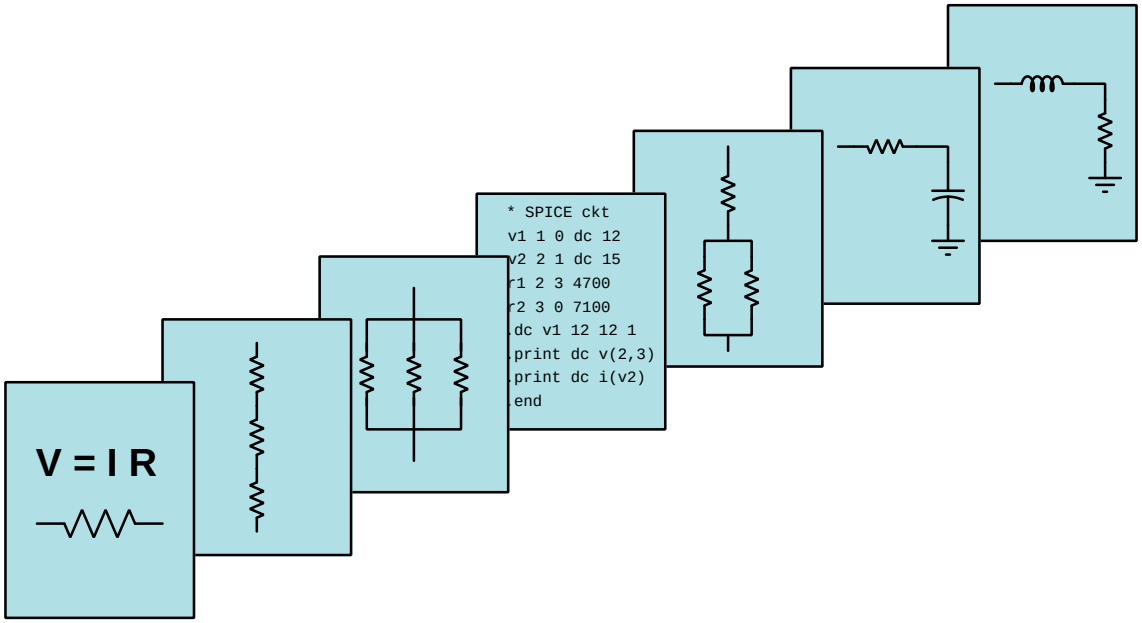
Modular Electronics Learning (ModEL) project



Amplifier Performance

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Chapter 1

Introduction

1.1 Recommendations for students

Amplifiers, like all electronic circuits, have limitations. This learning module focuses on common amplifier performance parameters, how to measure them, and various causes of performance limitations.

Important concepts related to amplifier performance include **gain**, **dimensional analysis**, **decibels**, **Joule's Law**, signal **distortion**, operational **classes**, **BJT behavior**, **tank circuits**, **rejection ratios**, **Maximum Power Transfer Theorem**, **transmission lines**, **bandwidth**, **filtering**, **negative feedback**, **biasing**, **gain-bandwidth product**, **linearity**, **FET behavior**, and signal **decomposition** (i.e. **equivalent waves**).

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 might an experiment be designed and conducted to measure the effective bandwidth 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?
- What does any "decibel" value mean for a signal or for a circuit?
- Why must we multiply by 20 instead of 10 when computing voltage and current decibel figures from gain ratios?
- What factors may lead to an amplifier clipping?
- What distinguishes the different "classes" of amplifier operation from one another?
- How does a differential amplifier differ from a single-ended amplifier?
- Why is impedance-matching important in some electronic circuit applications?

- What factors limit the bandwidth of any amplifier circuit?
- What is a *harmonic* frequency, and how does it relate to the *fundamental* frequency?
- What does it mean to say that a waveform is "equivalent" to a harmonic series?
- How may a spectrum analyzer be used to test the performance of an amplifier?

1.2 Challenging concepts related to amplifier performance

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

- **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.

- **Fourier's Theorem** – while this is no doubt a non-intuitive concept, it is incredibly useful. Knowing that any waveshape whatsoever may be reproduced by summing together the right combination of sinusoidal waves may defy our intuition, but at least seeing it is possible to synthesize common non-sinusoidal waveshapes like square and triangle using nothing but sine and/or cosine waves helps prove one can get non-round waves from lots of round waves added together. The practical upshot of this is that is it possible to consider very complex waveshapes as being nothing more than a set of sine waves added together. Since sine waves are easy to analyze in the context of electric circuits, this means we have a way of simplifying what would otherwise be a dauntingly complex problem: analyzing how circuits respond to non-sinusoidal waveforms. Time spent with a simple oscilloscope and spectrum analyzer viewing signal generator waveforms is also helpful in grasping how time-domain and frequency-domain representations relate. This concept is relevant to the study of amplifier performance, as any amplifier that distorts a waveform's time-domain shape adds harmonics to that signal's frequency composition.

1.3 Recommendations for instructors

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

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

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

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

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

- **Outcome** – Compute amplifier performance characteristics

  Assessment – Approximate voltage gain values for an amplifier circuit based on given component values; e.g. pose problems in the form of the "Gains and impedances of multi-stage amplifiers" Quantitative Reasoning question.

  Assessment – Approximate input and output impedance values for an amplifier circuit based on given component values; e.g. pose problems in the form of the "Gains and impedances of multi-stage amplifiers" Quantitative Reasoning question.

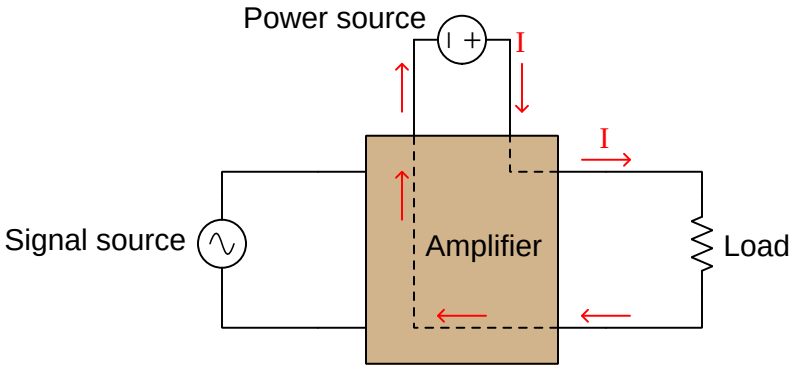
- **Outcome** – Independent research

  Assessment – Locate electronic amplifier datasheets and properly interpret some of the information contained in those documents including bandwidth, power output, gain, rolloff, harmonic distortion, etc.

Chapter 2

Tutorial

Amplifier circuits magnify the amplitude of electronic signals by using those signals to redirect, or control, the flow of energy from some power source to a load, making that flow of energy take on the same form as the original signal:



In order to achieve this feat, amplifier circuits utilize *active* components such as transistors to enable electronic signals to exert control over externally-sourced electrical energy. It should be clearly understood that although amplifiers boost signal power, they do not output more total energy than they receive. The additional power necessary for the boosted signal comes from the DC power source used to energize the amplifier circuit. Energy is always conserved, and amplification is just one more example of this conservation in action.

The perfect amplifier generates a flawless reproduction of the input signal that is magnified in amplitude (i.e. greater voltage, greater current, or both). Real amplifiers, however, always fall short of this ideal. A real amplifier's output signal is never a *perfect* reproduction of the input, although it may come very near to perfection. This module focuses on several practical limitations of amplifiers, and how we may quantify these circuits' performance for the purpose of improving their design.

2.1 Signal amplification (gain)

Perhaps the most important and obvious metric of any amplifier circuit is its *gain*, defined simply as the ratio of output to input signal amplitude, usually symbolized by the variable A. The value of A tells us how many times larger an amplifier's output signal is compared to its input signal. This ratio of output to input may be expressed in multiple ways. For example, we may speak of an amplifier having a *power* gain, a *voltage* gain, and a *current* gain, each gain calculated as the respective ratio of output to input for the specified quantity:

$$A_P = \frac{P_{out}}{P_{in}} \qquad A_V = \frac{V_{out}}{V_{in}} \qquad A_I = \frac{I_{out}}{I_{in}}$$

Gain expressed as a mathematical ratio is always unitless because it is a quotient of quantities having identical units of measurement (e.g. Watts out versus Watts in, Amperes out versus Amperes in). If we approach these formulae from the perspective of *dimensional analysis* where units of measurement cancel out in the same way algebraic variables cancel between numerator and denominator, we see the identical units on the top and bottom of the fraction canceling so that the result has no unit of measurement at all.

Signal amplification typically results in gain values exceeding 1, but the same concept of gain (A) may be used to quantify signal *attenuation* as well. For example, a signal reduced in amplitude by a voltage divider network is an example of a circuit having a "gain" value less than 1.

In systems where amplification and attenuation ratios are extreme, such as radio communication systems, it is common to express gains in *decibels* rather than as ratios. Decibels are a logarithmic expression of power ratios, similar to how the Richter scale is used to represent the mechanical power of an earthquake: an increase or decrease of ten in the decibel scale represents a *ten-fold* ratio of power amplification or attenuation.

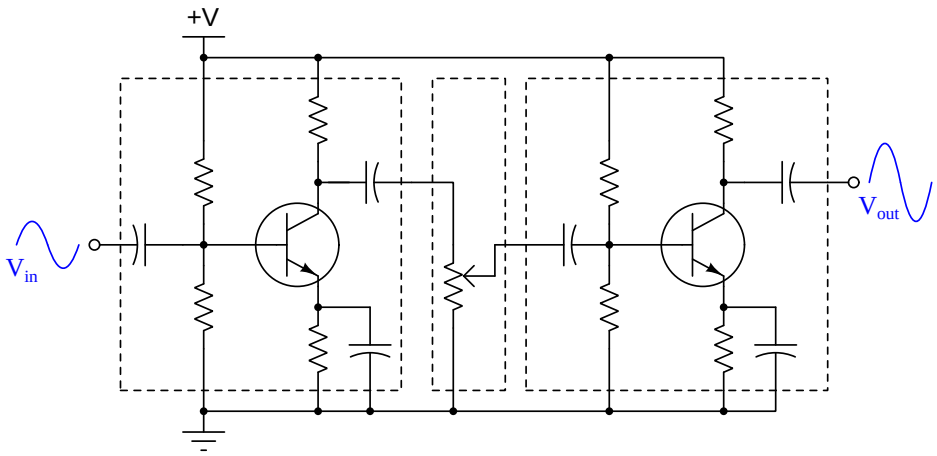
$$\text{dB} = 10 \log \left(\frac{P_{out}}{P_{in}} \right)$$

The following table gives examples of power gains in both ratio and dB form:

Power gain (ratio)	**Power gain (dB)**
$\frac{1}{10000}$	-40 dB
$\frac{1}{1000}$	-30 dB
$\frac{1}{100}$	-20 dB
$\frac{1}{10}$	-10 dB
1	0 dB
10	+10 dB
100	+20 dB
1000	+30 dB
10000	+40 dB

Round power-of-ten gain ratios were chosen for this table simply to clarify the relationship between ratios and decibels, since decibels use the *common logarithm* which is based on powers of ten. However, any power gain ratio is translatable into decibels. For example, a power gain of 2 equals 3.01 dB; a power gain of 4 equals 6.02 dB ; a power gain of $\frac{1}{2}$ equals -3.01 dB, a power gain of $\frac{1}{4}$ equals -6.02 dB, etc.

Decibels have the effect of "compressing" very large and very small ratios into relatively narrow range of numerical values. For example, a power gain of 3,566,920 is only 65.52 dB; a power "gain" (attenuation) of $\frac{1}{98,445}$ is only -49.93 dB. Decibels also simplify the computation of *multi-stage* amplification systems in that total decibel gain is the *sum* of individual stage gains while total ratio gain is the *product* of individual stage gains. A multi-stage audio signal amplifier shown below illustrates how gain ratios and gain decibels work, illustrating how the total gain (as a ratio) is equal to the *product* of the stage gain ratios, while the total gain (as a decibel figure) is equal to the *sum* of the stage gain decibel figures:

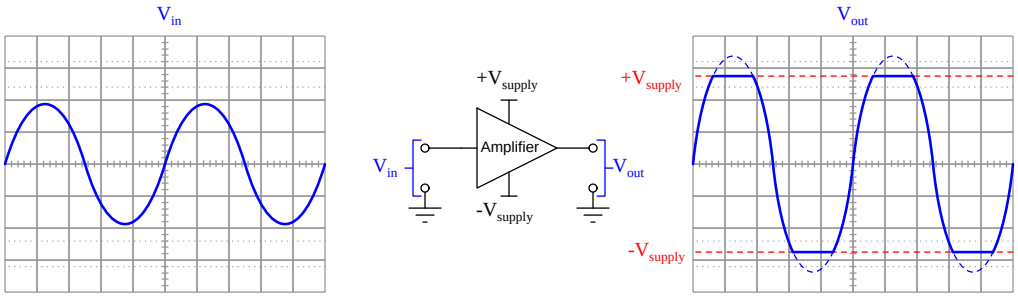


First amplifying stage	Volume control	Second amplifying stage	Total
$A_p = 14.7$	$A_p = 0.3$	$A_p = 2.6$	$A_{P(total)} = 11.466$
$A_p = 11.67$ dB	$A_p = -5.23$ dB	$A_p = 4.15$ dB	$A_{P(total)} = 10.59$ dB

Decibels are fundamentally an expression of *power* gain, which means if we wish to use dB to express either *voltage* or *current* gain we must do so in terms of how much *power* that voltage or current gain would imply. For any given load resistance, power is proportional to the *square* of voltage or current (Joule's Law, $P = \frac{V^2}{R}$ and $P = I^2R$), and so we must incorporate this square-relationship into the decibel formulae, as follows:

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

An important measure of amplifier performance related to voltage gain is *clipping*. This is what happens when the amplified signal attempts to rise above or below the limits of the DC power supply.



Amplifiers may also clip based on *current* limitations, if heavily loaded. In either case the fundamental principle at work is the very nature of electronic amplification: amplifier circuits function much like electrically-varying voltage dividers, "carving" out a reproduction of the input signal from the "raw material" provided by the DC power supply. No amplifier is able to boost its output signal to peak values beyond the "rail" voltages of the power supply, any more than an artist is able to paint a portrait larger than their canvas. Any attempt to do so results in the output signal being "clipped" as though someone cut the waveform's shape with a knife at the limit-points.

If the clipping is symmetrical as is shown above, possible solutions include the following:

- Reduce the input signal's amplitude
- Reduce the amplifier's gain
- Increase the DC power supply voltage if possible
- Optimize the impedance for a better match between amplifier and load

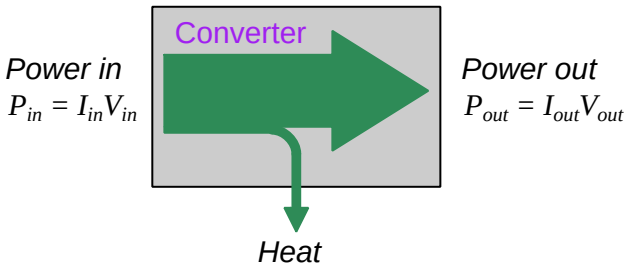
If the clipping is asymmetrical, another possible solution exists: adjust the amplifier's biasing.

