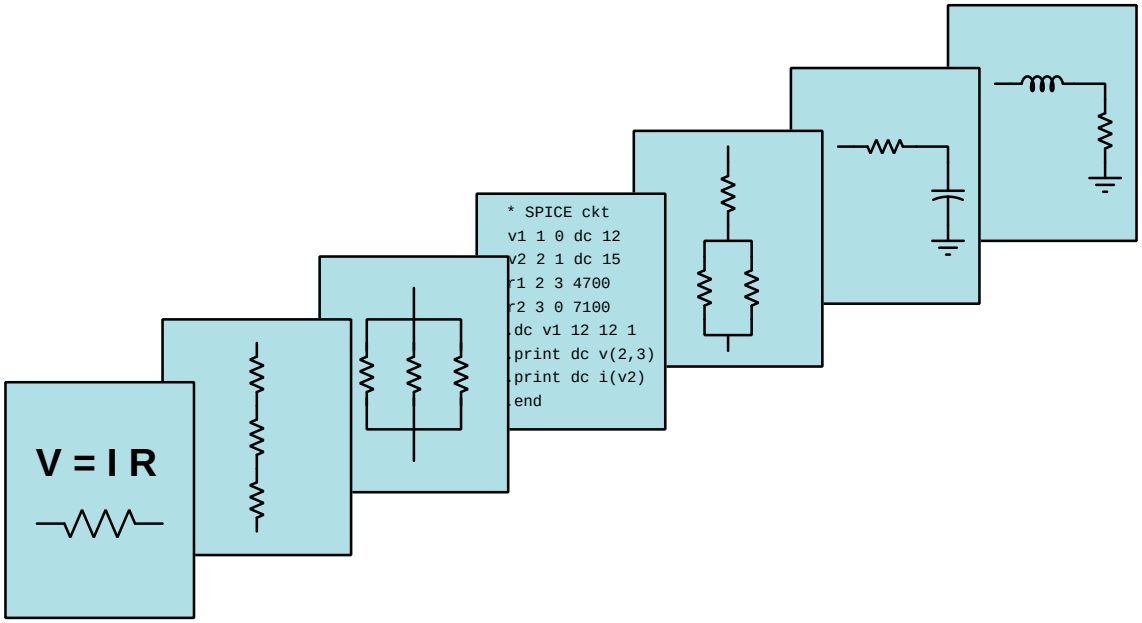
Modular Electronics Learning (ModEL) project



Transistor Biasing

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Chapter 1

Introduction

1.1 Recommendations for students

Transistors are useful for the purpose of *amplification* which is when a relatively small electrical signal exerts control over a relatively large electrical signal. However, they are limited in very important ways, primarily in their inability to control bidirectional currents. That is to say, transistors are *DC-only* devices. This poses a challenge when we wish to amplify AC signals, as the transistor simply cannot handle both polarities of voltage and directions of current. A popular solution to this problem is to *bias* the transistor with a certain amount of DC such that it never fully turns off at any point in time as it amplifies the AC signal. In other words, we "trick" this DC-only device into amplifying an AC signal by offsetting the AC signal with enough DC so that the signal never actually alternates in polarity.

Important concepts related to transistor biasing include **BJT** behavior, **FET** behavior, **AC** versus **DC**, **ground-referenced** versus **differential** voltage signals, **coupling capacitors**, **capacitive reactance**, **Superposition Theorem**, **voltage divider equation**, **filter networks**, **transformers**, **Kirchhoff's Voltage Law**, and **Ohm's Law**.

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

- How might an experiment be designed and conducted to measure the beta ratio for a bipolar junction transistor? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to plot a family of characteristic curves for a bipolar junction transistor? What hypotheses (i.e. predictions) might you pose for that experiment, and what result(s) would either support or disprove those hypotheses?
- Why do simple single-transistor amplifier circuits fail to fully reproduce the waveform of an AC signal?
- How does "biasing" work to solve this problem?
- What are some different methods for providing bias to a transistor amplifier circuit?

- How is the Superposition Theorem useful in analyzing transistor amplifier circuits?
- Why do we replace the transistor with an "open" when applying the Superposition Theorem to an amplifier circuit?
- What is the function of a coupling capacitor in a transistor amplifier circuit?
- What is the function of a transformer in a transistor amplifier circuit?
- How may we estimate the amount of biasing to apply to any particular amplifier circuit?
- What does it mean for an amplifier circuit to *clip*?
- What does the term *quiescent* mean for an amplifier circuit?
- How may we empirically determine that an amplifier circuit has been properly biased?
- Can a capacitively-coupled amplifier circuit amplify AC signals only, DC signals only, or both types of signals?
- Can a transformer-coupled amplifier circuit amplify AC signals only, DC signals only, or both types of signals?

1.2 Challenging concepts related to transistor biasing

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

- **Superposition of signals** – any linear-behaving circuit with multiple sources may be analyzed one source at a time, the results of those analyses simply added together to determine the composite result. We use this principle extensively in transistor circuit analysis where we have quiescent DC values superimposed on AC signals. Although transistors are not perfectly linear in their behavior, when properly biased for amplifier usage they are linear enough for superposition to yield approximately correct results.

- **BJT beta** – the "beta" (β or h_{FE}) value for a bipolar junction transistor predicts the number of electric charge carriers that are allowed through its collector terminal for every one charge carrier passing through its base terminal. While not particularly stable over different operating conditions, this amplification factor for a BJT is nevertheless useful in making approximate current calculations for BJT-based circuits. One important caveat of beta is that it represents an *upper limit* (i.e. *maximum*) collector-to-base current ratio. If the collector-emitter voltage drop is low enough, it is possible for the transistor to pass less current through its collector terminal than beta would predict, in which case we say the transistor is "saturated".

- **Necessary conditions for transistor operation** – bipolar junction transistors require a base current in the proper direction to inject minority carriers into the base layer (i.e. PNP transistors require hole injection from emitter to base, and so the emitter must be made positive and the base made negative, relative to each other; NPN transistors require electron injection from emitter to base, and so the emitter must be negative and the base positive.), and the collector-to-emitter voltage must be of the correct polarity (i.e. so that collector terminal current goes in the same direction as base terminal current, either *out* or *in*). Both currents join at the emitter terminal, making the emitter current the sum of the base and collector currents.

- **Signal inversion** – some transistor circuits have an "inverting" characteristic in which a rising input signal results in a falling output signal. This is not necessarily obvious upon first inspection, but a good way to make the concept clearer is to run "thought experiments" on the circuit with multiple values of V_{in}, computing the value of V_{out} for each scenario, and seeing for yourself the effect one signal has on the other.

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 section on proper biasing levels.

  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** – Apply the concept of superposition to transistor circuits

  Assessment – Demonstrate how a transistor amplifier circuit may be simplified (i.e. components eliminated) by analyzing it in terms of its multiple sources considered one at a time.

- **Outcome** – Apply foundational DC circuit concepts to transistor circuits

  Assessment – Calculate quiescent (DC) voltage and current values for a transistor amplifier circuit given component values; e.g. pose problems in the form of the "Quiescent base current" Quantitative Reasoning question.

- **Outcome** – Independent research

  Assessment – Locate bipolar transistor datasheets and properly interpret some of the information contained in those documents including maximum power dissipation, maximum base current, range of beta values (often shown as h_{FE}), etc.

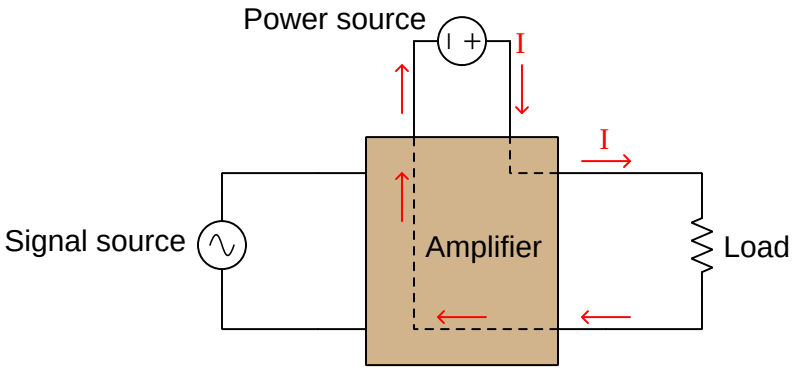
  Assessment – Locate JFET datasheets and properly interpret some of the information contained in those documents including maximum power dissipation, pinch-off voltage (gate-to-source), transconductance, etc.

Chapter 2

Tutorial

2.1 Transistors as amplifiers

Electronic circuits are a distinct class of electric circuits based on the inclusion of *active* devices permitting one electrical signal to exert control over another electrical signal. If the controlled signal's magnitude exceeds that of the controlling signal, which is usually the case for active devices, we say that device functions as an *amplifier*. This term, amplification, is somewhat misleading because it seems to imply a signal becoming expanded or magnified. The truth of the matter is that an amplifier functions by re-directing an external energy source according to the whim of a controlling (input) signal, directing that energy source to be a likeness of the controlling signal's image:



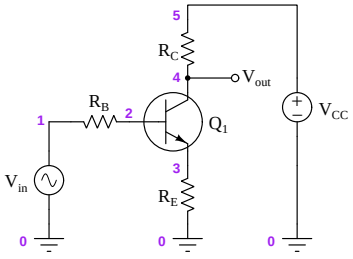
A number of different electronic devices function as amplifiers, the most common being called *transistors*. Two major categories of transistor include the *bipolar junction transistor* (BJT) and the *field-effect transistor* (FET), each with its own operating principle. BJTs function on the basis of minority charge carriers being injected into a region of the transistor formerly depleted of most charge carriers, with a greater injection rate translating into greater end-to-end conductivity. FETs function on the basis of majority charge carriers passing through a channel whose cross-sectional area may be varied by the application of a static-electric field, with an "enhancing" electric field making the channel larger and thus more conductive from end to end.

