1037.81 (at 14 Volts), but this represents a variance of only
-0.0365% to +0.0541% from the average, indicating a very consistent
proportionality -- results consistent with Ohm's Law.

ERROR SOURCES: one major source of error is the resistor's value itself.  I
did not measure it, but simply assumed color bands of brown-black-red meant
exactly 1000 Ohms.  Based on the data I think the true resistance is closer
to 1037 Ohms.  Another possible explanation is multimeter calibration error.
However, neither explains the small positive and negative variances from the
average.  This might be due to electrical noise, a good test being to repeat
the same experiment to see if the variances are the same or different.  Noise
should generate slightly different results every time.
```

The following is an example of a well-planned and executed *virtual* experiment, in this case demonstrating Ohm's Law using a computer (SPICE) simulation.

```
Planning Time/Date = 12:32 on 14 February 2019

HYPOTHESIS: for any given resistor, the current through that resistor should be
exactly proportional to the voltage impressed across it.

PROCEDURE: write a SPICE netlist with a single DC voltage source and single
1000 Ohm resistor, then use NGSPICE version 26 to perform a "sweep" analysis
from 0 Volts to 25 Volts in 5 Volt increments.

    * SPICE circuit
    v1 1 0 dc
    r1 1 0 1000
    .dc v1 0 25 5
    .print dc v(1) i(v1)
    .end

RISKS AND MITIGATION: none.

DATA COLLECTED:
       DC transfer characteristic  Thu Feb 14 13:05:08  2019
    ------------------------------------------------------------
    Index   v-sweep         v(1)            v1#branch
    ------------------------------------------------------------
    0       0.000000e+00    0.000000e+00    0.000000e+00
    1       5.000000e+00    5.000000e+00    -5.00000e-03
    2       1.000000e+01    1.000000e+01    -1.00000e-02
    3       1.500000e+01    1.500000e+01    -1.50000e-02
    4       2.000000e+01    2.000000e+01    -2.00000e-02
    5       2.500000e+01    2.500000e+01    -2.50000e-02

Analysis Time/Date = 13:06 on 14 February 2019

ANALYSIS: perfect agreement between data and hypothesis -- current is precisely
1/1000 of the applied voltage for all values.  Anything other than perfect
agreement would have probably meant my netlist was incorrect.  The negative
current values surprised me, but it seems this is just how SPICE interprets
normal current through a DC voltage source.