Interestingly, some amplifier applications actually rely on clipping. For example, purposeful over-driving of an amplifier circuit is one way to convert a sine wave into a pseudo-square wave, which can be a useful technique when interfacing an analog signal with a digital (on/off) circuit. Also, intentional clipping is what gives electric guitars their characteristic "distorted" sound, where the preamplifier stage of the electric guitar amplifier is adjusted to an excessive level of gain for the express purpose of converting the string pickup coil's AC signal into a clipped wave closely resembling a square wave. This not only alters the instrument's sound, but it also creates a false sense of prolonged sustain because the clipped signal waveform maintains a steady peak amplitude even as the string's oscillations gradually decay.

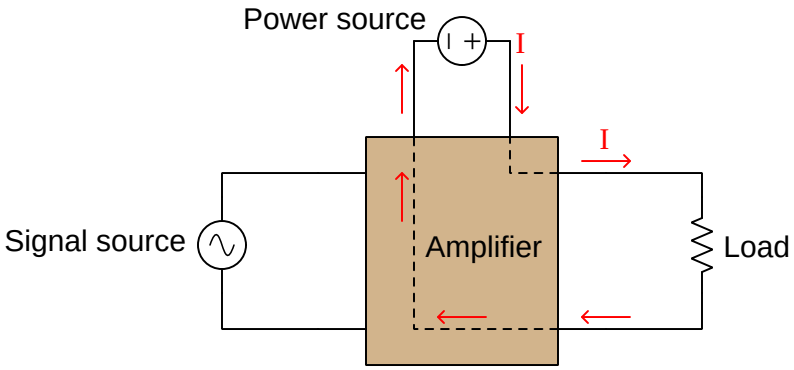
2.2 Amplifier energy efficiency

As defined earlier, an *amplifier* circuit is a collection of electronic components designed to magnify the amplitude of an electronic signal by using that signal to redirect, or control, the flow of energy from some power source to a load, such that the outgoing flow of energy reproduces the same wave-shape as the original signal. Like all energy-converting systems, some of the power source's energy invariably diverts from the intended path (toward the load) and instead takes forms such as heat.

Show in block-diagram form, the flow of energy into and out of any electrical energy-converting circuit may be represented as arrow symbols, the width of each arrow representing the amount of power (energy per unit time) flowing into and out of the circuit:



In the case of an amplifier circuit, total power in consists of DC power supplied by the power source plus the signal source; total power out is what the load receives:



Energy *efficiency* for any system is the ratio between the amount of energy converted by that system into the intended form versus the amount of energy delivered to that system:

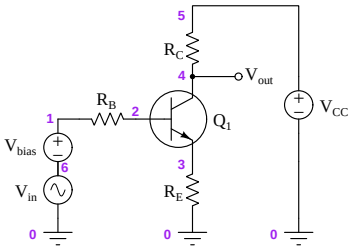
$$\text{Efficiency} = \frac{\text{Energy converted to intended form}}{\text{Energy input to system}} = \frac{P_{out}}{P_{in}}$$

100% energy efficiency is physically impossible, thanks to the Second Law of Thermodynamics. Some amplifier designs, as we shall soon see, are more energy-efficient than others.

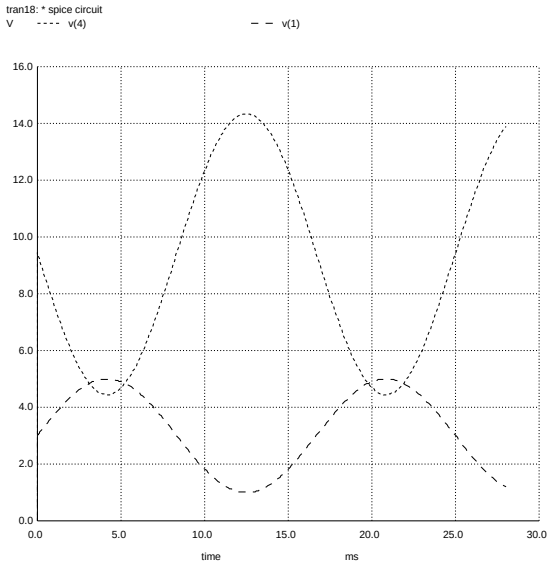
2.3 Classes of operation

Active devices such as transistors and vacuum tubes are fundamentally DC-only devices, in that they are only able to control the flow of current in one direction. In order to use one of these devices to reproduce the entire wave-shape of an alternating-current (AC) signal, we must *bias* it in order to maintain a state of constant conduction throughout the AC signal's cycle.

Consider the following example where a BJT is biased by a 3 Volt DC source in series with the AC signal source to offset that signal voltage above zero and thereby maintain the transistor in a constant state of conduction between collector and emitter:



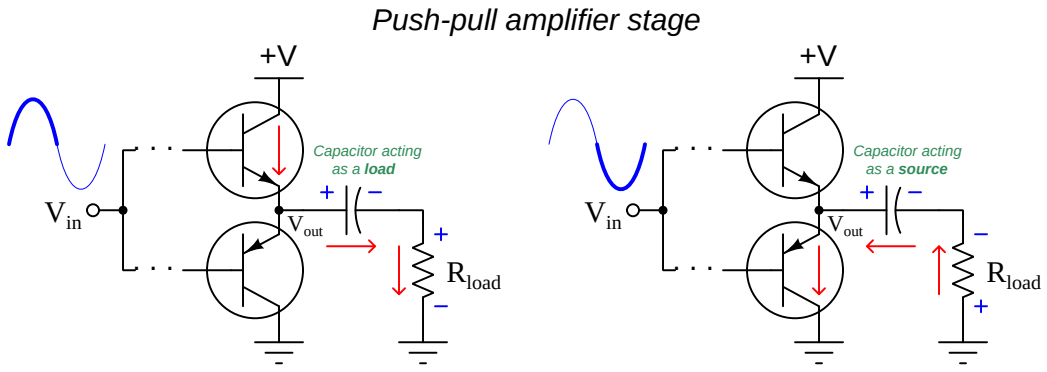

```
* SPICE circuit
vin 6 0 sin (0 2 60 0 0)
vbias 1 6 dc 3
vcc 5 0 dc 15
rc 5 4 3300
rb 1 2 10000
re 3 0 1200
q1 4 2 3 qmod
.model qmod npn
.tran 0.1m 28m uic
.plot tran v(1) v(4)
.end
```



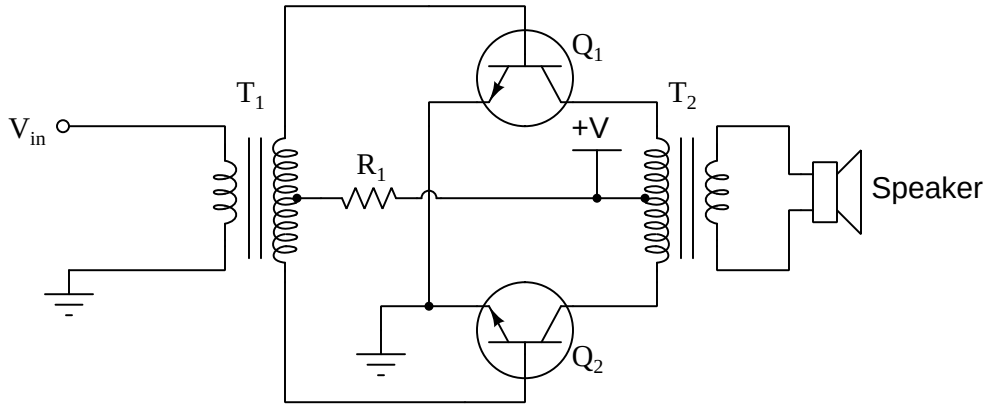
Thanks to the transistor remaining at least partially "on" at all times, V_{out} now resembles the same wave-shape as V_{in} (albeit in inverted form). The signal's biasing is clearly evident by viewing `v(1)` in the SPICE plot: the sine-wave signal peaks at a high value of 5 Volts and at a low value of 1 Volt. The "AC portion" of this signal still has a peak-to-peak value of 4 Volts, but the biasing moves its center value to 3 Volts so that it never dips into negative values (or below the 0.7 Volt minimum required by the transistor to turn on). This "always-on" mode of amplifier operation is referred to as *Class A*.

A price we pay for this faithful reproduction of the entire AC signal wave-shape is significant energy dissipation in the transistor. Since the transistor never fully turns off nor fully turns on, it always dissipates energy in the form of heat. This constitutes inefficiency, which may be a problem for a high-power amplifier circuit or for an amplifier powered by some limited energy source such as a chemical battery. For this reason, other classes of operation and amplifier circuit designs exist.

If the transistor is biased such that it activates only during one of the half-cycles of the AC signal waveform, it "rests" for half of the time and dissipates zero power when doing so. This is called *Class B* operation, and for faithful reproduction of the entire signal waveshape requires two transistors operating in a "push-pull" configuration:



Another form of push-pull audio amplifier circuit is shown here, using transformers for input and output signal coupling:

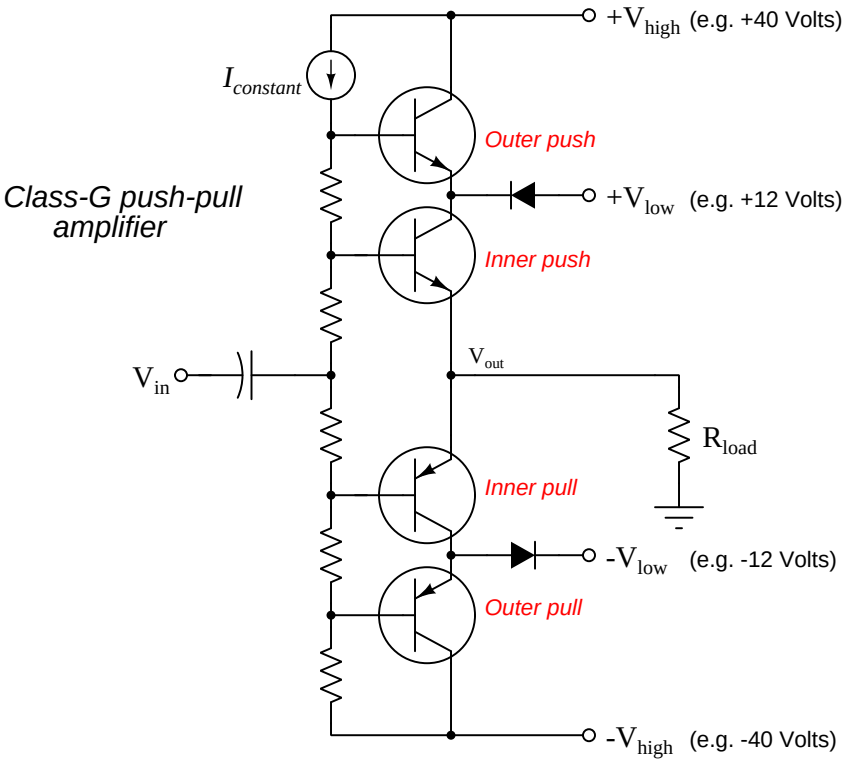


In this circuit proper biasing is a function of the DC supply voltage (+V) and resistor R_1, passing just enough current through the base terminals of each transistor to maintain them in a state of readiness to turn on at the slightest amount of input voltage, which one turning on depending on the polarity of the input signal at any given time.

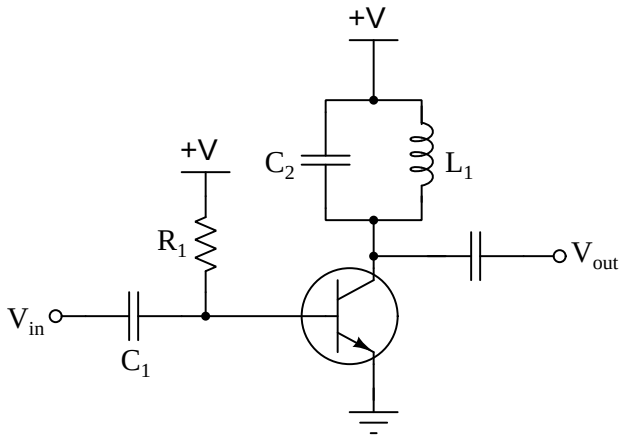
Not surprisingly, class-B operation has its own unique limitation: a problem called *crossover distortion* which occurs if the transistor biasing is imperfect and causes them to conduct less than 50% of the time, resulting in a brief period during every zero-crossing of the AC signal when *neither* transistor conducts and the output signal "flat-lines" at zero when it ought to seamlessly cross zero transitioning between positive and negative. A practical solution to this problem is to slightly over-bias the push-pull transistors to achieve mutual conduction at the zero-crossing point, so that we

never have a condition where both are simultaneously off. This results in slightly reduced energy efficiency, but not nearly as poor as a class-A amplifier where the transistor never stops conducting. This compromise form of operation is called *Class AB*.

A variation on this theme called *Class G* operation uses additional push-pull transistors to provide an extra DC power supply rail voltage "boost" to the primary push-pull transistors in order to permit higher output voltage swings while maintaining good energy efficiency at lower levels of output.



A third mode of operation is where the transistor spends significantly less than 50% of the time on. This, obviously, will fail to reproduce the AC waveshape and in fact is the very problem we sought to overcome with class-A biasing. However, in some applications this is a practical amplification technique, specifically in radio-frequency (RF) amplifiers where we may use LC "tank circuits" to sustain oscillations during the times when the transistor is off. We call this *Class-C* operation, a simple class-C amplifier shown in the following schematic:



The transistor in a class-C amplifier essentially "pulses" on at the peaks of the AC input signal and remains off for the remainder of each cycle, during which time the LC tank circuit rounds out the rest of the sinusoidal signal by resonating, relying on energy stored during the transistor's "on" time. Class-C amplifier circuits are highly efficient because the transistor spends most of its time either shut off or turned (nearly fully) on, but are limited in application to amplifying signals consisting of whole sinusoidal cycles. They find widespread application as RF (radio-frequency) power amplifiers where the signal being amplified has a very high frequency[1] and where its magnitude remains mostly constant within the span of any single cycle[2].

Many other amplifier classes exist, but all require substantially different circuit topologies to implement. Most of these other classes (D, F, I, S, T) use the transistor as a discrete on/off switch rather than as an analog "throttling" device, for the sake of reducing power dissipation at the transistor and thereby increasing the amplifier's energy efficiency.

[1] High frequency is practical here because it makes practical tank circuit networks using components of modest size.

[2] RF amplifiers used for radio service must, of course, handle signals more complex than a simple sinusoid. RF signals are always *modulated* in some way, but these modulation schemes usually involve alterations to the magnitude and/or frequency of the "carrier" signal that are relatively slow compared to the frequency of that carrier. In other words, an RF amplifier need not be able to alter the wave-shape within the span of a single cycle, and so the tank circuit "flywheel" principle of a class-C amplifier suffices.

2.4 Amplifier rejection

Good amplification isn't just about what an amplifier circuit *should* do, it's also about what an amplifier circuit *should not* do. A good amplifier should magnify the amplitude of the input signal by a predictable amount, but it should *not* allow variations in power supply voltage or other parameters to affect the amplification of the desired signal. Expressed in different terms, an amplifier should *accept* only the signal presented at its input terminal(s) and *reject* all other influences.