As the above illustration suggests, the task of an amplifier (in many practical cases) is to reproduce an *alternating-current* (AC) signal from a *direct-current* (DC) power source, and to do so using active components that are only capable of unidirectional current flow (vacuum tubes, BJTs, and most FETs). Key to doing this is to maintain the active device(s) in a state of continual conduction for the entirety of the input signals wave-shape. The most practical method of achieving this goal is to *bias* the active device in such a way that it defaults to a half-way-on state of conduction with no input signal, which means a positive input signal pushes the active device to be either more or less conductive and a negative input signal polarity to do the opposite.

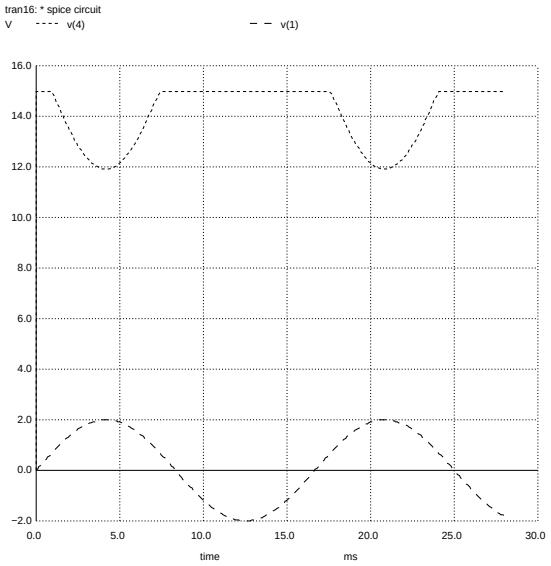
In the following sections of this Tutorial we will explore how transistor-based amplifier circuits fail to work without this biasing, how they perform much better with biasing, and various ways of properly biasing an amplifier circuit.

2.2 BJT biasing

Most active devices happen to function only with direct-current (DC) electrical signals, and this fact poses a problem for any application requiring the amplification of alternating-current (AC) quantities. Consider the following BJT amplifier simulated using SPICE computer software:




```
* SPICE circuit
vin 1 0 sin (0 2 60 0 0)
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
```



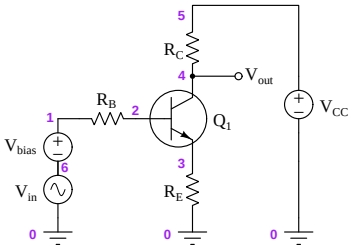
Note how the AC input voltage (V_{in}) at node 1 appears as a clean sine wave on the SPICE plot, but the output voltage (V_{out}) at node 4 (both voltages measured with respect to ground, node 0) is anything but. The output signal reaches its negative peaks at the same moments in time the input signal attains its positive peaks, but the two wave-shapes are otherwise dissimilar.

Let's figure out why V_{out} is so strange-looking. This is an NPN transistor, which means the emitter (node 3) must inject electrons into the P-type base (node 2) in order to make the transistor conduct current between its collector and emitter terminals (nodes 4 and 3). In order to inject electrons from emitter to base, the emitter must be negative with respect to the (positive) base. Thus, this transistor can only turn on when the AC input source is positive on top and negative on bottom. Every half-cycle when the signal source's polarity reverses the transistor will be receiving the wrong base-emitter polarity and therefore cannot turn on. Under the best conditions, then, the transistor is guaranteed to be completely off (thus making node 4 equal to DC supply voltage) during every negative half-cycle of the AC signal. What is more, the transistor cannot even turn on until its base-emitter voltage reaches approximately 0.7 Volts in the correct polarity, which means only *part* of the AC signal's positive half-cycle will ever be enough to turn the transistor on. Most of the AC signal is "unintelligible" to this amplifier circuit, and so cannot be replicated at the output terminal.

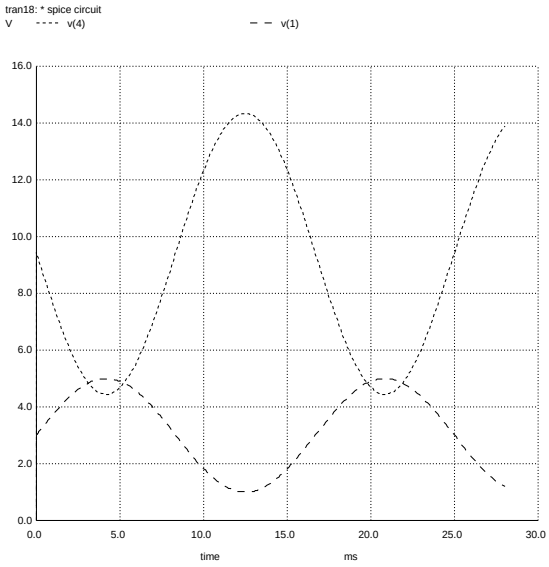
If a BJT is a DC-only device, capable of conduction only in one polarity, then how can we possibly force it to amplify an AC signal? There is a solution, and that is to make the AC signal remain the same polarity all the time. This may seem like a contradiction in terms, since the "A" in "AC"

stands for *alternating* (polarity), but the proposal makes sense if we consider shifting the AC signal upward on the graph so that it never dips below the zero line and becomes a *sinusoidally-varying DC signal*.

Consider the following example, where we insert a 3 Volt DC "bias" source in series[1] with the AC signal source to offset that signal voltage above zero:




```
* 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
```

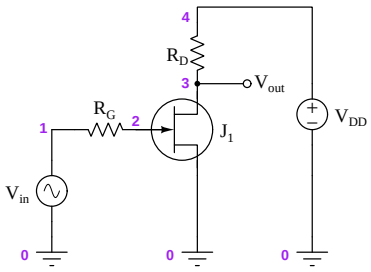


With this bias voltage in place, the transistor is able to remain on at all times, and as a result V_{out} now resembles the same wave-shape as V_{in}, albeit in inverted form. The signal's biasing is clearly evident by viewing `v(1)` in the SPICE plot: the sine-wave signal peaks at a high value of 5 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 keeps the transistor on to varying degrees at every point in time, thus allowing it to faithfully reproduce the AC wave-shape at the circuit's output.

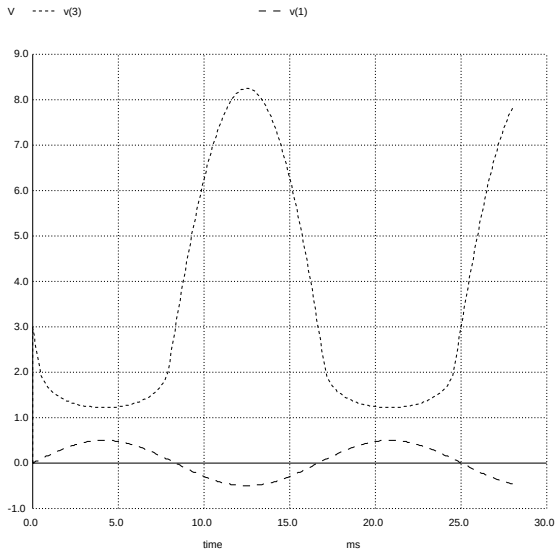
[1] Alternatively, we could have simply edited the `vin` line of the SPICE netlist to say `vin 6 0 sin (3 2 60 0 0)` instead of `vin 6 0 sin (0 2 60 0 0)`, since the first argument passed to SPICE's "sine" function is its DC offset value. However, showing the DC bias voltage as its own separate source connected in series with the AC signal source more closely mimics the real-world implementation where the AC signal source may not be capable of producing its own DC bias.

2.3 JFET biasing

We encounter a similar problem if we attempt to apply an unbiased AC voltage signal to a junction field-effect transistor (JFET) amplifier circuit:




```
* SPICE circuit
vin 1 0 sin (0 0.5 60 0 0)
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
```



Here, our SPICE simulation shows a highly distorted output waveform, with the distortion clearly evident in each negative peak of V_{out}. The input and output signal waveforms should be 180 degrees out of phase with each other, and *both* sinusoidal if the amplifier is functioning well.

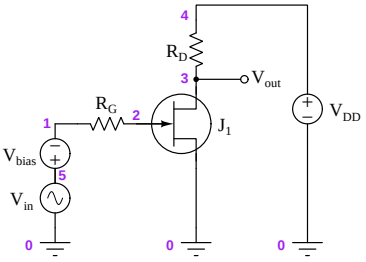
Once again we must revisit the fundamental operating principle of the transistor in question to determine why the output wave-shape is distorted. All field-effect transistors (FETs) work on the principle of a conductive channel's cross-sectional area becoming wider or narrower with the influence of a transverse electric field. In this case, the FET is a *junction* field-effect transistor (JFET) with an N-type channel, and the controlling electric field exists between the gate and source terminals across a PN junction. JFETs are supposed to be operated with the PN junction reverse-biased, as it is the depletion region between the P and N materials which expands or contracts to modulate the channel's area. As the reverse-bias voltage between gate and source terminals grows stronger, the depletion region expands and chokes off the channel to restrict the flow of majority charge carriers through that channel. Forward-biasing the gate-source PN junction of a JFET does little[2] to enhance the channel's area because in a zero-bias condition the channel is already fairly conductive.