ERROR SOURCES: none.
```

As gratuitous as it may seem to perform experiments on a physical law as well-established as Ohm's Law, even the examples listed previously demonstrate opportunity for real learning. In the physical experiment example, the student should identify and explain why their data does not perfectly agree with the hypothesis, and this leads them naturally to consider sources of error. In the computer-simulated experiment, the student is struck by SPICE's convention of denoting regular current through a DC voltage source as being *negative* in sign, and this is also useful knowledge for future simulations. Scientific experiments are most interesting when things *do not* go as planned!

Aside from verifying well-established physical laws, simple experiments are extremely useful as educational tools for a wide range of purposes, including:

- Component familiarization (e.g. *Which terminals of this switch connect to the NO versus NC contacts?*)
- System testing (e.g. *How heavy of a load can my AC-DC power supply source before the semiconductor components reach their thermal limits?*)
- Learning programming languages (e.g. *Let's try to set up an "up" counter function in this PLC!*)

Above all, the priority here is to inculcate the habit of hypothesizing, running experiments, and analyzing the results. This experimental cycle not only serves as an excellent method for self-directed learning, but it also works exceptionally well for troubleshooting faults in complex systems, and for these reasons should be a part of every technician's and every engineer's education.

6.1.5 Constructing projects

Designing, constructing, and testing projects is a very effective means of practical education. Within a formal educational setting, projects are generally chosen (or at least vetted) by an instructor to ensure they may be reasonably completed within the allotted time of a course or program of study, and that they sufficiently challenge the student to learn certain important principles. In a self-directed environment, projects are just as useful as a learning tool but there is some risk of unwittingly choosing a project beyond one's abilities, which can lead to frustration.

Here are some general guidelines for managing projects:

- Define your goal(s) before beginning a project: what do you wish to achieve in building it? What, exactly, should the completed project *do*?
- Analyze your project prior to construction. Document it in appropriate forms (e.g. schematic diagrams), predict its functionality, anticipate all associated risks. In other words, *plan ahead*.
- Set a reasonable budget for your project, and stay within it.
- Identify any deadlines, and set reasonable goals to meet those deadlines.
- Beware of *scope creep*: the tendency to modify the project's goals before it is complete.
- Document your progress! An easy way to do this is to use photography or videography: take photos and/or videos of your project as it progresses. Document failures as well as successes, because both are equally valuable from the perspective of learning.

6.2 Experiment: (first experiment)

Conduct an experiment to . . .

EXPERIMENT CHECKLIST:

- Prior to experimentation:
  - ☑ Write an hypothesis (i.e. a detailed description of what you expect will happen) unambiguous enough that it could be disproven given the right data.
  - ☑ Write a procedure to test the hypothesis, complete with adequate controls and documentation (e.g. schematic diagrams, programming code).
  - ☑ Identify any risks (e.g. shock hazard, component damage) and write a mitigation plan based on best practices and component ratings.
- During experimentation:
  - ☑ Safe practices followed at all times (e.g. no contact with energized circuit).
  - ☑ Correct equipment usage according to manufacturer's recommendations.
  - ☑ All data collected, ideally quantitative with full precision (i.e. no rounding).
- After each experimental run:
  - ☑ If the results fail to match the hypothesis, identify the error(s), correct the hypothesis and/or revise the procedure, and re-run the experiment.
  - ☑ Identify any uncontrolled sources of error in the experiment.
- After all experimental re-runs:
  - ☑ Save all data for future reference.
  - ☑ Write an analysis of experimental results and lessons learned.

Challenges

- Science is an *iterative* process, and for this reason is never complete. Following the results of your experiment, what would you propose for your *next* hypothesis and *next* experimental procedure? Hint: if your experiment produced any unexpected results, exploring those unexpected results is often a very good basis for the next experiment!
- ???.
- ???.

6.3 Project: (first project)

This is a description of the project!

PROJECT CHECKLIST:

- Prior to construction:
  - ☑ Prototype diagram(s) and description of project scope.
  - ☑ Risk assessment/mitigation plan.
  - ☑ Timeline and action plan.
- During construction:
  - ☑ Safe work habits (e.g. no contact made with energized circuit at any time).
  - ☑ Correct equipment usage according to manufacturer's recommendations.
  - ☑ Timeline and action plan amended as necessary.
  - ☑ Maintain the originally-planned project scope (i.e. avoid adding features!).
- After completion:
  - ☑ All functions tested against original plan.
  - ☑ Full, accurate, and appropriate documentation of all project details.
  - ☑ Complete bill of materials.
  - ☑ Written summary of lessons learned.

Challenges

- ???.
- ???.
- ???.

Appendix A

Problem-Solving Strategies

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

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

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

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

Appendix B

Instructional philosophy

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

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

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

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

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

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

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

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

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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.

15 October 2025 – added more instructor notes.

21 October 2024 – added capacitor C_6 to image_4708 and image_4709 so as to not mess up the DC biasing of the transistor as would happen with inductor L_2 shorting DC to ground.

30 September 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors. Also added a new Derivations section on the mathematics of signal mixing.

14 March 2024 – corrected a schematic diagram error where decoupling capacitor C_5 was misconnected in image_4708 and image_4709 for the high-frequency common-emitter amplifier circuit. I had it connected to the RF side of the choke, when it should have been on the DC side. Also added comments to the Tutorial about balanced versus unbalanced signals.

23 October 2023 – minor edits to the Tutorial text.

13 June 2023 – added a Quantitative Reasoning question challenging students to analyze a tank circuit simulation program utilizing arrays to store multiple L and C component values.

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

9 December 2021 – edited instructor notes on the "Faults in a low-power CW transmitter" Diagnostic Reasoning question.

2 November 2021 – added a Case Tutorial chapter with sections showing photographs of RF power amplifiers and low-noise amplifier PCBs.

26 October 2021 – added text and a photograph regarding the use of dummy loads to simulate an antenna when testing a power amplifier.

10 May 2021 – commented out or deleted empty chapters.

27 April 2021 – minor edits to instructor notes on a couple of questions.

9 December 2020 – minor edits to the Tutorial, and a typo correction in the "Tank circuit calculations" question.

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

25-28 November 2020 – added content throughout the module.

22 November 2020 – document first created.

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