Power supply rejection ratio (PSRR), often called *ripple rejection ratio*, refers to the effect that any variation in DC power supply voltage might have on the amplifier's output signal. A well-designed amplifier will have a very large rejection ratio, signifying that large variations in DC power supply voltage would be necessary to significantly influence the amplifier's output signal. An ideal amplifier has an infinite power supply rejection ratio. Since these ratio values are enormous, it is customary to express them as decibel (dB) figures, with 100 dB typically being the minimum for a modern integrated-circuit amplifier. One way to calculate power supply rejection is shown below:

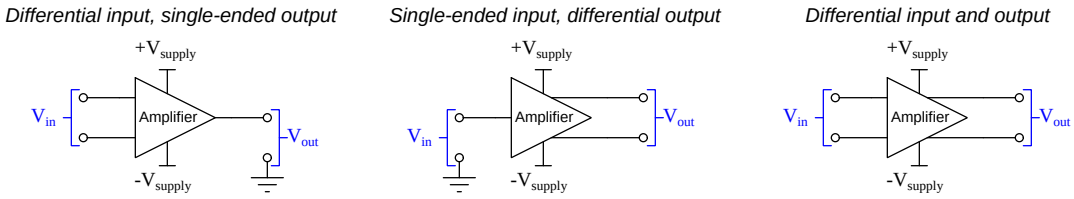
$$\text{PSR} = 20 \log \left(\frac{\Delta V_{PS}}{\Delta V_{out}} \right)$$

Where,

PSR = Power Supply Rejection, in decibels
ΔV_{PS} = Variation in DC power supply voltage, in Volts
ΔV_{out} = Variation in amplifier output voltage signal, in Volts

Unfortunately, there appears to be little standardization regarding how power supply rejection figures are calculated. Some manufacturers express rejection as the inverse ratio (i.e. $\frac{\Delta V_{out}}{\Delta V_{PS}}$) which results in a *negative* rather than a positive decibel figure. Another method is to calculate power supply rejection in terms of its equivalent effect on the amplifier's *input* signal; i.e. how much power supply variation would be necessary to duplicate the effect of the input signal varying[3].

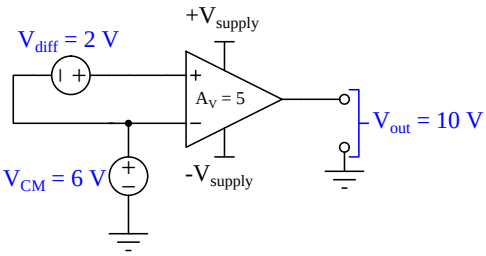
A type of rejection ratio specific to *differential* amplifiers is called *common-mode rejection*. Recall that a differential amplifier is one designed to amplify the difference in potential between two input terminals, as opposed to the more customary "single-ended input" amplifier designed to amplify the potential at one input terminal with respect to ground:



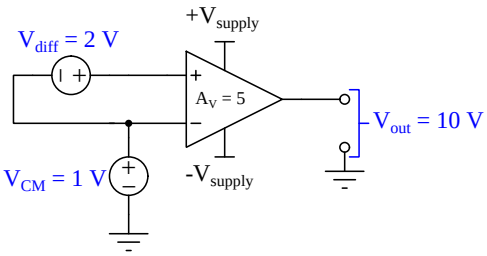
[3] This may seem like a strange way to quantify power supply rejection, because it's really corruption of the *output* signal by power supply ripple that we're worried about here. However, there is a certain rationale to it if you're interested in comparing the effect of power supply variance against the effects of *noise* in the input signal. It also has the desirable marketing effect of inflating the rejection ratio, by comparing a given amount of power supply variance to the amplifier's input signal amplitude (that input signal of course being smaller than the output signal)! As usual, *caveat emptor*.

With V_{in} defined as a potential *difference* between two input terminals on a differential-input amplifier, such an amplifier should *only* amplify that potential difference and *reject* any amount of voltage common to both of those input terminals and ground. The following diagrams illustrates an ideal differential amplifier with a voltage gain of five rejecting a change in "common-mode" voltage from 6 Volts to 1 Volt:

2 Volts differential + 6 Volts common-mode



2 Volts differential + 1 Volt common-mode



Note how this ideal differential-input amplifier only accepts the differential input voltage and rejects any common-mode voltage: its output remains unchanged at 10 Volts despite a six-fold change in common-mode voltage.

Real differential amplifiers, of course, are actually affected by common-mode voltage just as they are affected by DC power supply fluctuations. The quantification of this rejection follows a formula similar to that of power supply rejection:

$$\text{CMR} = 20 \log \left(\frac{\Delta V_{CM}}{\Delta V_{diff}} \right)$$

Where,

CMR = Common-Mode Rejection, in decibels

ΔV_{CM} = Variation in common-mode input voltage, in Volts, to produce a certain amount of ΔV_{out}

ΔV_{diff} = Variation in differential input voltage, in Volts, to produce the same amount of ΔV_{out}

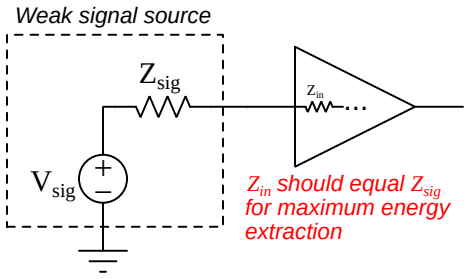
As with power supply rejection, modern integrated-circuit amplifiers often boast common-mode rejection figures exceeding 100 dB.

2.5 Amplifier impedance

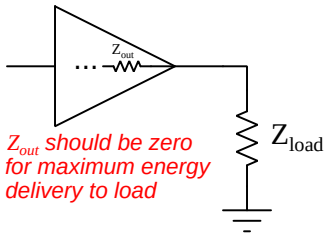
The amount of impedance an amplifier presents *as* a load to its input signal source, as well as the amount of impedance an amplifier presents *to* a driven load, are both important amplifier specifications. An amplifier with input and/or output impedance values poorly matched to its external device(s) may not perform optimally.

On the input side, amplifier impedance is defined by the biasing resistor network as well as the transistor itself, and to a lesser degree the load it powers. The *Maximum Power Transfer Theorem* tells us a network will accept the most power from a source when its impedance is adjusted to match the internal impedance of that source. If the goal is to extract as much power from the signal source as possible, then it makes sense to design an amplifier so its input impedance closely matches the source, and furthermore achieving that match by passing most of the extracted power through the amplifying element (e.g. the transistor) instead of simply dissipating it within circuit resistances (e.g. bias resistors).

A good case for close impedance-matching of an amplifier's input with the signal source is in the presence of *noise* sources having different impedances: an amplifier matched to the desired signal source but mis-matched with noise sources will draw more signal power than noise power, improving signal-to-noise ratio.



On the output side, amplifier impedance simply limits[4] power delivery to the external load. In terms of raw power delivery, the less internal impedance at an amplifier's output terminal, the more effectively it may deliver energy to the load. However, this does not necessarily mean zero output impedance is ideal: one beneficial use of output impedance in an amplifier is self-protection against a short-circuited load.

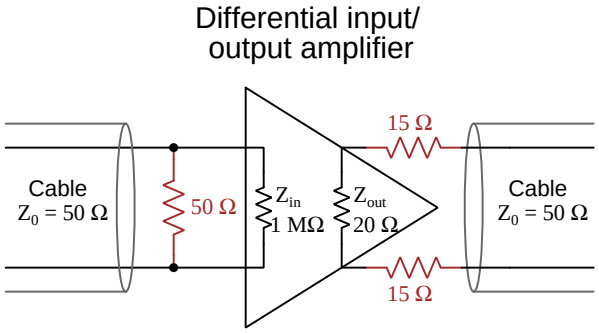


[4] A common misconception about the Maximum Power Transfer Theorem is that source impedance needs to be adjusted to match load impedance for maximum energy transfer. This is not true. It is the load which must be *adjusted* to match the source, not the other way around. The ideal source impedance for maximum energy transfer is always zero!

One application where good impedance-matching on both amplifier input and output is essential is when the amplifier connects to *transmission lines* where reflected signals on those lines would degrade signal quality. This is relevant for high-frequency amplifiers sending and/or receiving signals through relatively[5] long conductors. Whenever a pulse or otherwise alternating electrical signal is sent through a long cable (called a *transmission line*), that pulse energy travels along the cable's length and will "reflect" off the far end of that cable unless it encounters an impedance value matching the cable's own *surge impedance* or *characteristic impedance*.

Ideally an amplifier receiving a pulse signal from a transmission line will be designed to have an input impedance matching that of the line itself, to prevent reflected signals returning to the source. Likewise, an amplifier sending a pulse signal into a transmission line should be designed to have an output impedance matching the line's, to absorb any reflected energy that might return from the other end of the line.

If an amplifier's input and/or output impedance happens to be mis-matched to the transmission line(s) it connects to, external resistors may be added to make the necessary corrections. In the example shown below, two transmission lines rated at 50 Ω surge impedance each connect to a fully differential amplifier having 1 MΩ input impedance and 20 Ω output impedance:

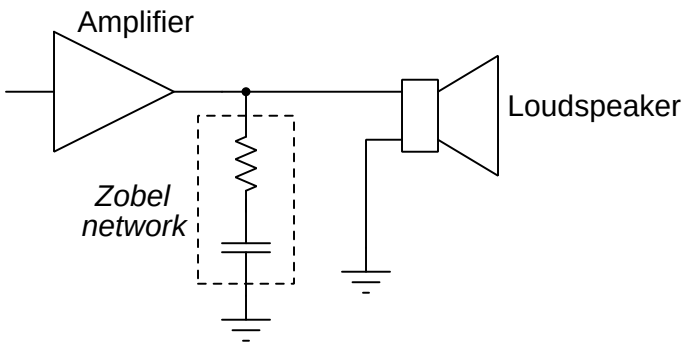


Here, we have augmented the amplifier's mis-matched internal impedances with external resistors[6] so that both cables "see" 50 Ω when "looking into" the amplifier. Of course, these added resistors help match impedances at the expense of dissipating energy in the form of heat, and thus they actually decrease over-all efficiency. However, in applications where reflected signals absolutely cannot be tolerated, it might be a worthwhile compromise to discard some signal power in order to prevent signal reflections on long cables.

[5] Here, "relatively" refers to conductor length as compared to the AC signal's wavelength λ.

[6] Yes, technically the resistor paralleled with the amplifier's input terminals should be *slightly* greater than 50 Ohms so that in parallel with the 1 million Ohms of the amplifier it will make exactly 50 Ohms for perfect cable termination. However, cable termination need not be *perfect* to adequately dissipate reflected signal energy, and no cable has an impedance of *exactly* 50 Ohms anyway. Besides, where would you find a *50.0025 Ohm* resistor? The reason we use two 15 Ohm resistors on the output rather than a single 30 Ohm resistor is to ensure both of the amplifier's differential output terminals are *balanced* with respect to ground because we are assuming a balanced (i.e. ungrounded) transmission line.

In applications where load impedance varies considerably with frequency and we need the amplifier to "see" a more stable load impedance at its output, we may place special reactive networks at the output as shown below. In this example, the load is a loudspeaker which contains both resistive (dissipative) and reactive (inductive) properties:



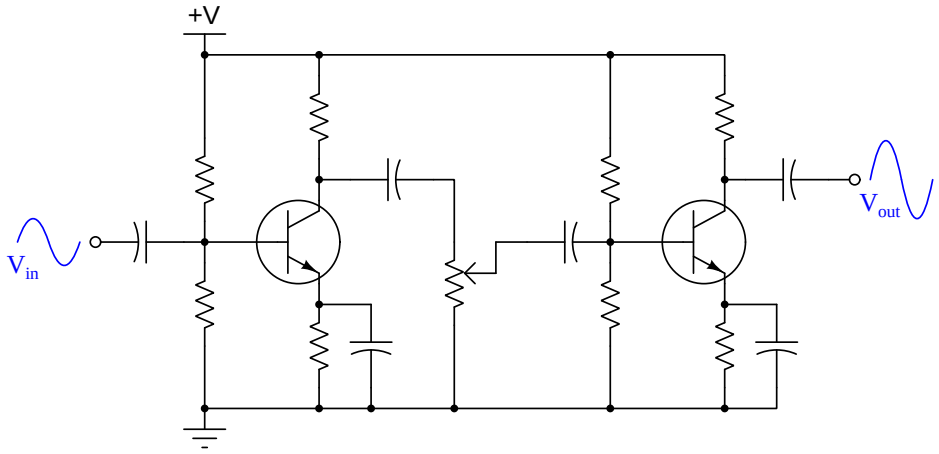
These impedance-stabilizing networks are typically external to the amplifier itself, as their component selections vary with the load's characteristics. They are generally known as *Zobel networks* in honor of Otto Zobel who devised them while working at Bell Labs in the 1920's. In the above example, the RC Zobel network's impedance falls with increasing frequency as the inductive loudspeaker's impedance rises. Properly sized, the RC network will compensate for the loudspeaker's impedance increase by functioning as an auxiliary load to the amplifier at higher frequencies. This may be necessary to prevent the amplifier from self-oscillating at high frequencies.

A good example of a Zobel network applied to audio amplification may be seen in technical literature for the popular LM386 audio power amplifier IC, that recommended stabilizing network consisting of a series combination of 10 Ohms resistance and 0.05 microFarads capacitance for a typical 8-Ohm loudspeaker.

2.6 Bandwidth

The ideal electronic signal amplifier is capable of amplifying signals of *all* frequencies equally well, but this is an unattainable goal in practice. Instead, real amplifiers behave somewhat like *filter networks* with practical frequency-cutoff limits.

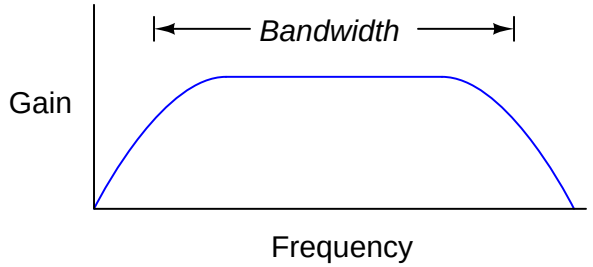
Consider the multi-stage audio amplifier shown earlier, as an example of an amplifier circuit with definite frequency limitations:



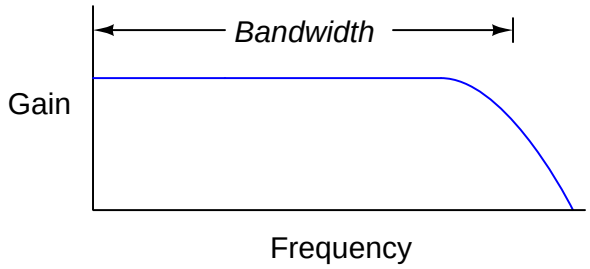
The existence of capacitors throughout this circuit creates a frequency-dependent response. Clearly, we could not amplify a DC voltage signal using this amplifier because the three coupling capacitors (drawn horizontally) would all block that signal's passage through. The two bypass capacitors (drawn vertically) boost gain by shunting around the emitter resistor of each amplification stage, furthermore limiting the amplifier's practicality at low signal frequencies.

Conversely, this amplifier cannot amplify radio-frequency signals either due to the parasitic capacitance existing between each transistor's base and collector terminals. This parasitic capacitance acts to "feed back" signal from the collector (output) to the base (input) at each amplifying stage, and because those two signal voltages are 180 degrees out of phase with each other (measured with respect to any other point in the circuit), this feedback is *negative* or *degenerative*, the effect being to cancel voltage gain.