This particular JFET is an N-channel type, which means the gate connects to a P-type semiconductor region. Correct reverse-biasing of this PN junction demands the gate be more negative than the source at all times. Looking at the SPICE plot, we see the distortion happens on every *positive* half-cycle of V_{in}, when the transistor's gate-source PN junction is forward-biased rather

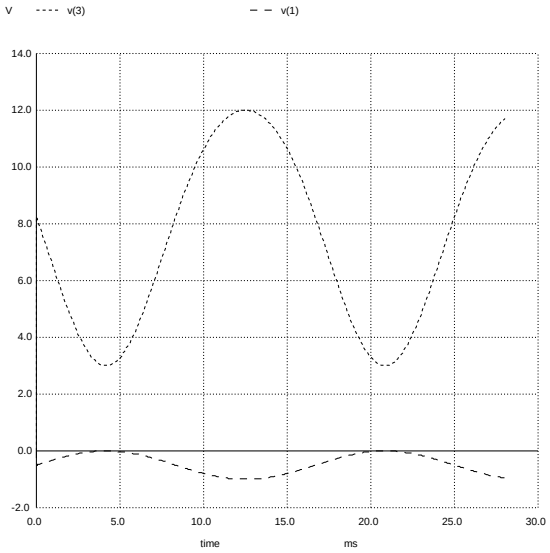
[2] In fact, even small amounts of forward-biasing of a JFET's PN junction may damage it because it is not constructed to carry substantial current!

than reverse-biased. During the negative half-cycles of V_{in}, the wave-shape of V_{out} looks far less distorted. Clearly, the JFET's gate is being forward-biased when it should never be.

Applying the same solution explored in the BJT circuit, we may maintain the JFET's gate-source PN junction in a constant state of reverse-bias by shifting the AC input signal downward so that it is always negative with respect to ground. As before, this is easy to simulate by inserting a DC voltage source in series with the AC source. With a DC "bias" source in place, the aggregate input signal will be a superposition of AC and DC rather than an *alternating*-polarity signal, and this should "trick" the transistor into functioning properly throughout the entire signal wave-shape:




```
* 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
```



Properly biasing the input signal keeps the transistor actively restricting drain current at all times, and as a result V_{out} is a much closer[3] reproduction of V_{in} (with a 180 degree phase shift). The signal's biasing is clearly evident by viewing `v(1)` in the SPICE plot: the sine-wave signal peaks at a maximum value of 0 Volts and a minimum value of -1 Volt. The "AC portion" of this signal still has a peak-to-peak value of 1 Volt, but the biasing moves its center value to -0.5 Volts so that it never rises above zero to forward-bias the JFET.

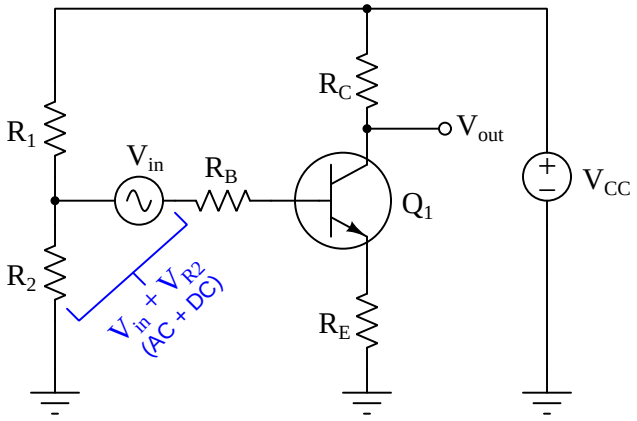
It is important to note the practical difficulty in determining an appropriate value for V_{bias} for any FET amplifier design due to variations from one FET to another. Unlike BJTs where the base-emitter forward voltage drop is fairly close to 0.7 Volts over a wide range of conditions, the threshold voltage, transconductance, and other performance parameters of JFETs tend to vary significantly from transistor to transistor, and also vary as a function of other parameters such as temperature. The insertion of a precise V_{bias} source is just a proof-of-concept test of our simulated JFET amplifier circuit.

[3] Interestingly, a JFET-based amplifier of such simple design cannot precisely replicate the input wave-shape because the transistor's active behavior is fundamentally nonlinear. To be precise, field-effect transistors are *square-law* devices, which means drain current is proportional to the mathematical *square* of the applied gate-to-source voltage rather than being directly proportional to V_{GS}. Expressed mathematically, $I_D = k(V_G - V_T)^2$.

2.4 Biasing networks

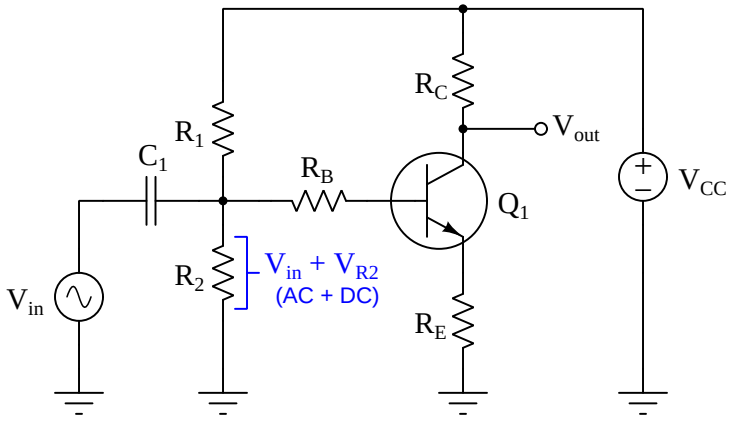
Clearly, judicious biasing is a practical solution to the problem of forcing a transistor to amplify an AC signal, but how is this done in practice? Inserting independent DC voltage sources into amplifier circuits in the form of batteries would be impractical. It would be convenient to exploit the presence of the DC power supply voltage since it is already present in the circuit, but how?

One solution would be to add a voltage divider network to the amplifier circuit, and connect the AC input source's reference terminal to it instead of ground:



With the voltage divider formed by R_1 and R_2, the input signal's DC bias is effectively offset by the voltage drop across R_2. While this strategy certainly would work to bias the transistor without requiring the addition of a DC source to the circuit (rather, just the addition of two resistors), it is clumsy in one regard: the AC signal source can no longer be *ground-referenced*. In many cases it is preferable to have all signal input and output voltages referenced to ground (i.e. one pole of each signal being electrically common to ground).

A clever alternative to this design is to once again ground-reference the AC input source, but couple it to the voltage divider through a capacitor, the value of this "coupling capacitor" chosen to yield a negligible AC reactance compared to the voltage divider's resistances:



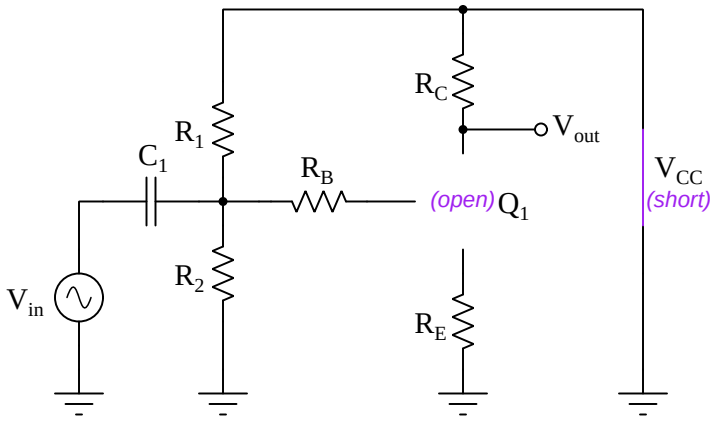
The coupling capacitor presents an "AC-only pathway" for V_{in}'s signal to reach the transistor's base terminal while allowing a DC voltage established by the voltage divider network of R_1 and R_2 to bias the transistor in a partially-on state, the end-result being a base-to-ground voltage and base current that is a mixture of AC (input signal) and DC (bias).

One way to understand the function of this capacitor/divider network is to apply the *Superposition Theorem*:

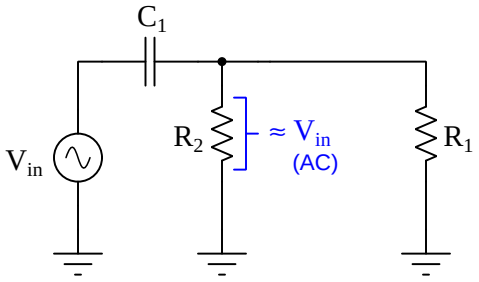
> **Any given voltage or current in a multi-source network is equal to the sum (superposition) of that same voltage or current resulting from each source considered one at a time.**

If we consider the effect of each source in this circuit, one at a time, while the other source is "disabled", and then superimpose those two sets of effects, we may more easily understand their combined effects. The next two pages show the Superposition Theorem applied in this manner, first by considering the effects of just V_{in} and next by considering the effects of just V_{CC}.