As a result of these dual limitations, this amplifier's frequency-response function looks something like a band-pass filter with a fairly flat pass-band:

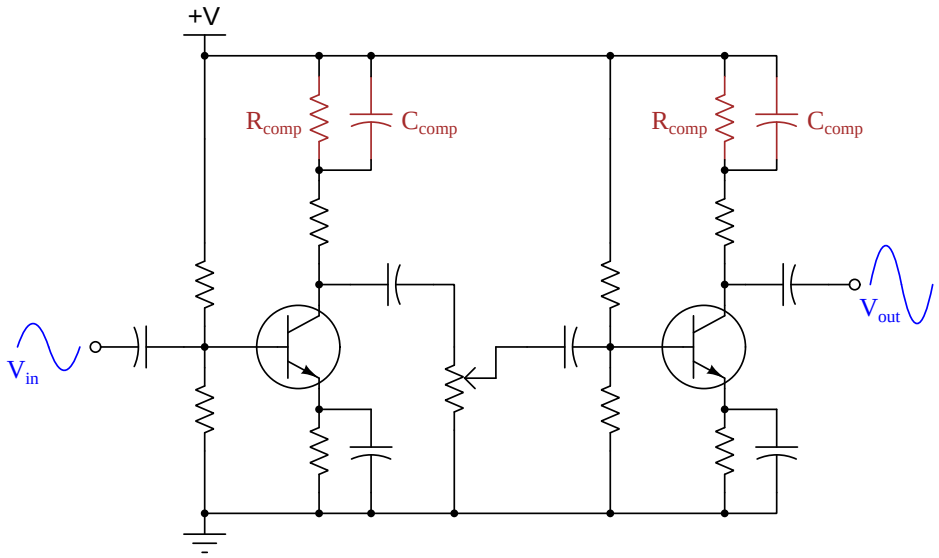


Direct-coupled multi-stage amplifiers have frequency responses similar to low-pass filter networks, their usable bandwidths extending all the way down to 0 Hz (DC), but still cutting off at high frequencies as shown in the following graph:



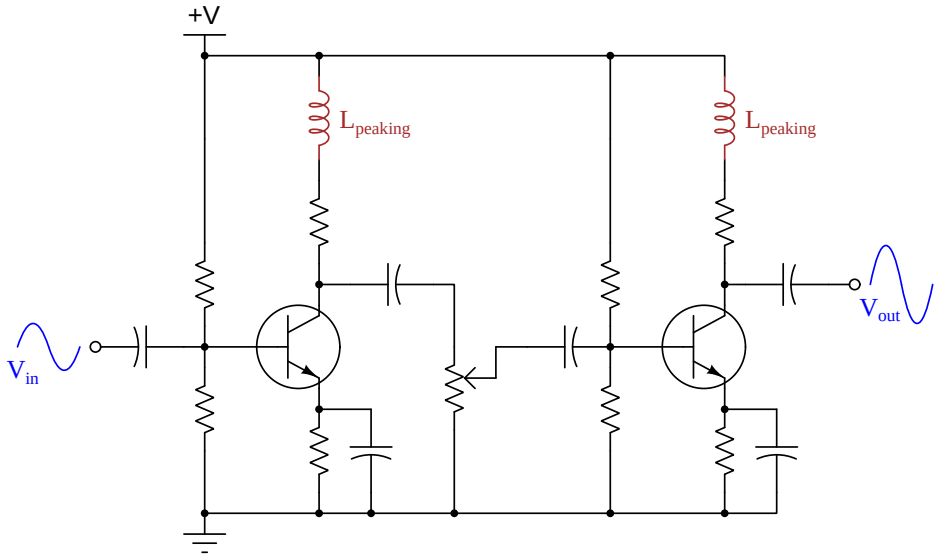
Of course, direct-coupled multi-stage transistor amplifiers have other limitations too, namely the tendency for each stage's biasing to affect the biasing of all the other stages. AC-coupled multi-stage amplifiers avoid this problem because their inter-stage coupling blocks all DC signals, of which biasing could be considered a DC signal. The price we pay in avoiding the "bias drift" problem of direct-coupled amplifiers is the inability to convey DC and other low-frequency signals.

One technique useful for extending the low end of an amplifier's bandwidth without abandoning AC coupling is to incorporate "compensating" resistance and capacitance on the collector side of the transistor:

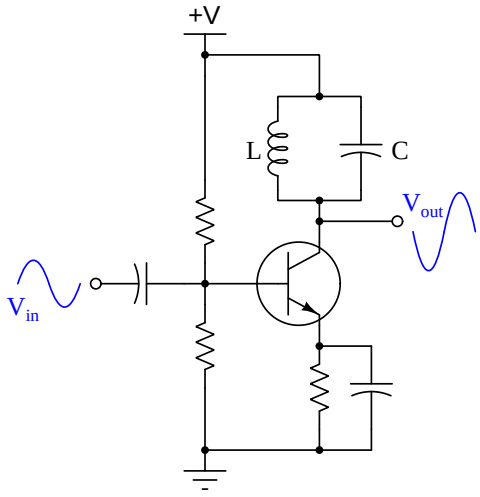


The idea of this is to increase the effective collector-side resistance of each common-emitter amplifier stage as frequency decreases. Voltage gain for a common-emitter amplifier is approximately $\frac{R_C}{R_E}$, and so increasing R_C will boost gain. The R_{comp} / C_{comp} network effectively does this by "un-bypassing" R_{comp} as frequency decreases.

A similar technique used to help compensate for the degradation of common-emitter amplifier gain at high frequencies is to install a *peaking coil* in the collector pathway of the circuit. Inductive reactance increases with increasing frequency ($X_L = 2\pi f L$), and so by placing an inductor on the collector-side of a common-emitter amplifier the total impedance on that side will grow with frequency and thereby provided a high-frequency gain boost:



When constructing amplifiers intended for extremely high (i.e. "radio") frequencies even peaking coils are not enough to maintain a usable voltage gain, and so instead of using resistance on the collector side of a common-emitter amplifier to develop an output voltage we commonly see an LC "tank" circuit network used instead:



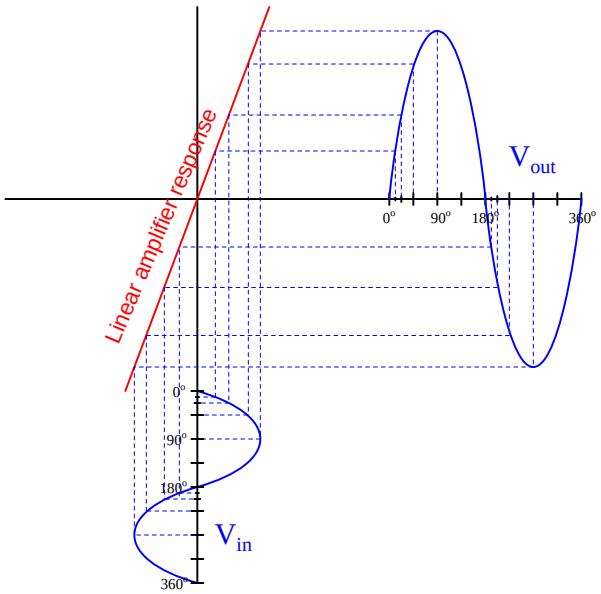
Of course, the resonant LC network gives the amplifier a fairly narrow bandwidth, but this is generally a desirable feature in an amplifier intended for radio applications where the communication channel is defined by a specific frequency.

A common performance parameter specified for electronic amplifiers is called the *gain-bandwidth product*, abbreviated *GBW*. This figure is calculated by multiplying the measured gain of an amplifier by the frequency of the test signal at that measured gain value, and for many amplifiers this figure is approximately constant over a wide range of frequencies. For example, if an amplifier circuit has a GBW of 1.2 million, it ideally means it can offer a gain of 1.2 million at a signal frequency of 1 Hz, a gain of one at a signal frequency of 1.2 MHz, or any combination in between where the product of gain and frequency is 1.2 million.

Approximate though this parameter may be, it holds an important lesson for us in understanding the frequency response of an amplifier: it is impossible for any amplifier to exhibit both an arbitrarily high gain and an arbitrarily high bandwidth. Instead, in order to achieve one of these goals we must sacrifice the other.

2.7 Distortion

To provide flawless reproduction of an input signal, an amplifier must be *linear*. A good way to visually understand the role that an amplifier's linearity plays in the faithful reproduction of an AC signal is to graph the amplifier's response as a line against which points along the AC input signal's waveform will be projected and reflected to form new points on the AC output signal's waveform. In the following illustration, a straight red line represents the linear response of the amplifier while blue curves outline the AC signal waveforms:

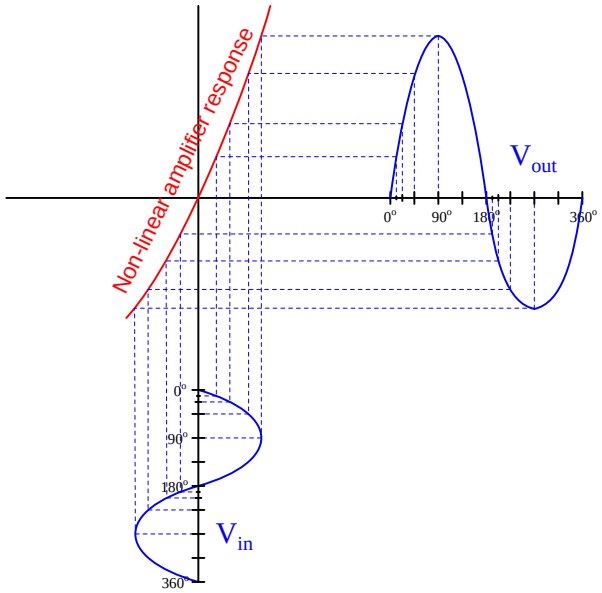


The *slope* of this line represents the amplifier's voltage gain. A gain of 1 (0 dB) would be a line at 45^o (i.e. a slope of 1). Voltage gains greater than unity (1) are reflected as slopes steeper than a 1:1 pitch.

So long as the amplifier response is a straight line (i.e. *linear*), the wave-shape of V_{out} must be the same as the wave-shape of V_{in}. A truly linear amplifier may *magnify* the wave, but it cannot *distort* the wave[7].

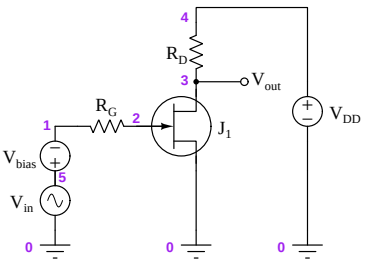
[7] This basic principle applies to *any* linear network, not just linear amplifiers. Voltage dividers and other attenuator networks are also fundamentally linear, and as such they will never change the shape of the wave even though they may diminish its amplitude. The linear response line of a resistive attenuator network, for example, is merely a line with a slope less than 1 so that V_{out} is less than V_{in}.

The same cannot be said of an amplifier having a non-linear response. Such an amplifier is guaranteed to distort the wave-shape because points along the output waveform's amplitude will not be proportionate in amplitude to those corresponding points along the input waveform. Below is an illustration showing an example of this phenomenon, where the amplifier's response is a J-shaped curve rather than a straight line:

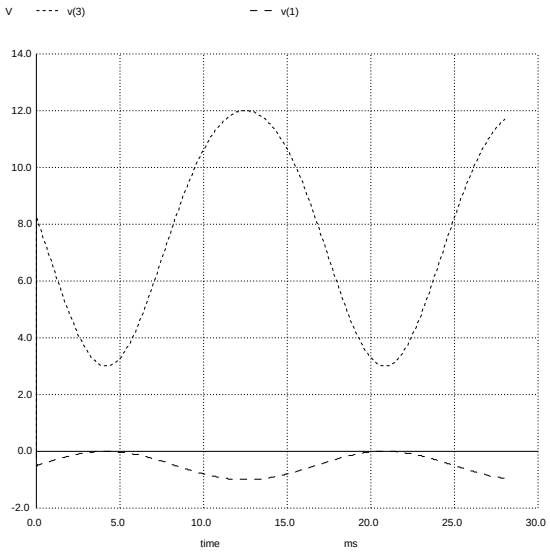


Note how one-half of the output waveform appears "fatter" than the other: clearly a distorted reproduction of the original (symmetrical) wave-shape.

Field-effect transistors, being *square-law* devices, exhibit a similar J-shaped response curve, which explains why single-transistor FET amplifier circuits tend to exhibit the same distortion characteristic[8] as seen in the following SPICE simulation:




```
* SPICE circuit
vin 5 0 sin (0 0.5 60 0 0)
vbias 5 1 dc 0.5
vdd 4 0 dc 15
rd 4 3 30000
rg 1 2 10000
j1 3 2 0 qmod
.model qmod njf
.tran 0.1m 28m uic
.plot tran v(1) v(3)
.end
```



Gross levels of distortion such as what we see with this single-stage JFET amplifier is easy enough to detect by visual inspection of the oscillograph, but more subtle degrees of distortion require other means of detection. One such diagnostic technique is to view an amplifier's output using a *spectrum analyzer* rather than an oscilloscope. Spectrum analyzers represent signals in the *frequency domain* rather than in the *time domain*.

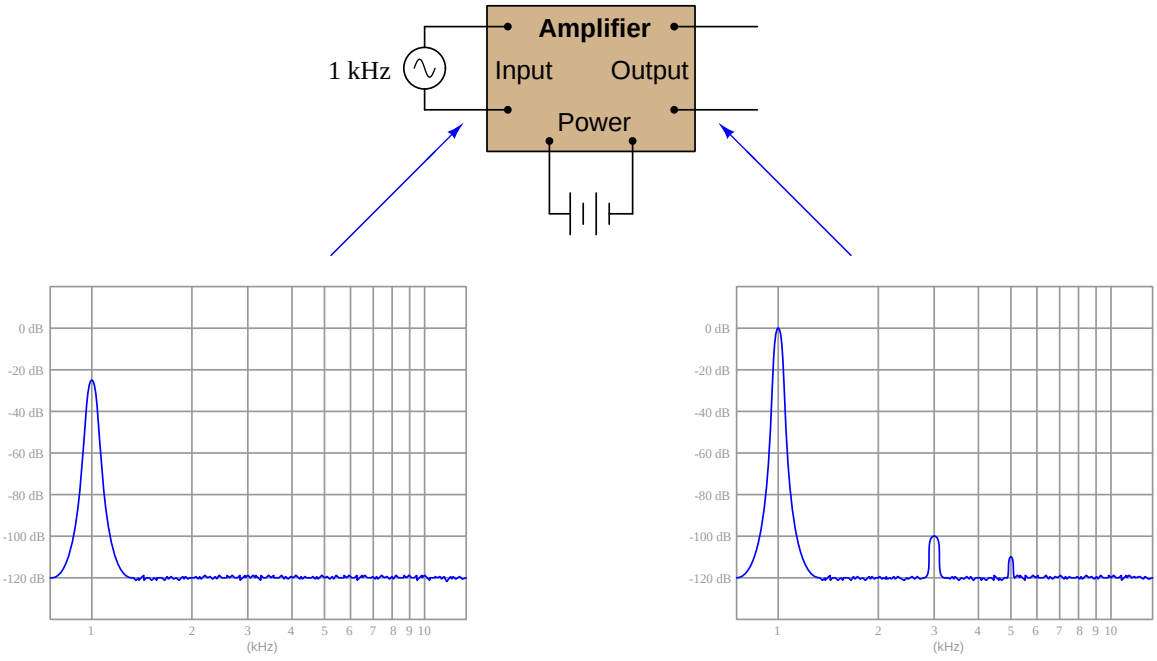
Fourier's Theorem states that any wave-shape – no matter how simple or complex – may be expressed in terms of pure sinusoids (i.e. sine-wave or cosine-wave shapes). A simple sine or cosine wave, for example, is by definition sinusoidal. What is not so obvious is the fact that even non-sinusoidal wave-shapes are actually equivalent to a series (summation) of multiple sinusoids[9] at different frequencies and amplitudes. Jean Baptiste Joseph Fourier made this mathematical discovery, and for this reason we often refer to the "decomposition" of non-sinusoidal waves into sinusoidal series *Fourier decomposition*. A *Fourier series* consists of a summation of multiple sine or cosine terms, each with its own amplitude, frequency, and phase angle. For periodic waveforms the frequencies are all integer-multiples of the lowest frequency (called the *fundamental*), with each of the higher frequencies called *harmonics*.

[8] The reason the distorted output waveform in the FET simulation appears inverted compared to our sketch is because the common-source FET amplifier is *inverting* in the same manner as a common-emitter amplifier.

[9] Interestingly, it is also possible to decompose any wave-shape into a series of other function types, so long as those function types are mathematically *orthogonal*. For example, it is possible to express any waveshape as a series of *impulse functions*, or as a series of *exponential functions*, or as a series of *step* functions. Sinusoids just happen to be convenient from both mathematical and engineering perspectives, and so this is by far the most popular form of decomposition.

Sinusoidal decomposition is not just an interesting theoretical principle, but a very practical tool for analyzing amplifier performance. The basic idea is quite simple: a pure sine wave output by a signal generator should consist of just one peak on a spectrum analyzer's display (the "fundamental"). After amplifying that sine-wave signal, the amplifier's output spectrum should also consist of just one peak representing that same fundamental frequency, albeit at a greater amplitude than the input signal, and likely shifted in phase from the input signal as well. However, if the amplifier is not perfectly linear, any distortion it contributes to the output signal make that signal's wave-shape non-sinusoidal, and this will translate into *multiple peaks on the spectrum*. The number and amplitude of these spectral peaks indicates how much *harmonic distortion* the amplifier has.

In the illustration shown below, a 1 kHz sinusoidal signal is sent to the input of an electronic amplifier circuit, with spectrum displays shown of input and output signal voltages:

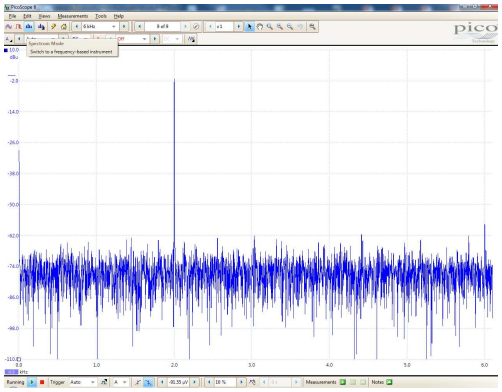


On the input spectrum we see a single peak at 1 kHz, representing the fundamental frequency of the pure sine-wave signal generated by the AC signal source. On the output spectrum we see a fundamental peak[10] at 1 kHz as well as smaller peaks at 3 kHz and 5 kHz, the 3rd and 5th *harmonics* of the fundamental. In this particular example the 3rd harmonic amplitude is −100 dB less than the fundamental, and the 5th harmonic is −110 dB below the fundamental. These figures represent very low levels of distortion: a 1 kHz sinusoid added to a 3 kHz sinusoid of $\frac{1}{100000}$ the fundamental's

[10] Note how the fundamental peak on both input and output spectra measure 0 dB. This may seem strange if we expect the amplifier to *boost* the amplitude of the signal. However, this is typical for two *separate* signal measurements, where the fundamental peak is usually adjusted to be the reference amplitude against which all other peak heights are compared. This is called a *normalized* measurement. The input and output spectra would have to be simultaneously displayed by a spectrum analyzer, normalized to the output signal fundamental, in order to compare the amplitudes of output versus input and thereby perceive the amplifier's gain.

amplitude, added to a 5 kHz sinusoid of only $\frac{1}{316228}$ the fundamental's amplitude. Such low levels of distortion would be utterly imperceptible on an oscillograph display of the output waveshape – i.e. it would appear to the unaided eye as a perfect sine wave – but on a spectrum display the presence of distortion is obvious.

That said, a real amplifier test will not be quite as simple as this example. No signal generator outputs *perfectly pure* sine waves, and so what we would typically see is an input spectrum with some low-level harmonics, and an output spectrum with those same harmonics (and perhaps others as well!) at greater amplitudes. The comparison of normalized harmonic amplitudes between output and input would tell us how much distortion the amplifier contributes above and beyond the inherent distortion of the signal generator. Also, real spectra always show a *noise floor* consisting of a jagged[11] rather than a flat base-line at the bottom of the display. The following screenshot of a digital oscilloscope's FFT (spectrum) display shows a 2 kHz sine-wave signal generator output with substantial noise:



A common metric of amplifier distortion is *Total Harmonic Distortion*, or *THD*. This is mathematically defined as the ratio of total harmonic signal power versus fundamental signal power, usually expressed as a percentage:

$$\text{THD} = \frac{P_H}{P_F} \times 100\%$$

Where,

P_F = Signal power of the fundamental frequency (i.e. the 1st harmonic), in Watts

P_H = Signal power of all higher-order harmonic frequencies, in Watts

Single-purpose test instruments called *distortion analyzers* exist to measure THD. They work on the principle of *notch filtering*: using a narrow-band band-stop filter to filter out the fundamental frequency from a signal, leaving nothing but the higher-order harmonics which are then measured.

[11] While periodic waveforms consist of a fundamental sinusoid added to one or more harmonics of that fundamental, non-periodic waveforms contain non-harmonic frequencies, and in most cases solid *bands* of frequencies spanning certain ranges. Noise is usually random in nature, and so a spectrum's noise floor appears as a jagged "band" of frequencies rather than a set of clearly-defined peaks.

Chapter 3

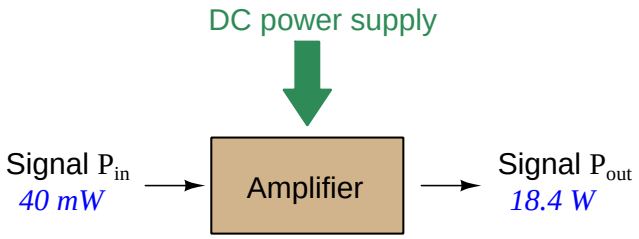
Derivations and Technical References

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

3.1 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:

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

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

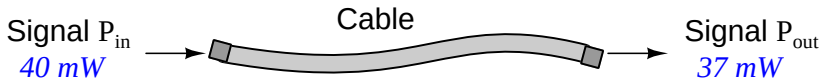
$$\text{Ratio} = 460$$

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:



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

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

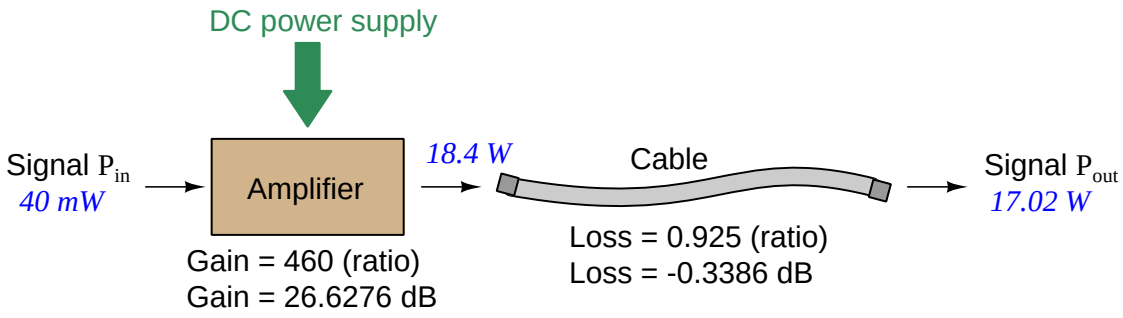
Contrasting this result against the previous result (with the amplifier) we see a very important property of decibel figures: any power *gain* is expressed as a *positive* decibel value, while any power *loss* is expressed as a *negative* decibel value. Any component outputting the exact same power as 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.

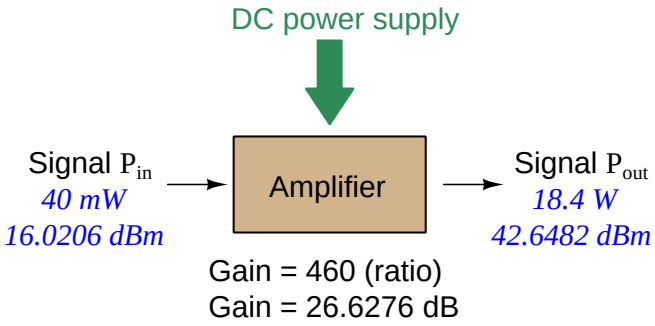
Decibels always represent comparisons of power, but that comparison need not always be P_{out}/P_{in} for a system component. We may also use decibels to express an amount of power compared to some standard reference. If, for example, we wished to express the input power to our hypothetical amplifier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

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

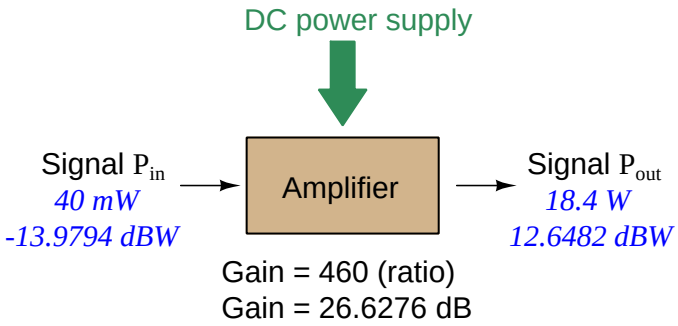
$$16.0206 \text{ dBm} + 26.6276 \text{ dB} = 42.6482 \text{ dBm}$$

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:

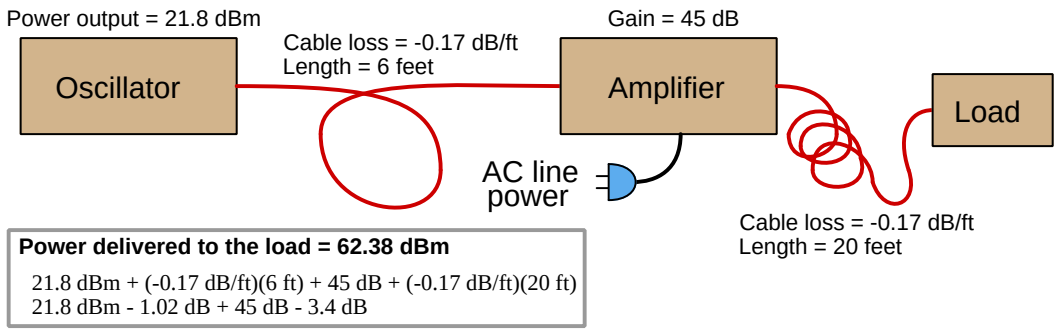
$$P_{in}(\text{dB}) + P_{gain}(\text{dB}) = P_{out}(\text{dB})$$

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

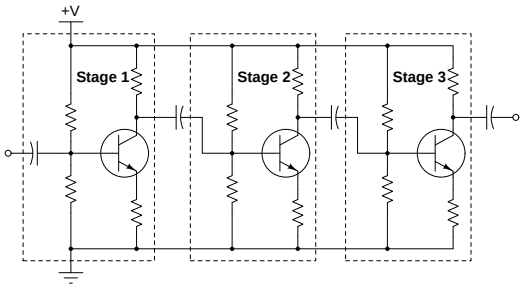
An electronic signal that begins 13.9794 dB less than 1 Watt, when boosted by an amplifier gain of 26.6276 dB, will become 12.6482 dB greater than the original reference power of 1 Watt.

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:

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

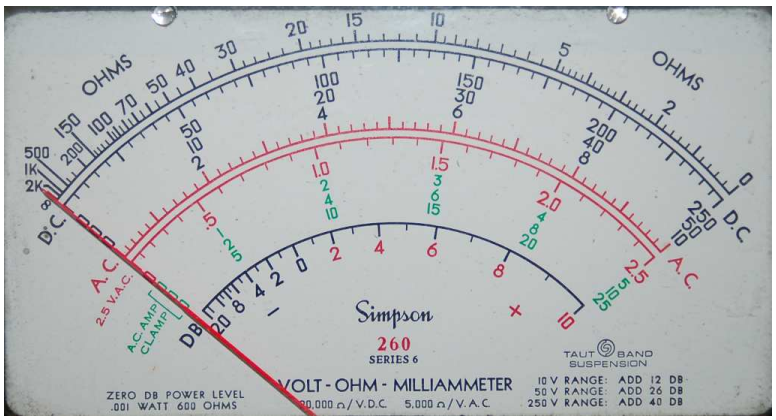
Therefore, we may simplify the decibel formula for voltage gain by removing the "2" power and making it a multiplier:

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

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

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.

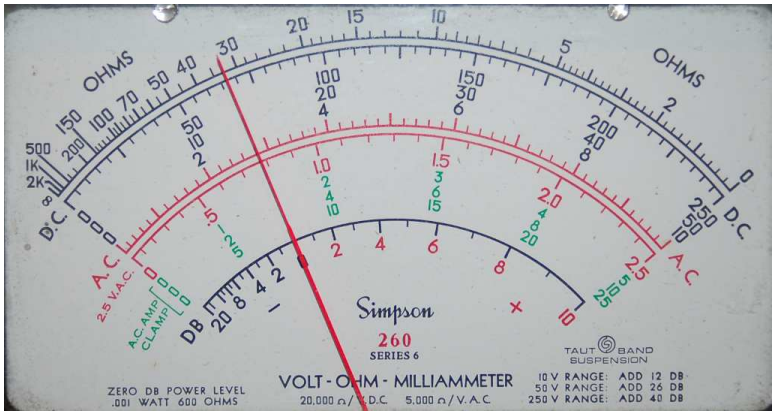
[4] Such mis-labeling is not that uncommon in the profession, the expectation being that the technician or engineer working with the instrument ought to be familiar enough with the concept of decibels to know when dB really means dBm, or dBW, etc.

[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):

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

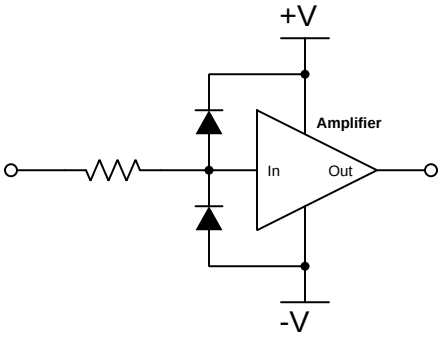
$$20 \log \left(\frac{2.5}{250} \right) = -40.0 \text{ dB}$$

3.2 Protecting amplifier inputs from over-voltage

Electronic amplifier circuits are extremely useful devices, comprising portions of many practical integrated-circuit (IC) electronic components such as digital logic gates, comparators, operational amplifiers, signal mixers, etc. Solid-state amplifier circuits use *transistors* to allow one electrical signal to control another, and these transistors tend to be susceptible to damage from excessive applied signal voltage. In the case of MOSFET transistors, an excess of signal voltage may puncture the extremely thin layer of metal-oxide insulation separating the transistor's gate terminal from its current-carrying channel. In the case of bipolar (NPN, PNP) transistors, an excess of signal voltage may break down reverse-biased PN junctions inside the transistor, often causing them to fail in "shorted" states. Excessive applied signal voltage may also cause damage to bipolar transistors if forward-biasing PN junctions to the extent that they conduct high amounts of current which may lead to thermal damage.