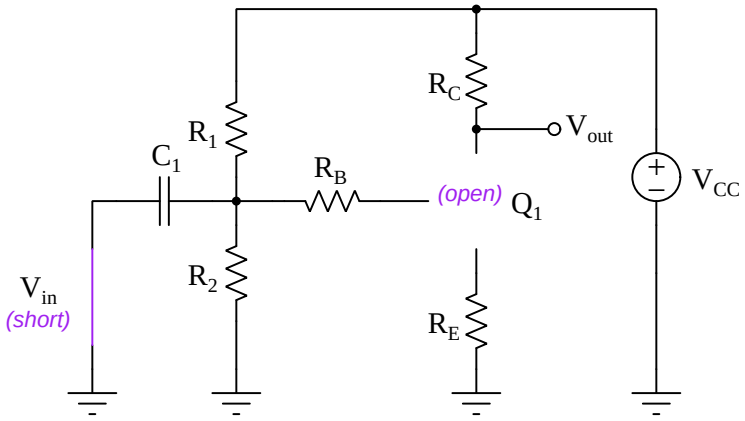
Here we will consider the voltage drop across resistor R_2 (i.e. the signal input to the amplifier) as the sum of the AC source's effect plus the DC power supply's effect. First we will consider the AC source's effect, replacing all other sources in the circuit with their equivalent internal resistances. This substitution includes the BJT which functions as a current regulator in its linear or "active" operating mode (and therefore exhibits the same internal resistance – infinite – as a current source):



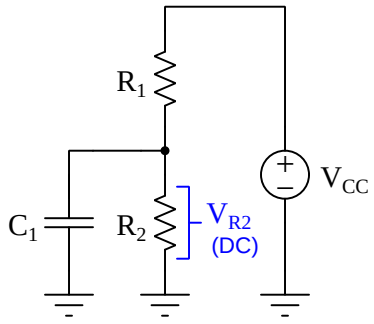
Re-drawn, this circuit is equivalent to a simple RC network, where practically all the AC signal's voltage gets dropped across R_2 assuming capacitive reactance is far less than the parallel-equivalent resistance of R_1 and R_2 (i.e. assuming $X_{C1} << R_1||R_2$):



Next, we consider the voltage drop across R_2 with just the DC power supply active:



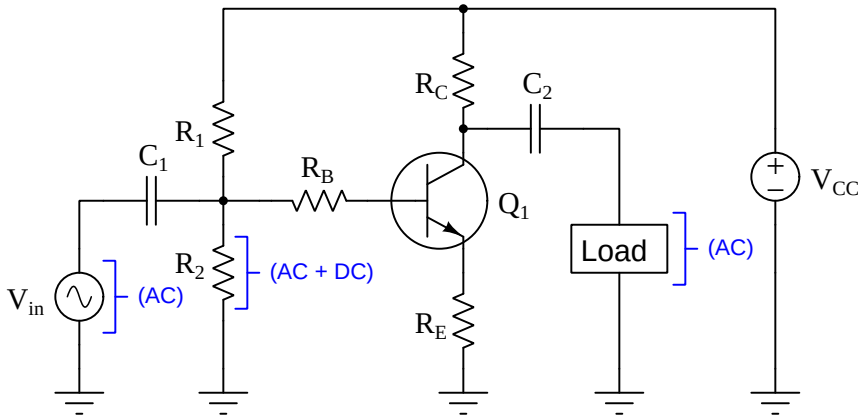
Re-drawn, this circuit is equivalent to a simple RC network where after a short time delay the voltage across R_2 stabilizes very nearly[4] at the value predicted by the voltage divider equation, where $V_{R2} = V_{CC}\left(\frac{R_2}{R_1+R_2}\right)$:



With these two results superimposed on each other, the voltage dropped across R_2 with both AC and DC sources active will be the sum of the AC signal plus the voltage divider's V_{R2}. Therefore, this simple combination of two resistors and one capacitor gives us the DC biasing we need for proper amplification as well as the ability to maintain a ground-referenced signal source.

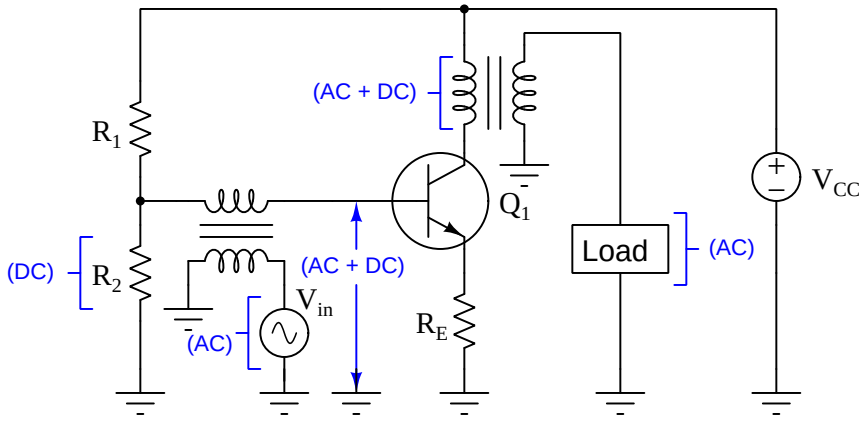
[4]The assumption that the transistor appears as an "open" to the biasing network is not completely true. We know that a small amount of current does indeed pass through the transistor's base terminal, and as a result the R_1/R_2 voltage divider network will experience some voltage "sag" because it is powering a load. Thus, the bias voltage across R_2 will be slightly *less* than what the simple voltage divider formula would predict ($V_{R2} = V_{CC}\left(\frac{R_2}{R_1+R_2}\right)$). The bulk of this loading will be caused by the resistance of R_E as seen "through" the transistor's base terminal, and this "image" of R_E will be approximately $\beta + 1$ times larger than R_E itself due to the transistor's current-amplification behavior. Correcting the voltage divider formula for this additional resistance value, we get $V_{R2} = V_{CC}\left(\frac{R_2||(\beta+1)R_E}{R_1+(R_2||(\beta+1)R_E)}\right)$. The inclusion of the $(\beta+1)R_E$ terms doesn't substantially alter the predicted bias voltage for most circuits because $(\beta+1)R_E >> R_2$ (i.e. the parallel equivalent of $(\beta+1)R_E$ and R_2 is only *slightly* less than R_2 alone), and so it is usually safe to use the simple voltage divider formula.

Interestingly, we may use the same "coupling capacitor" strategy to filter out the AC component of the mixed AC+DC output signal for the purpose of having the amplifier drive a load with a purely AC signal. A complete BJT amplifier circuit with AC coupling on input and output, therefore, would resemble the following:



At both the input and output of this amplifier, the respective coupling capacitor acts as a *high-pass filter* allowing the AC signal to pass through but blocking the DC bias. This allows the AC signal source to operate free of any DC bias imposed by the amplifier, and it also allows the load to experience only AC with no DC.

Other clever methods exist to couple AC signals into and out of a DC-biased amplifier circuit besides capacitors. One such alternative is to use signal transformers:

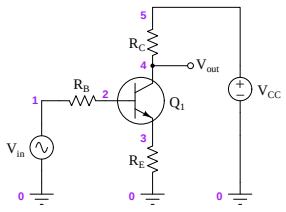


Transformers, of course, work on the principle of electromagnetic induction whereby a *varying* magnetic field links with a coil of wire to induce a voltage. Since induction only occurs when the magnetic field varies in strength (i.e. the induced voltage is proportional to the *speed* at which the field strengthens or weakens), only the AC portion of a mixed AC+DC signal passes through from primary to secondary windings. Transformers are less popular for signal coupling in amplifier circuits due to their bulk, expense, and parasitic properties[5], but they do confer the advantage of *complete electrical isolation* between the signal source, amplifier circuit, and load (i.e. there are no conductive pathways connecting these three portions of the circuit) which may be important in certain applications.

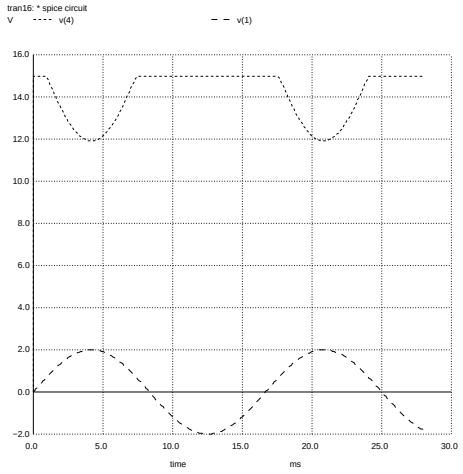
[5]Since transformers typically require many turns of wire wrapped around a ferrous core, they present significant parasitic capacitance, equivalent resistance in the forms of wire resistance as well as magnetic losses, and "leakage" inductance from lines of magnetic flux that do not fully couple from one winding to the next.

2.5 Proper biasing levels

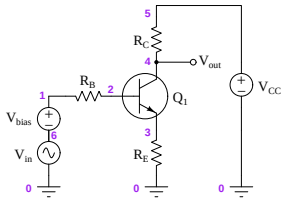
Clearly, proper biasing is necessary to force unidirectional components such as transistors to amplify AC signals. A question we have left unanswered up until now is *how much biasing is appropriate?* We need to explore the ill effects of insufficient bias and of excessive bias by computer simulation to fully understand the problem. First, the simple BJT amplifier with no DC biasing we saw earlier in this tutorial:



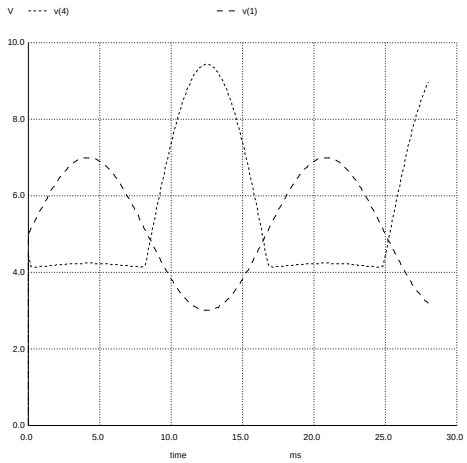

```
* SPICE circuit
vin 1 0 sin (0 2 60 0 0)
vcc 5 0 dc 15
rc 5 4 3300
rb 1 2 10000
re 3 0 1200
q1 4 2 3 qmod
.model qmod npn
.tran 0.1m 28m uic
.plot tran v(1) v(4)
.end
```



Now, let's compare with an example having *too much* bias:




```
* SPICE circuit
vin 6 0 sin (0 2 60 0 0)
vbias 1 6 dc 5
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
```



Carefully compare the previous SPICE simulations, the first with 0 Volts of bias and the second with 5 Volts of DC bias. In the unbiased amplifier, only the positive peaks of the AC signal were reproduced at the output because the rest of the time the transistor was completely "cut off" which meant it dropped full source voltage (15 Volts). In the over-biased amplifier, only the negative peaks of the AC signal were reproduced because the rest of the time the transistor was "saturated" in its fully-on state which meant it dropped very little voltage[6] between collector and emitter. In both cases we see a "clipped" output waveshape. The goal of proper biasing for this amplifier, then, must consist of finding the right amount of DC bias voltage to avoid both transistor cutoff *and* transistor saturation throughout the AC input signal's full waveform.