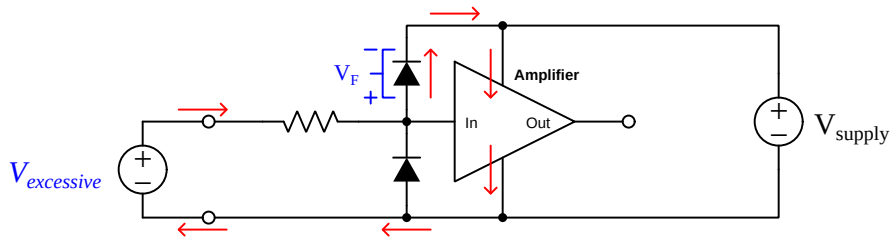
Sources of excessive signal voltage may be broadly categorized as *electro-static discharge* (ESD) or *electrical over-stress* (EOS). ESD happens when some object external to the circuit (including human bodies) accumulates an electro-static charge in its own capacitance, and this capacitively-stored charge is suddenly send to the circuit where it drops a voltage across circuit components high enough to cause damage. EOS is a more broad description of any over-voltage or over-current condition caused by one circuit sourcing energy to another, such as when an electrical test instrument is connected to a signal source that is too great for that instrument to handle.

A simple and effective way to limit both applied voltage and applied current to the input of any electronic amplifier is to connect a current-limiting resistor in series between the input terminal and the amplifier, as well as connect diodes between the input terminal and either DC power supply "rail" terminal:



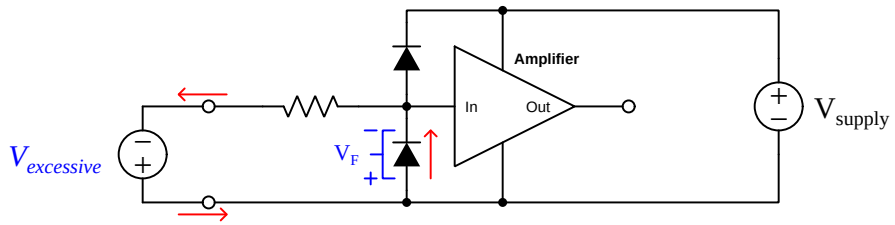
It matters not how the amplifier itself is internally constructed, nor what its larger purpose is – whether it be part of a digital logic gate, a comparator, an operational amplifier, or something even more complex. The purpose of these two diodes and the series resistor is to prevent any component within the amplifier from experiencing either too much voltage and/or too much current. Such resistor-diode networks are generally known as *clipping networks* because they truncate or "clip" an incoming signal's amplitude so as to never exceed some maximum value(s).

To understand how this protection network functions, consider the following circumstance where an excessive positive potential is applied to the input terminal by some external source. Here, "excessive" is defined as any voltage greater in magnitude than the DC power source energizing the amplifier:



The upper diode of the protection network forward-biases to permit current from the offending source to pass into the positive power bus of the amplifier. The resistor's function is to drop however much of the applied voltage exceeds the power supply rail potential plus the protection diode's forward voltage drop ($V_{supply} + V_F$), and to limit the current to a value acceptable to the protection diode and to the circuit's DC power supply so that neither of those is over-stressed. With a normal silicon diode this means a voltage no greater than 0.7 Volts plus the positive DC rail voltage. If Schottky diodes are used in the protection network, it means a voltage no greater than 0.4 Volts beyond the positive rail. Such mild over-voltage conditions are unlikely to cause damage to any of the amplifier's internal transistors.

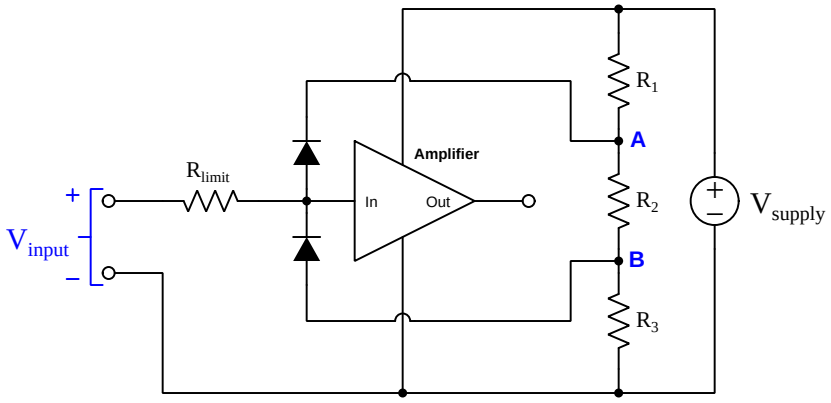
Similarly, if an excessive negative voltage is applied by an external source ("excessive" being any significant potential below that of the negative DC power supply rail):



Here the lower protection diode forward-biases and permits current from the external source to pass through the limiting resistor. While this occurs, the amplifier will never see more than that protection diode's forward voltage drop (V_F) between its input terminal and the negative DC rail bus, which again is unlikely to damage any transistor inside the amplifier. Again, the resistor should be sized to limit current to a value tolerable to the protection diode. However, this resistor should not be made so large that it might impair the normal operation of the amplifier when the protection diodes are not conducting: i.e. it should drop negligible voltage from the amplifier's normal input terminal current.

Such protection networks are often found inside of integrated circuits, sometimes without a series protection resistor in their most basic forms. Protection diodes are standard for CMOS digital logic gates to help protect their constituent MOSFET transistor gates from damage from ESD.

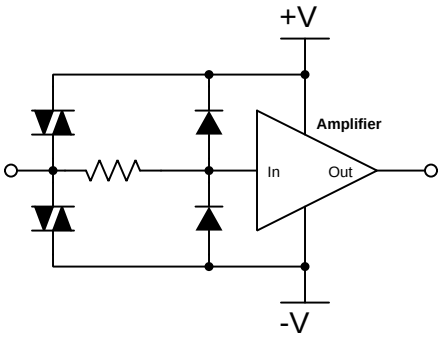
For some devices it is not sufficient for a diode network to clamp the input voltage to some value(s) slightly in excess of the device's power supply rail potential(s). For example, a device operating on a 5 Volt DC supply may tolerate input voltages no lower than zero and no greater than 5 Volts. A relatively simple solution to this problem is to provide the diode network with a set of "protection rails" just shy of the actual power supply rail potentials. Consider the following example as an illustration of this technique:



Here, resistors R_1, R_2, and R_3 form a voltage divider to produce two electrical potentials (labeled **A** and **B**), each one diode forward-voltage drop shy of the nearest rail potentials. For example, if the DC power supply output 5 Volts and the two protection diodes each dropped 0.7 Volts when forward-biased, the voltage divider would need to be designed such that point **A** was +4.3 Volts and point **B** was +0.7 Volts with respect to the DC supply's negative terminal. This would prompt the upper diode to turn on and clamp the amplifier's input potential to +5 Volts if ever the input potential exceeded +5 Volts, the limit resistor dropping the rest. Likewise, the lower diode would turn on if ever the input terminal's potential fell below the power supply's negative rail, clamping the amplifier's input terminal potential to exactly the same as that negative rail with R_{limit} dropping the rest.

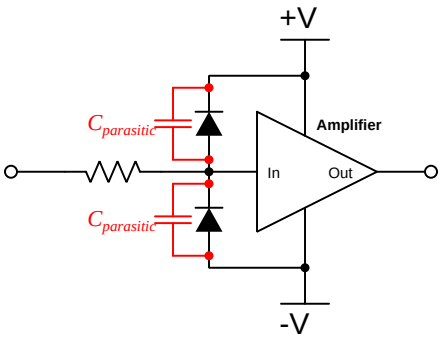
An important caveat to this strategy is that the voltage divider resistors R_1 and R_3 must be relatively small compared to the resistance of R_{limit} in order to ensure that those "protection rail" potentials **A** and **B** do not vary significantly when the protection diodes begin to conduct. A general engineering design principle here is to size R_{limit} at least ten times greater than either R_1 or R_3. If we size the resistors properly, this voltage-divider-based protection strategy may even be made *adjustable* by incorporating potentiometers into the voltage-divider network.

When protection must be provided against extraordinarily strong sources, additional protection may be added in their form of *DIACs* connected between each input terminal and power supply rail:



DIACs are classified as *thyristors*, because once triggered into an electrically conductive state by sufficiently high voltage (and/or sufficiently high *rate of change* of voltage, $\frac{dV}{dt}$) they will remain "on" so long as sufficient "holding" current passes through them even if voltage falls far below the initial triggering value. In summary, a thyristor acts as a very effective snubbing device to tame over-voltage conditions, essentially acting as a near-short to that offending source.

Protection networks, however, are not without their disadvantages. Chief among these is their tendency to adversely affect the signal being sensed by the amplifier being protected. Ideally a protection network should not corrupt the sensed signal at all, and only come into play if and when that signal becomes strong enough to pose threat of damage to the amplifier, but this would only be true if the protection diodes (and DIACs) had no parasitic properties when non-conducting. This is unfortunately untrue, as both diodes and DIACs exhibit *parasitic capacitance* which not only has the effect of storing electrical charge that the amplifier may interpret as a voltage that should not be present, but along with the protection resistor will form a *low-pass filter network* preventing the amplifier from being able to fully sense rapidly-changing input signals:



In other words, even with applied signals weak enough to pose absolutely no threat of harm to the amplifier, the capacitance inherent to the protection diodes will conspire with the series resistor

to "slow down" rates of rise and fall for any voltage arriving at the amplifier's input, thus making the amplifier "think" the signal isn't changing as rapidly as it really is.

In order to minimize the effects of parasitic capacitance within the protection diodes, we must choose diodes with as little of that capacitance as possible and also select a protection resistor with as low a value as possible that still limits maximum current to a value safe for the amplifier.

Chapter 4

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

4.1 Conceptual reasoning

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

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

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

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

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

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

4.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

4.1.2 Foundational concepts

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

Energy

Conservation of Energy

Gain

Decibels

Dimensional analysis

Common logarithm

Joule's Law

Rejection

Ripple

Common-mode voltage

Maximum Power Transfer Theorem

Impedance

Transmission line

Filter

Negative feedback

Parasitic effect

Bandwidth

Resonance

Linearity

Square-law characteristic

Time domain

Frequency domain

Sinusoidal decomposition (i.e. Fourier's Theorem)

Fundamental frequency

Harmonic frequency

Fourier series

Fourier Transform

Noise

Gain-bandwidth product

4.1.3 Amplifier roll-off

Most of the simple amplifiers you will be initially studying tend to lose gain as the frequency of the amplified signal increases. This loss of gain is sometimes quantified in terms of *roll-off*, usually expressed in units of decibels per octave (dB/octave).

What, exactly, is "roll-off?" Furthermore, explain the meaning of "octave" in the context of the units of measurement used to specify roll-off.

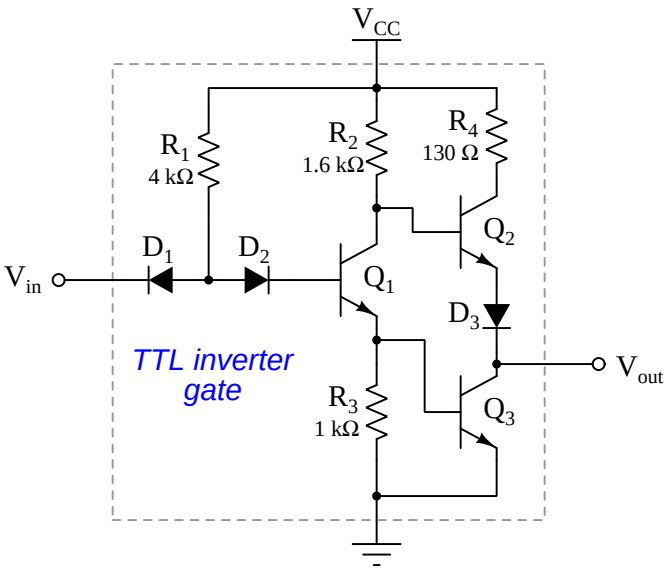
If we were to plot the response of a typical amplifier in the form of a Bode plot, what type of filter circuit characteristic (band-pass, band-stop, etc.) would it best resemble?

Challenges

- Identify some reasons why amplifiers behave as filters.

4.1.4 TTL logic gate as an amplifier

Integrated-circuit (IC) devices known as *logic gates* are essentially transistor amplifiers, designed to operate in discrete (on/off) mode rather than amplify analog signals. An example of a logic gate is shown below, this one a transistor-transistor-logic (TTL) gate known as an *inverter*:



Start by determining the state of each transistor when the input signal is "high":

- Q_1 = *on* or *off*?
- Q_2 = *on* or *off*?
- Q_3 = *on* or *off*?

Next, determine the state of each transistor when the input signal is "low":

- Q_1 = *on* or *off*?
- Q_2 = *on* or *off*?
- Q_3 = *on* or *off*?

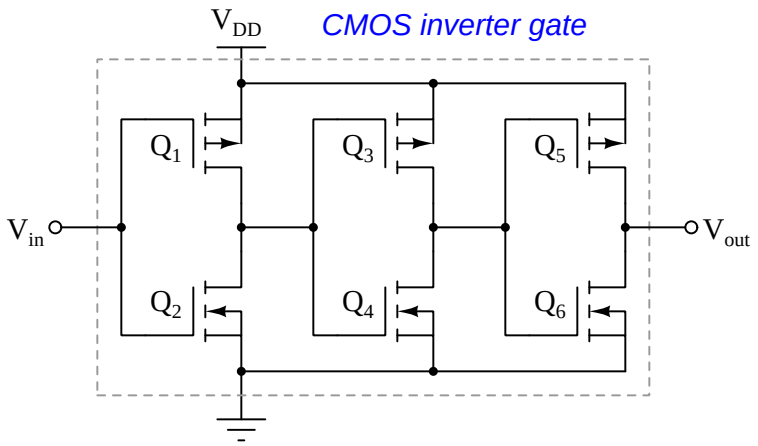
Lastly, apply the performance criteria you've been studying for amplifiers in general to this logic gate. If you are already familiar with digital logic circuitry, relate some of the terms and concepts from analog amplifier performance measurement to the equivalent terms and concepts in digital.

Challenges

- Logic gates are intended to function strictly with discrete (high/low) signals. Comment on how this perspective may be gainfully used to help you analyze the basic behavior of *any* amplifier circuit.
- From the perspective of Q_2's base terminal, is Q_1 functioning as a common-collector, common-emitter, or common-base amplifier?
- From the perspective of Q_3's base terminal, is Q_1 functioning as a common-collector, common-emitter, or common-base amplifier?
- A DC logic signal is either high or low (+V or zero), but an AC signal could be thought of as having three states: high (+V), zero, and low (−V). How would this logic circuit respond to a "low" AC signal (−V)?
- Identify distinct *amplification stages* within this logic gate circuit.

4.1.5 CMOS logic gate as an amplifier

Integrated-circuit (IC) devices known as *logic gates* are essentially transistor amplifiers, designed to operate in discrete (on/off) mode rather than amplify analog signals. An example of a logic gate is shown below, this one a complementary-metal-oxide-semiconductor (CMOS) gate known as an *inverter*:



Start by determining the state of each transistor when the input signal is "high":

- Q_1 = *on* or *off*?
- Q_2 = *on* or *off*?
- Q_3 = *on* or *off*?
- Q_4 = *on* or *off*?
- Q_5 = *on* or *off*?
- Q_6 = *on* or *off*?

Next, determine the state of each transistor when the input signal is "low":

- Q_1 = *on* or *off*?
- Q_2 = *on* or *off*?
- Q_3 = *on* or *off*?
- Q_4 = *on* or *off*?
- Q_5 = *on* or *off*?
- Q_6 = *on* or *off*?

Lastly, Apply the performance criteria you've been studying for amplifiers in general to this logic gate. If you are already familiar with digital logic circuitry, relate some of the terms and concepts from analog amplifier performance measurement to the equivalent terms and concepts in digital.

Challenges

- Logic gates are intended to function strictly with discrete (high/low) signals. Comment on how this perspective may be gainfully used to help you analyze the basic behavior of *any* amplifier circuit.
- Are transistors Q_5 and Q_6 operating as common-source, common-drain, or common-gate amplifiers?
- A DC logic signal is either high or low (+V or zero), but an AC signal could be thought of as having three states: high (+V), zero, and low (−V). How would this logic circuit respond to a "low" AC signal (−V)?
- Identify distinct *amplification stages* within this logic gate circuit.

4.1.6 Impulse testing

The Hewlett-Packard Application Note 17 ("Square wave and pulse testing of linear systems") written by B.M. Oliver in 1966 explains very clearly how square-wave signals and brief pulses ("impulse" signals) may be used to test the response of electronic circuits such as amplifiers. In this document the author explains how linear systems may be tested using pure sinusoidal signals of various frequency values (called "steady-state" testing), and then goes on to explain how testing with short-duration "impulse" signals and/or square-wave signals often provides the same useful information in less testing time.

His rationale for using non-sinusoidal test signals to "probe" a linear electronic network is explained in the first two paragraphs of a section of this document entitled *The Response of Linear Systems to Impulses*:

> While steady state measurements are very useful for the reasons pointed out in the last section, they are quite time consuming and for many purposes observing the transient response of the system certain particular types of input waves may provide all the information necessary . . .
>
> Consider, for example, the case where the input, $f(t)$, is an impulse of negligible duration and, say, unit area. The spectrum of such an impulse contains all frequencies at equal amplitude, and in phase in the sense that they all add at $t = 0$. In other words the spectrum is a constant $F(\omega) = 1$. Now by superposition, it obviously makes no difference whether all frequencies are introduced one after the other as in steady state testing, or simultaneously by applying an impulse. The frequencies will all be modified in the same way by the linear system. You might say that an impulse test is equivalent to an instantaneous steady state test. They both give the same information. The problem is merely one of interpreting the results in either case.

Explain what the author of this Application Note means when he says *"an impulse test is equivalent to an instantaneous steady state test"*.

Challenges

- Propose a pulse-generating circuit capable of outputting extremely short-duration impulse signals.

4.2 Quantitative reasoning

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

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

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

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

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

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

4.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.2.2 Introduction to spreadsheets

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.2.3 Gain ratios into decibels

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

- $A_P = 25$; $A_{P(dB)} =$
- $A_V = 10$; $A_{V(dB)} =$
- $A_I = 37$; $A_{I(dB)} =$
- $A_P = 150$; $A_{P(dB)} =$
- $A_I = 41$; $A_{I(dB)} =$
- $A_V = 3.4$; $A_{V(dB)} =$
- $A_P = 18$; $A_{P(dB)} =$
- $A_V = 100$; $A_{V(dB)} =$

Challenges

- Suppose a student mistakenly computes 10 dB for $A_V = 10$ (ratio). Explain what went wrong, and why the correct answer is different.

4.2.4 Decibels into gain ratios

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

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

Challenges

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

4.2.5 Amplifier gains

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

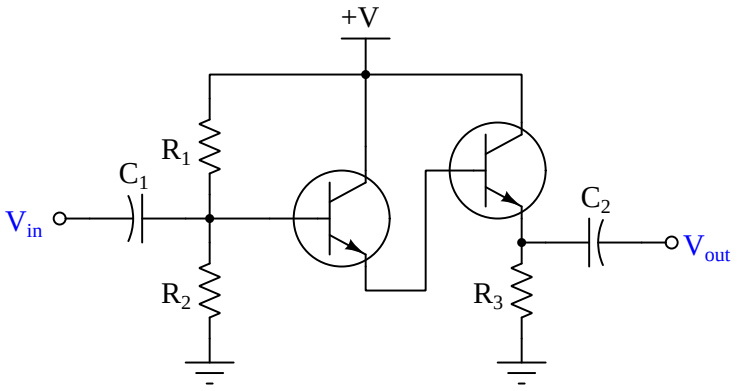
- Power gain (as a ratio) =
- Power gain (dB) =
- Voltage gain (dB) =
- Current gain (dB) =

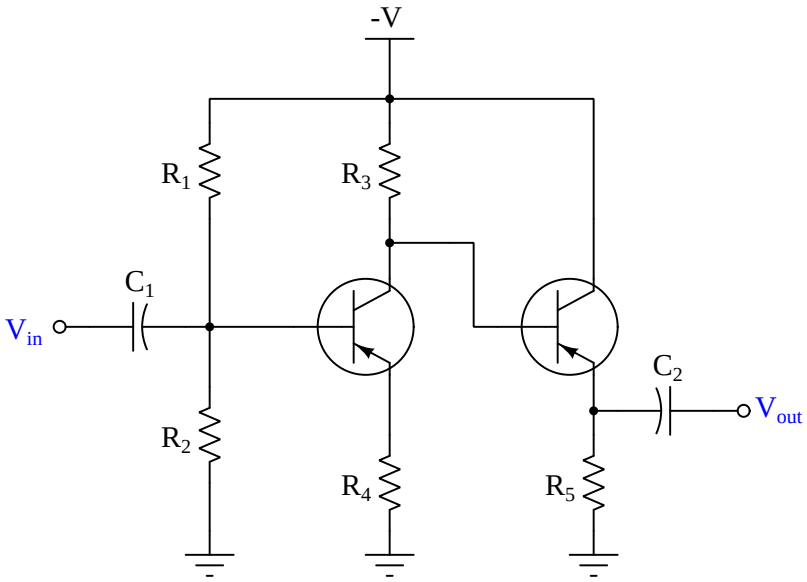
Challenges

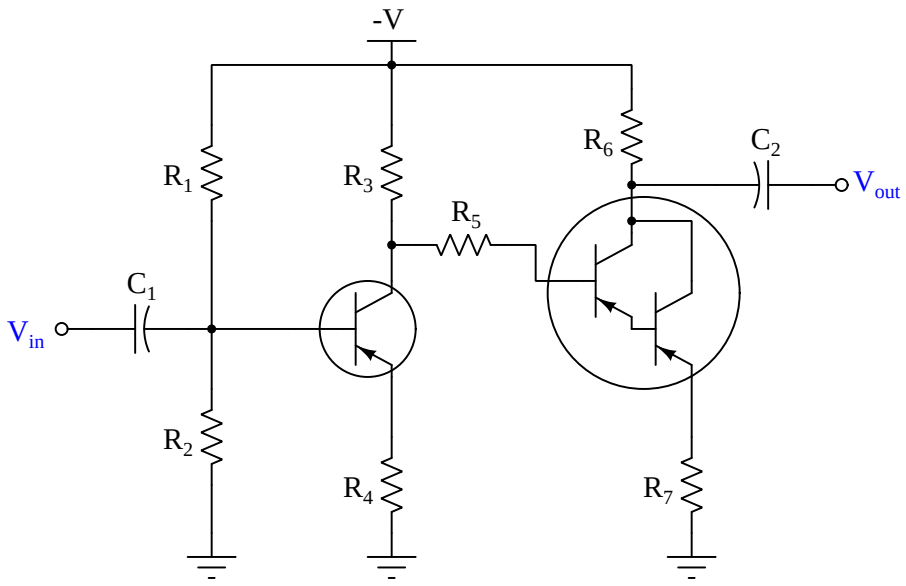
- Suppose a student calculates 6.9897 dB for the voltage gain of this amplifier. Explain where they made a mistake in this calculation.

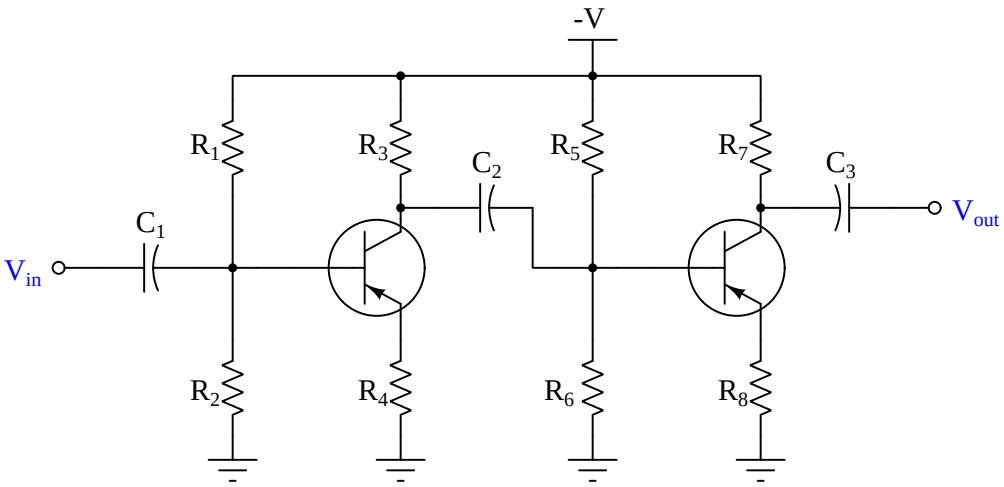
4.2.6 Gains and impedances of multi-stage amplifiers

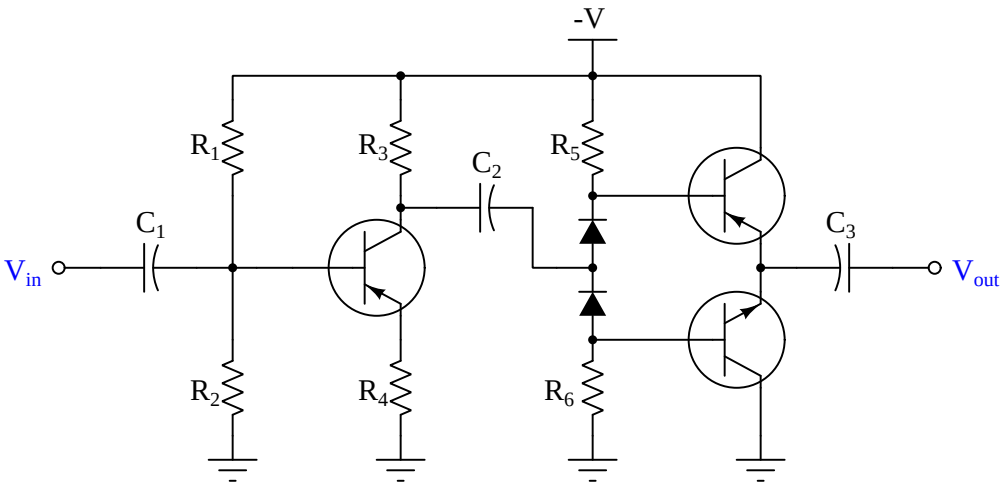
Write a formula estimating the over-all AC voltage gain (ratio) for each of the following multi-stage amplifier circuits, as well as other formulae for each circuit's input and output impedance values:

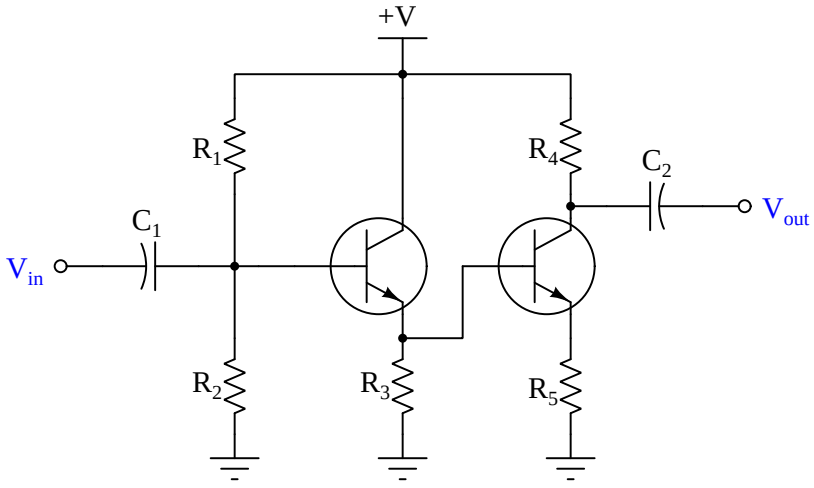





-V
R1
R3
R6
C2
Vout
R5
C1
Vin
R2
R4
R7


-V
R1
R3
C2
R5
R7
C3
Vout
C1
Vin
R2
R4
R6
R8



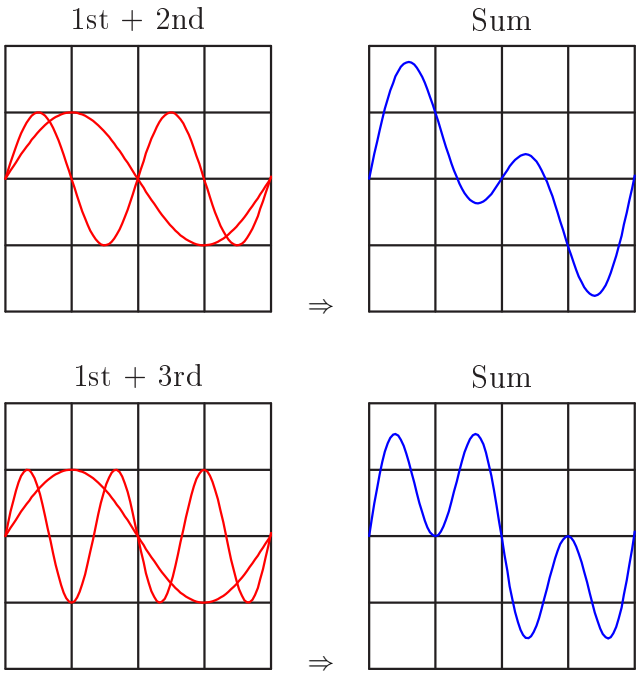


Challenges

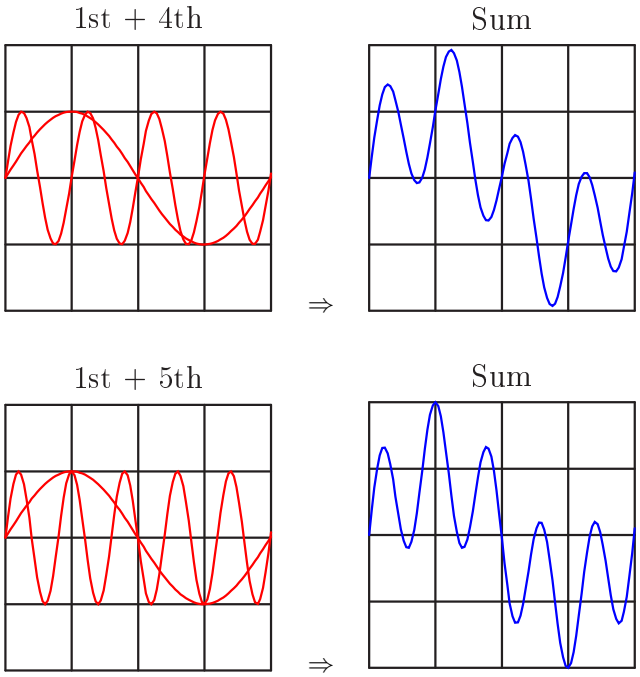
- Identify components that do *not* substantially influence A_V, and explain what their role is in each circuit.