Good biasing may, of course, be found by experiment: simply make the DC biasing adjustable[7] and determine by trial-and-error what range of values avoids signal "clipping". However, we may also estimate an appropriate bias voltage value by calculation. The founding assumption of this calculation approach is that the transistor should be exactly *half-on*[8] when the AC signal crosses zero. In other words, with the amplifier's input *only* experiencing V_{bias} and no AC signal, the transistor's state should be mid-way between its two extremes of cutoff and saturation. This should provide the most "headroom" or "margin" to accommodate both halves of the AC signal's waveform. Therefore, our calculation procedure should begin with amplifier being in a *quiescent* (i.e. "resting") state where the DC bias voltage is the only signal input to the amplifier, and with that amount of applied DC input voltage the transistor should be half-on.

Defining what constitutes "half-on" for the transistor depends entirely on the transistor's DC supply voltage and the resistors connected to its collector and emitter terminals. When cut off, the transistor should drop the entirety of V_{CC} between collector and emitter and pass no current; when saturated "fully on", the transistor should drop nearly zero voltage and pass as much current as V_{CC} and R_C and R_E will allow. It should make sense for a "half-on" transistor's voltage and current values to be mid-way between those extreme limits.

For our example circuit where V_{CC} is 15 Volts, we would expect V_{CE} to be 15 Volts at cutoff and nearly 0 Volts[9] at saturation, therefore "half-on" should be when V_{CE} is approximately 7.5 Volts. The remaining 7.5 Volts is split between R_C and R_E, and with base current being so small compared to emitter or collector current we may for the sake of simplicity assume $I_C = I_E$ which means V_{RC} and V_{RE} should be proportional to their resistance values. 7.5 Volts dropped across a combined total of 4500 Ohms[10] yields a quiescent current of 1.667 milliAmperes for I_C and I_E alike. Applying Kirchhoff's Voltage Law to the base-emitter circuit loop where V_{bias} is the only source and where I_B is assumed to be negligible means that V_{bias} must be the sum of V_{RE} and the 0.7 Volt V_{BE} PN-junction voltage drop. Ohm's Law tells us V_{RE} must be approximately 2 Volts ($V = IR$ where $I = 1.667$ mA and $R = 1200\ \Omega$), which means V_{bias} will need to be approximately 2.7 Volts.

[6] You will notice from the SPICE plot of `v(4)` that the output signal rests slightly greater than 4 Volts during each of its "flat" portions. Since V_{out} is measured between nodes 4 and 0, this voltage constitutes the drop between the transistor's collector and emitter terminals *plus* the drop across resistor R_E. With 5 Volts being sufficient to saturate the transistor, it leaves approximately 4.3 Volts across R_E (i.e. 5 Volts − 0.7 Volts V_{BE}). Added to the negligible drop across nodes 4 and 3, we would expect the output signal voltage to be slightly greater than 4 Volts in this condition.

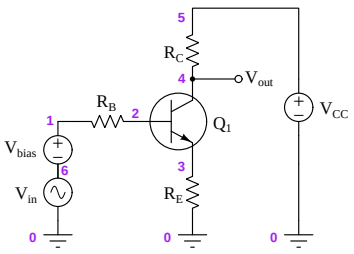
[7] If using a pair of resistors to form a voltage divider network for V_{bias}, the resistor pair may be replaced by a potentiometer.

[8] Or half-off, depending on your world-view and general optimism.

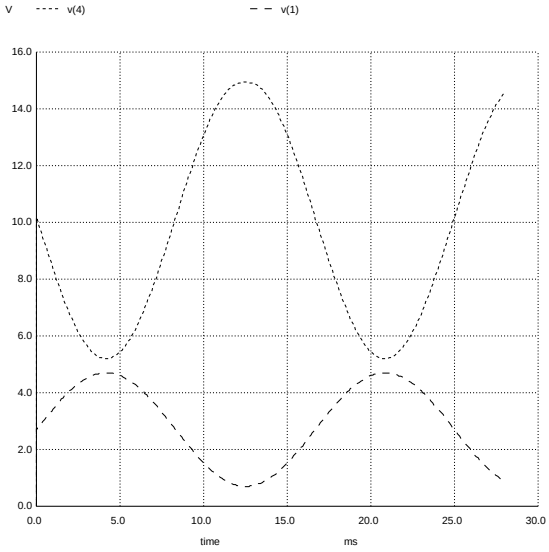
[9] A safe assumption is 0.3 Volts for most bipolar junction transistors, but this small amount of voltage has little impact on the bias estimate and so we will ignore it for simplicity's sake. If we include the 0.3 Volt V_{CE} drop in our calculations, we end up with a predicted V_{bias} of 2.66 Volts instead of 2.70 Volts.

[10] 3300 Ohms R_C plus 1200 Ohms R_E in series with each other.

Re-simulating our BJT amplifier circuit with this calculated V_{bias} value of 2.7 Volts, we obtain the following results:




```
* SPICE circuit
vin 6 0 sin (0 2 60 0 0)
vbias 1 6 dc 2.7
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
```



As you can see, these results are quite similar to those obtained earlier in the simulation using a 3 Volt V_{bias}.

Chapter 3

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

3.1 Vacuum-tube telephony amplifier biasing

Early telephone systems designed, built, and maintained by the Bell Telephone company used vacuum tubes as electronic amplifying elements, and amplifiers using vacuum tubes required biasing just as amplifiers using transistors, and for the exact same reasons. Both vacuum tubes and transistors are unidirectional (i.e. DC-only) devices, and as such cannot convey true alternating-current (AC) signals.

An article in Volume 1 of the *Bell System Technical Journal* (circa 1922) by James Pilliod revealed schematic diagrams of the tube-based amplifier circuits used to boost (or "repeat") the power of weak telephony signals. The schematic diagram shown below (on the left-hand wide) and a corresponding photograph of a vacuum tube (on the right-hand wide) comes from that article:

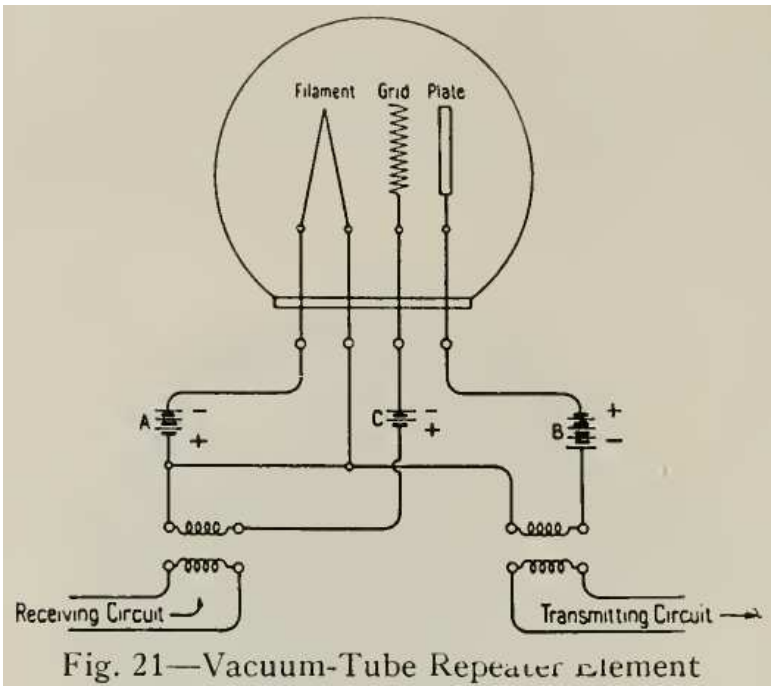


Fig. 21—Vacuum-Tube Repeater Element

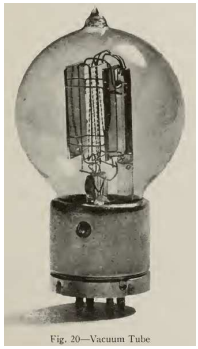


Fig. 20—Vacuum Tube

Interestingly, the + and − polarity symbols shown in this diagram are correct, but the battery component symbols are mis-drawn (where the long-line sides should all be + and the short-line sides should all be −). Battery A provides excitation to the vacuum tube's filament, which must be maintained at a high temperature in order to emit free electrons into the vacuum space between the filament and plate. The plate is maintained at a positive polarity (compared to the filament) by battery B to attract negatively-charged electrons toward it through the vacuum. The grid is a metal screen placed between the filament and plate, with any voltage between it and the filament regulating the flow of electrons through the spaces in-between the grid wires from the filament to the plate.

This amplifier receives its AC input signal through the left-hand signal transformer. That

transformer's secondary voltage appears between the grid and filament, modulating[1] the flow of electrons from filament to plate. As the AC input signal varies over time, so does the plate's current. This time-varying current passes through the primary winding of the right-hand signal transformer, inducing an AC voltage at the secondary winding which constitutes the amplified ("repeated") signal.

Biasing for the vacuum tube comes from battery C, offsetting the grid's potential to be more negative than it would be otherwise. This is necessary because vacuum tubes behave much like N-channel junction field-effect transistors (JFETs) where a larger range of control exists on the depletion side than the enhancement side of the device's characteristic curve. Without some negative biasing, this amplifier would likely distort the AC signal, resulting in "rounding" or even "clipping" of the waveform with each positive peak of the input signal.