4.2.7 Even versus odd harmonics

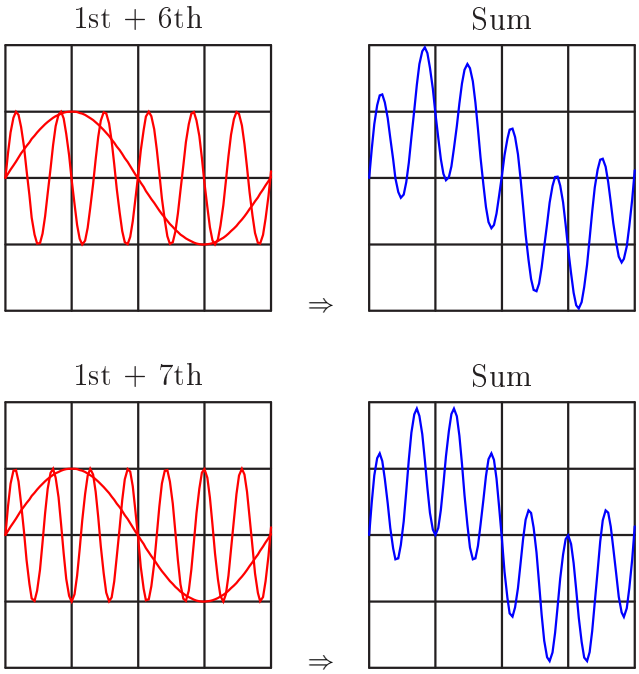
Note the effect of adding the second harmonic of a waveform to the fundamental, and compare that effect with adding the *third* harmonic of a waveform to the fundamental:



Now compare the sums of a fundamental with its fourth harmonic, versus with its fifth harmonic:



And again for the 1st + 6th, versus the 1st + 7th harmonics:



Examine these sets of harmonic sums, and indicate the trend you see with regard to harmonic number and symmetry of the final (Sum) waveforms. Specifically, how does the addition of an *even* harmonic compare to the addition of an *odd* harmonic, in terms of final waveshape?

Challenges

- Identify a practical application of this knowledge.

4.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

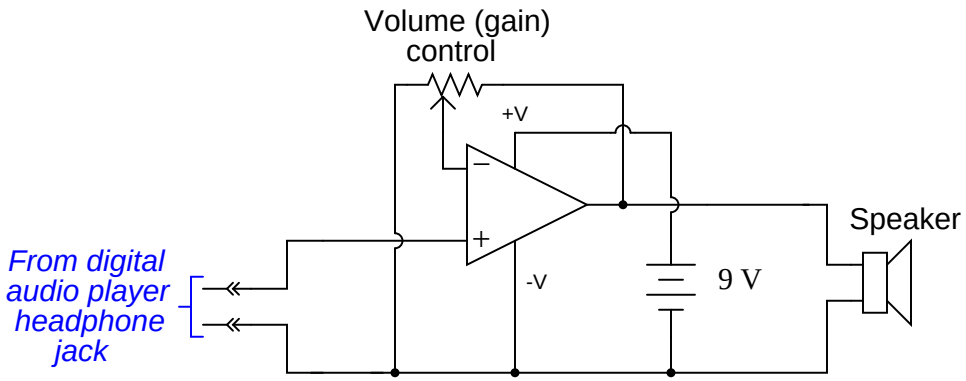
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

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

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

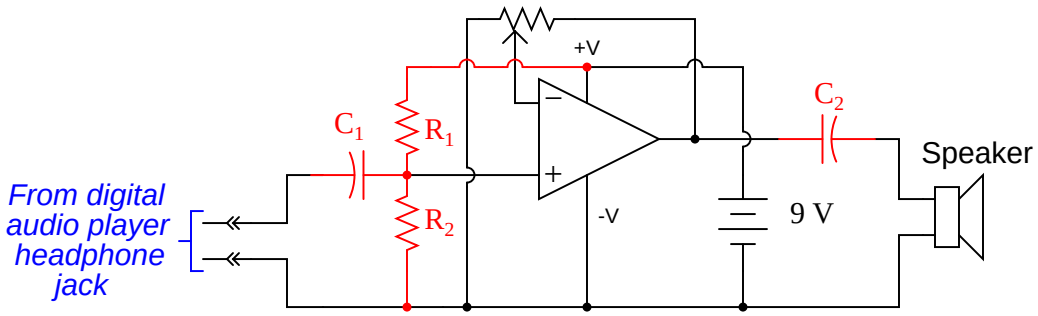
4.3.1 Audio amplifier design improvement

A student wishes to build a variable-gain audio amplifier circuit using an operational amplifier and a potentiometer, to drive a small loudspeaker so he can listen to the output of a digital audio player without having to use headphones:



Before building the project in a finalized form, the student prototypes it on a solderless breadboard to make sure it functions as intended. And it is a good thing he decided to do this before wasting time on a final version, because it sounds terrible!

When playing a song, the student can hear sound through the headphones, but it is terribly distorted. Taking the circuit to his instructor for help, the instructor suggests the following additions:



$C_1 = C_2 = 47\ \mu F$

$R_1 = R_2 = 33\ k\Omega$

After adding these components, the circuit works great. Now, music may be heard through the speaker with no noticeable distortion.

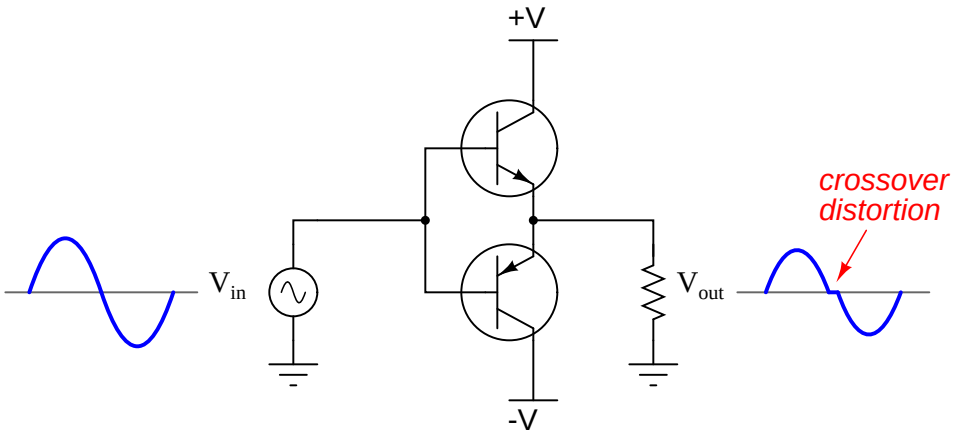
Explain what functions the extra components perform, and why the circuit did not work as originally built.

Challenges

- Another problem this student notes while prototyping his audio amplifier is that he can never turn the volume all the way off. Even at the lowest volume setting, you can still hear some sound from the loudspeaker. Identify the problem, and modify the circuit accordingly to fix it.

4.3.2 Push-pull voltage follower

A complementary push-pull transistor amplifier built exactly as shown would perform rather poorly, exhibiting crossover distortion:



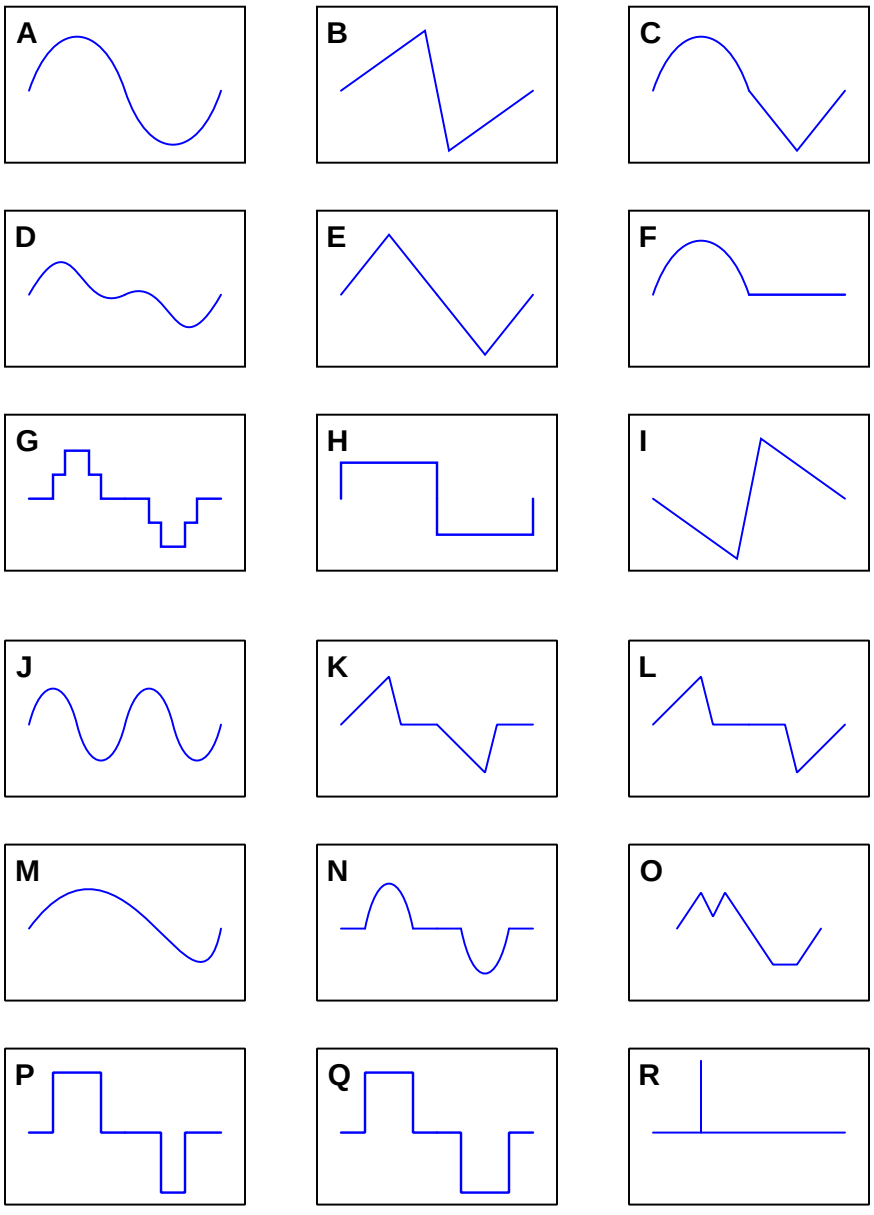
Explain how such distortion would present on the display of a spectrum analyzer.

Challenges

- Propose a design change to this circuit that will eliminate crossover distortion.

4.3.3 Discerning even/odd harmonics from the time domain

By visual inspection, determine which of the following periodic waveforms contain even-numbered harmonics:

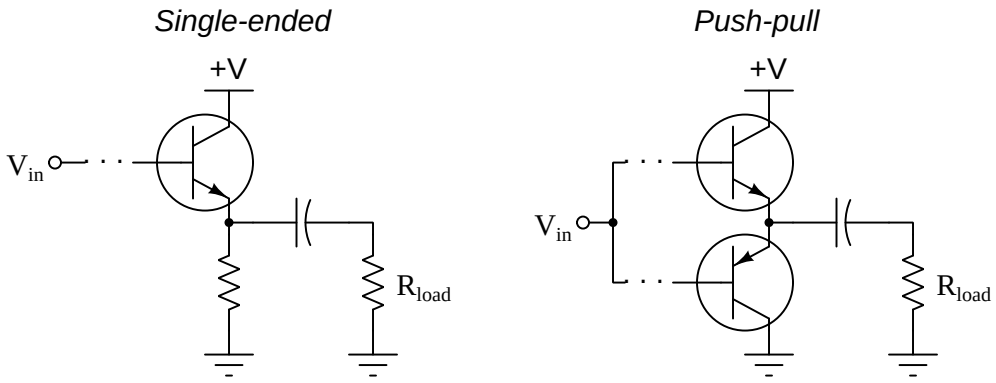


Challenges

- Identify a practical application of being able to discern even/odd harmonics from time-domain plots.

4.3.4 Single-ended versus push-pull amplifier distortion

A criticism of single-ended power amplifier stages versus push-pull power amplifier stages is that the single-ended designs tend to produce more *even-numbered* harmonic distortion:



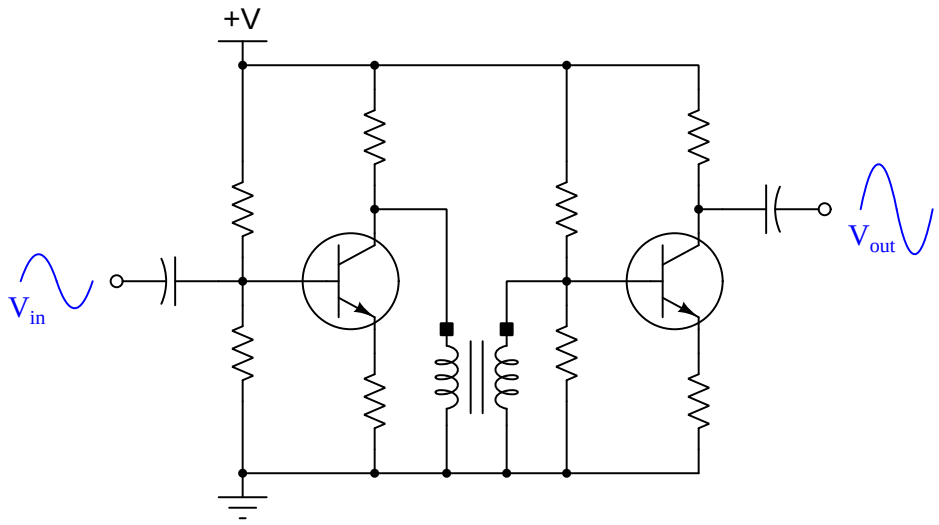
Explain why this is.

Challenges

- What other disadvantage(s) do single-ended power amplifiers have compared to push-pull?

4.3.5 Improving low-end amplifier performance

Suppose this amplifier circuit is tested and found to have insufficient voltage gain at low frequencies. Its mid-range and high-end gains are perfectly acceptable, but its bandwidth "rolls off" too much on the low end:



Identify any modifications that may help.

Challenges

- How could we *measure* roll-off at each stage of this circuit, rather than just at the very end.

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.

27-28 September 2026 – edited multiple schematic diagrams in the Tutorial chapter to include a coupling capacitor between the first amplifier stage and the potentiometer stage. Also changed the title of the Tutorial section "Rejection" to "Amplifier rejection" in order to make it more sensible when doing section-title searches.

11 May 2026 – added content to the "Amplifier impedance" section of the Tutorial discussing Zobel networks. Also corrected a mis-spelling.

25 September 2025 – added some more elaboration on amplifier impedance matching to the Tutorial.

24 September 2024 – minor edit made to image_3305.

17 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.

20-21 January 2024 – added a new Technical Reference section on protecting amplifier inputs against overvoltage from electro-static discharge (ESD) as well as electrical over-stress (EOS) from improperly connected signal sources. Also edited some of the Tutorial text for clarity.

27 September 2023 – elaborated on Class G operation.

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.

3 November 2021 – explicitly stated Fourier's Theorem.

29 September 2021 – corrected a typographical error in the Tutorial, identified by Jacob Stormes.

13 September 2021 – added a one-page section reviewing energy efficiency as it applies to amplifier circuits.

10 May 2021 – commented out or deleted empty chapters.

2 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 November 2020 – added Tutorial section on class of operation.

10 August 2020 – added Tutorial text on gain-bandwidth product (GBW).

11 May 2020 – added a new Quantitative problems showing a variety of different multi-stage amplifiers and asking for formulae estimating the voltage gain and impedances of each.

29 April 2020 – added new Conceptual problems on logic gates, as well as a new Diagnostic problem on improving low-end performance for a transistor-coupled amplifier.

15 April 2020 – added book to Reference list.

27-31 March 2020 – worked on writing Tutorial and other chapters in the document.

26 March 2020 – document first created.

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