[1] A negatively-charged grid (with reference to the filament) repels negatively-charged electrons and thereby restricts their motion toward the plate. A positively-charged grid attracts electrons to accelerate them toward the plate.

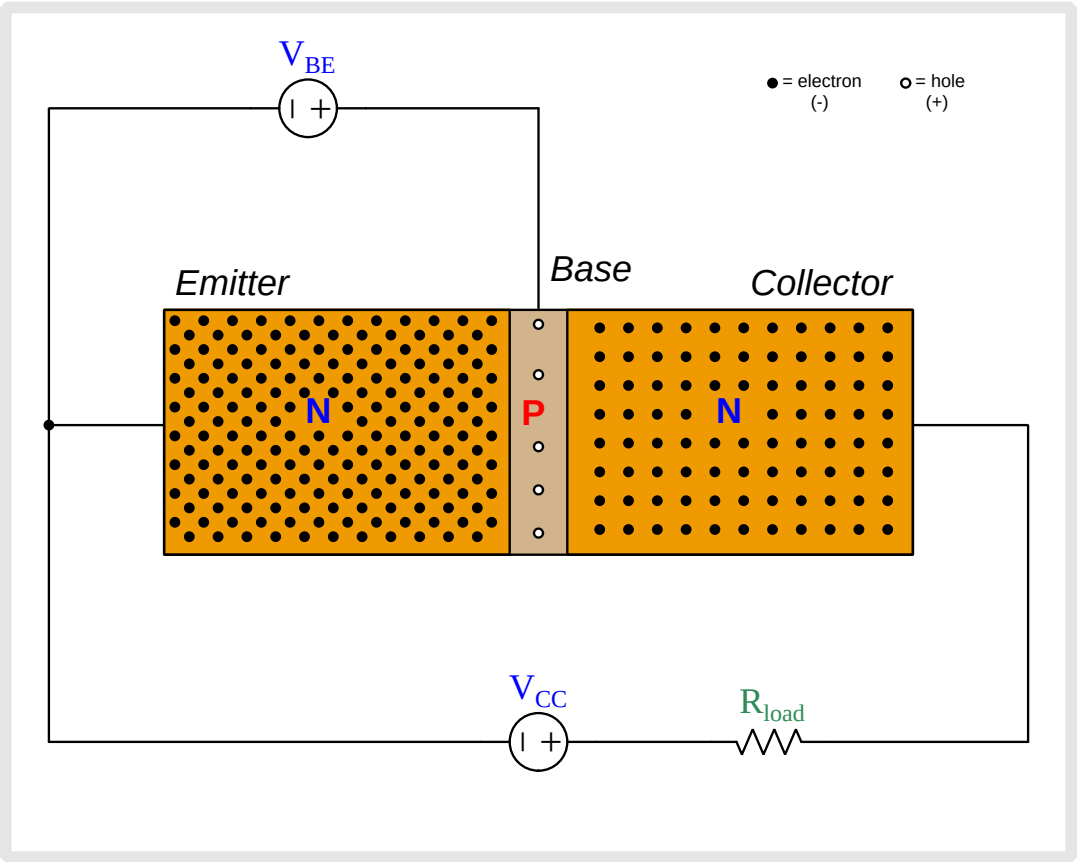
Chapter 4

Animations

Some concepts are much easier to grasp when seen in *action*. A simple yet effective form of animation suitable to an electronic document such as this is a "flip-book" animation where a set of pages in the document show successive frames of a simple animation. Such "flip-book" animations are designed to be viewed by paging forward (and/or back) with the document-reading software application, watching it frame-by-frame. Unlike video which may be difficult to pause at certain moments, "flip-book" animations lend themselves very well to individual frame viewing.

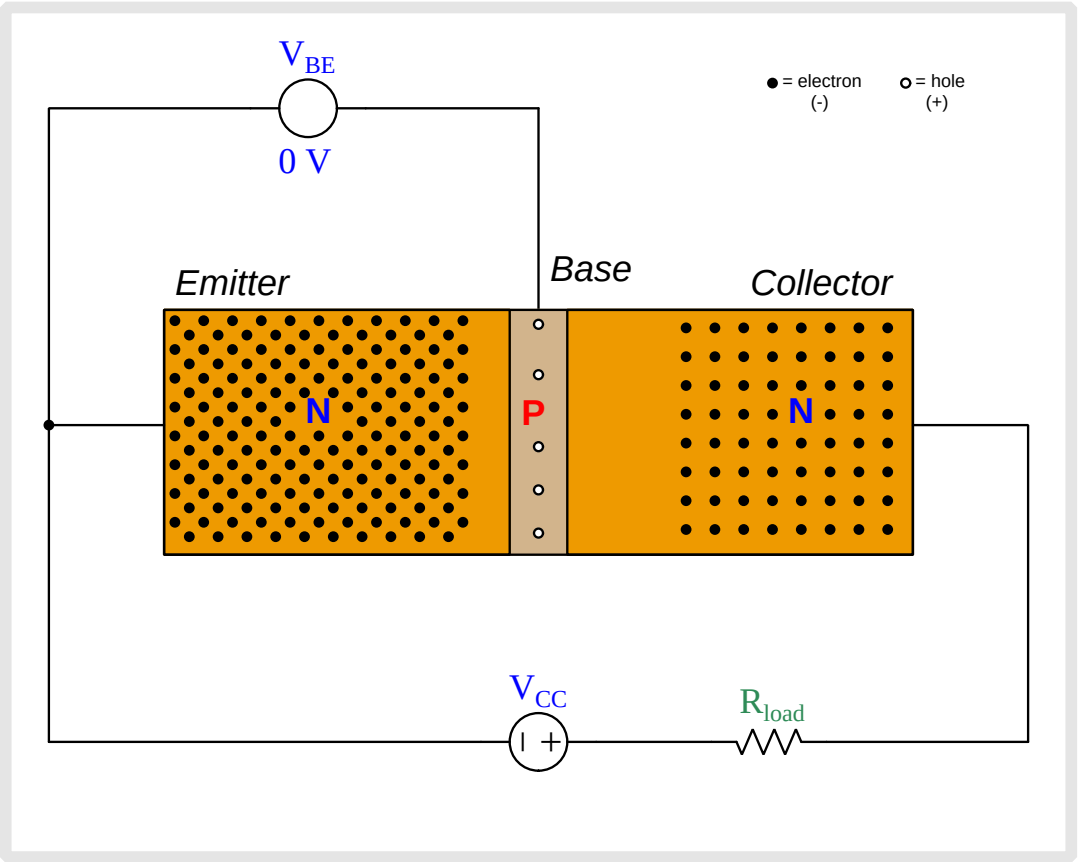
4.1 Animation of an NPN BJT turning on

Bipolar junction transistors are naturally "off" devices, having no continuous channel of conductive semiconductor material joining emitter and collector terminals. Instead the NPN or PNP sandwich interrupts that path with two series-opposed PN junctions. However, when the base-emitter PN junction is forward-biased by an external source, majority charge carriers from the emitter region are drawn into the thin and lightly-doped base region where some of them travel out the base but most carry past into the depletion region of the base-collector PN junction to be swept into the collector region. For an NPN transistor this means electrons from the N-type emitter region will be injected into the P-type base region (as "minority" type carriers there) before most of them get swept into the N-type collector region.

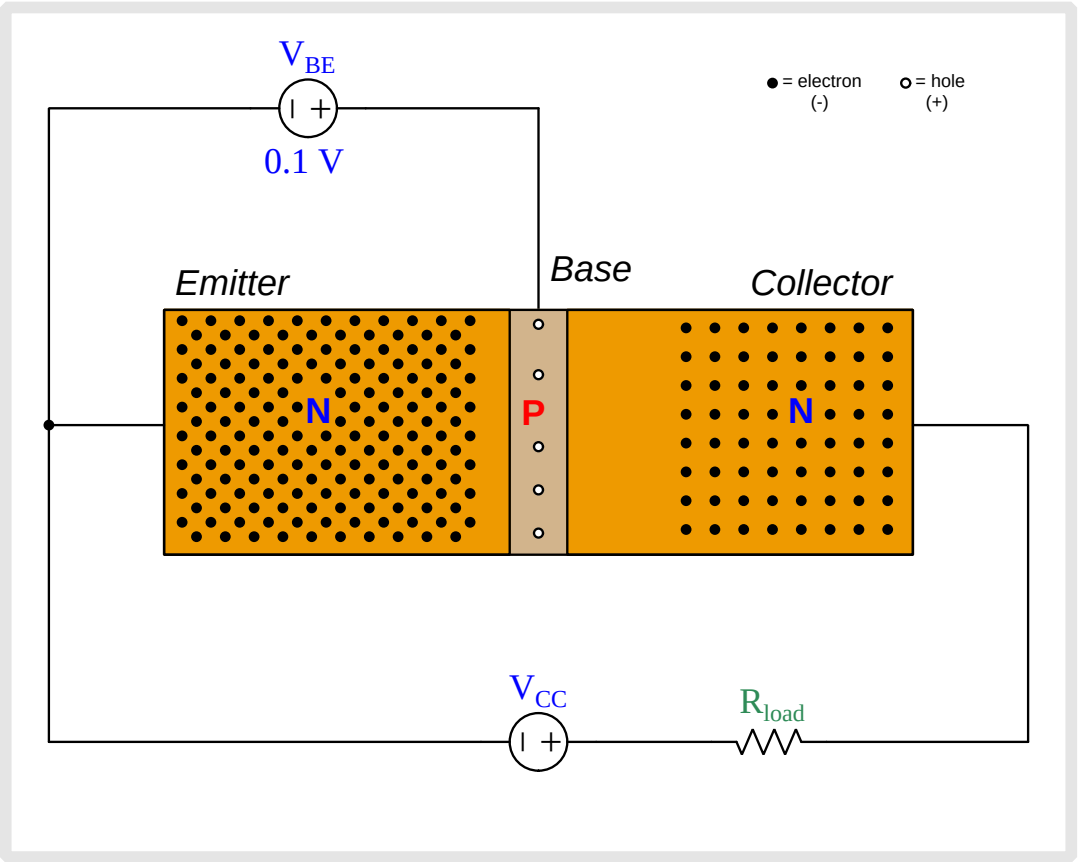


Above we see an NPN bipolar junction transistor connected to two sources. V_{BE} applies a controlling voltage between the base and emitter. V_{CC} is the voltage source which will drive current through the load resistor once the transistor begins to conduct.

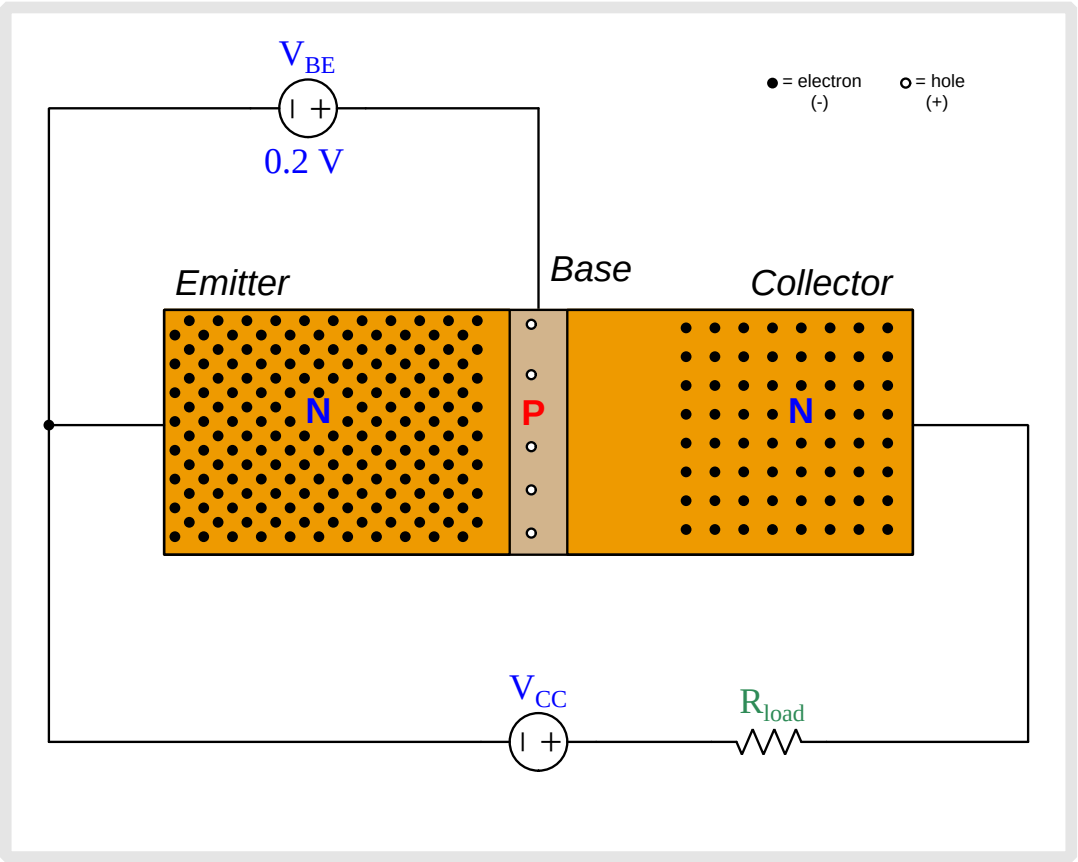
The N-doped emitter region is heavily doped and therefore contains many free electrons (negatively-charged) as mobile charge carriers. The collector region is also doped as an N-type semiconductor but the dopant concentration is less than that of the emitter. The P-doped base region is the least-doped of them all with just a few holes (positively-charged) as mobile charge carriers. Note that when load current begins to flow, its direction will be shown in *conventional flow notation* which is the same direction in which holes move but is opposite to the direction free electrons move.



Note the depletion regions shown as areas with no free charge carriers, the base-collector depletion region being wider than the base-emitter depletion region due to the applied reverse-bias potential of V_{CC}.



As we begin to apply a base-to-emitter voltage with the base positive and emitter negative, that applied potential difference drives the emitter and base regions' respective charge carriers toward each other, collapsing the base-emitter depletion region.



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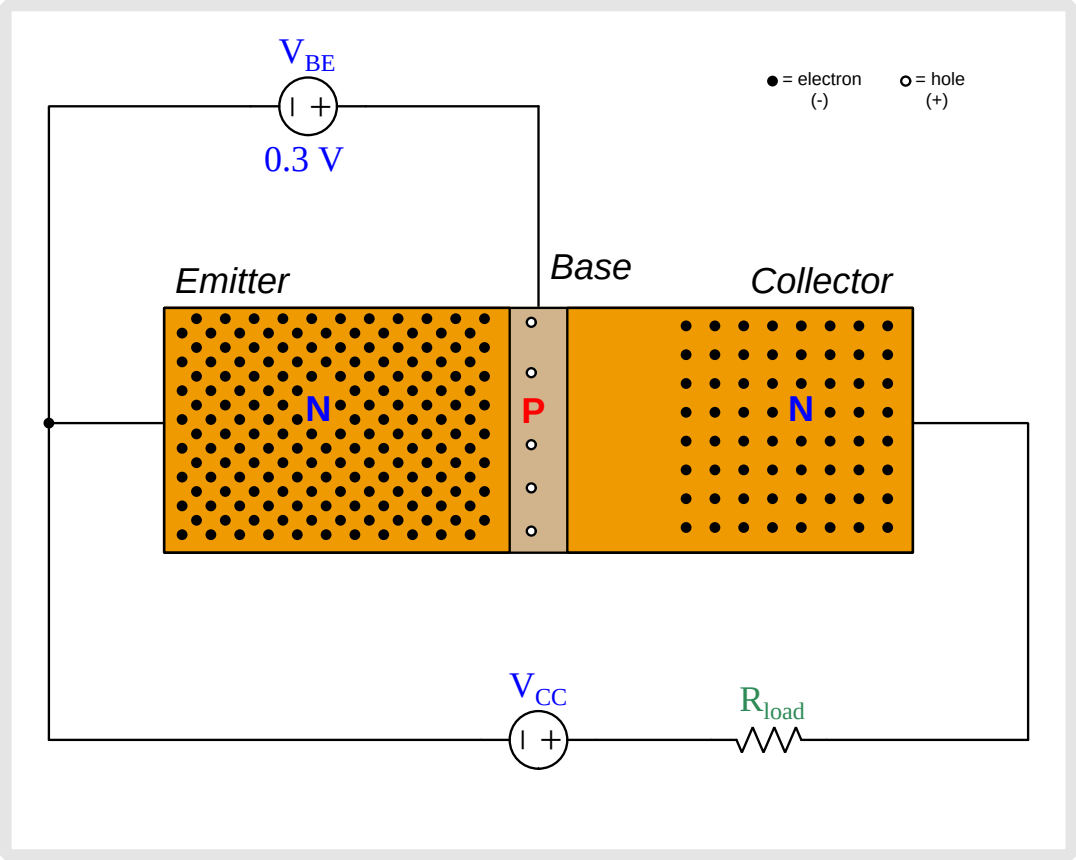

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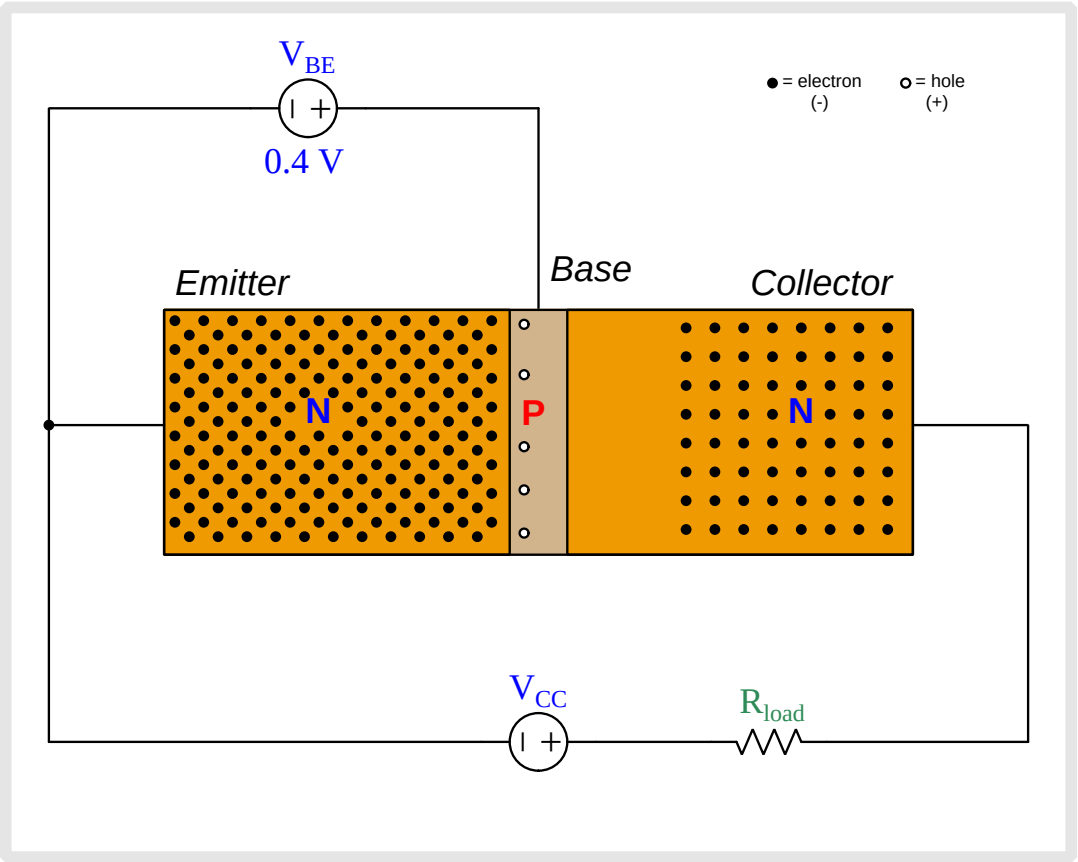

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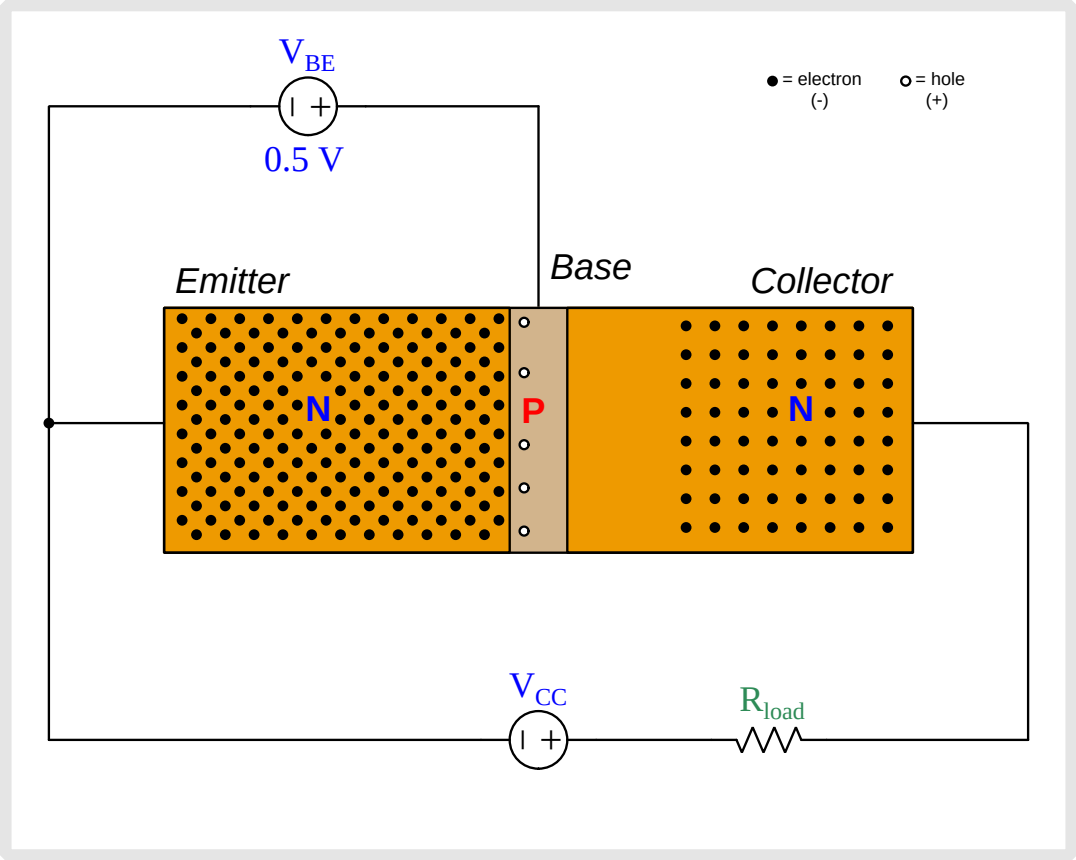

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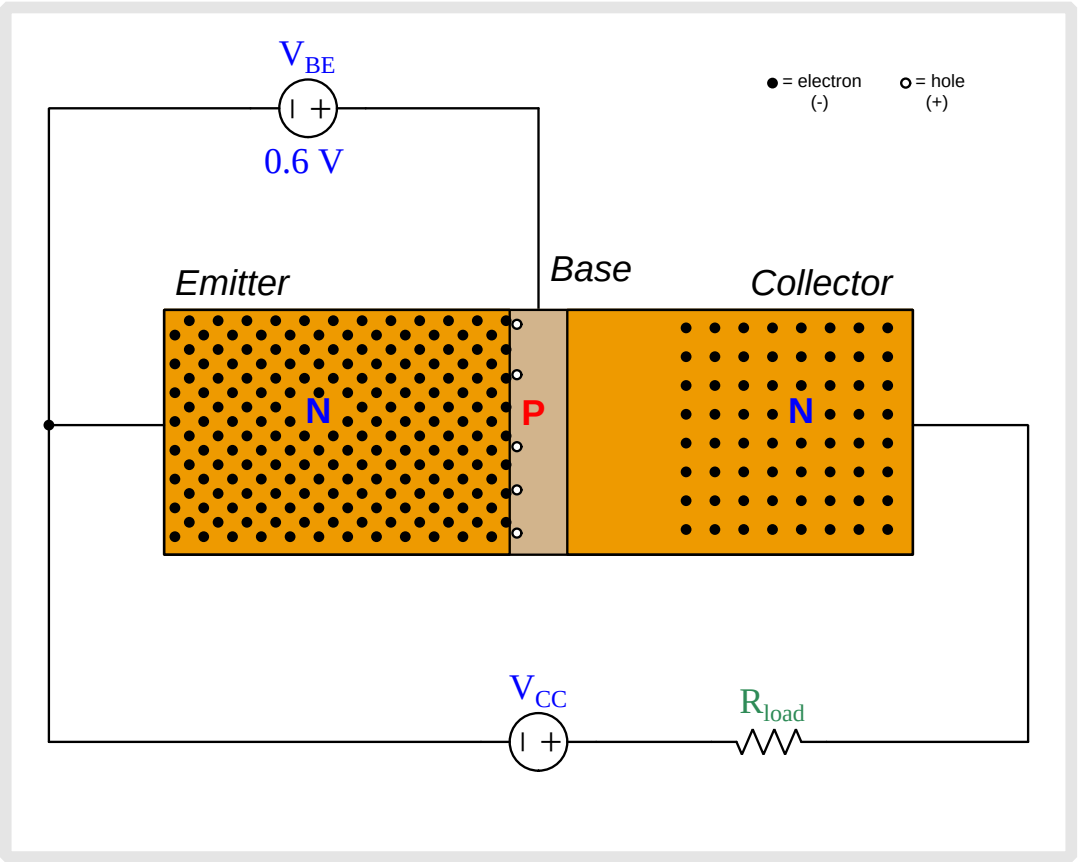

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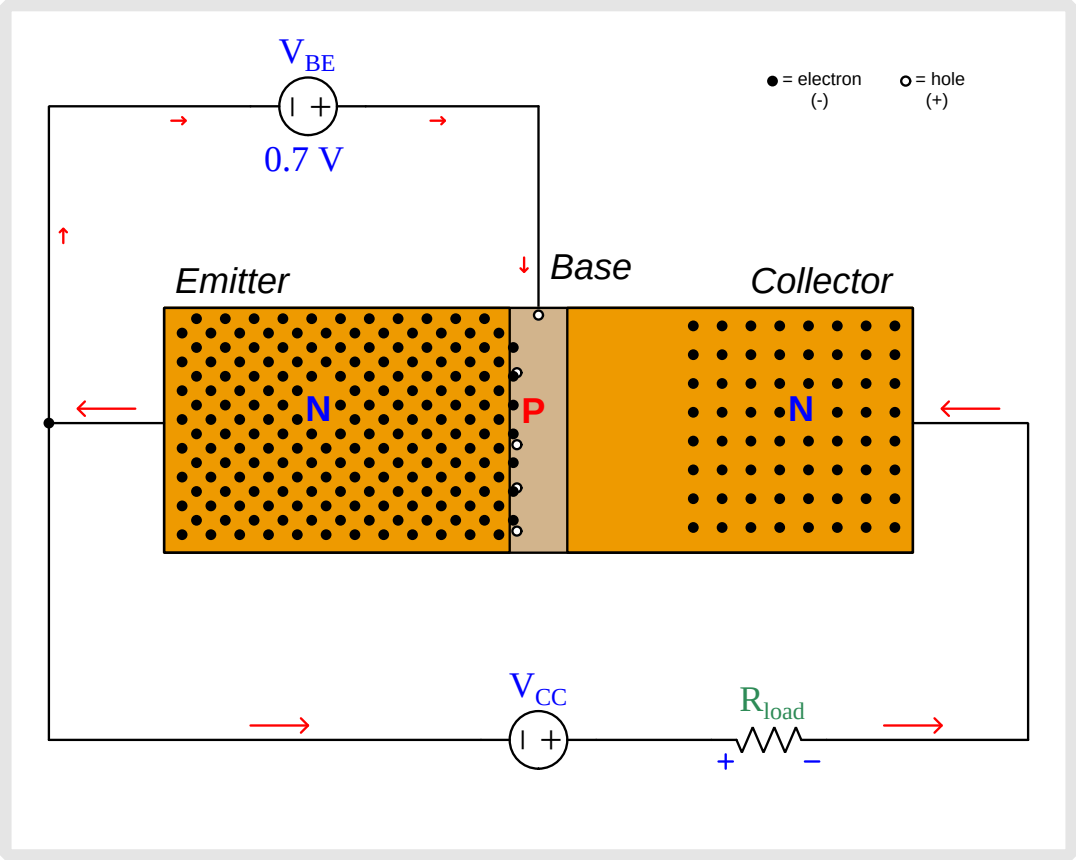
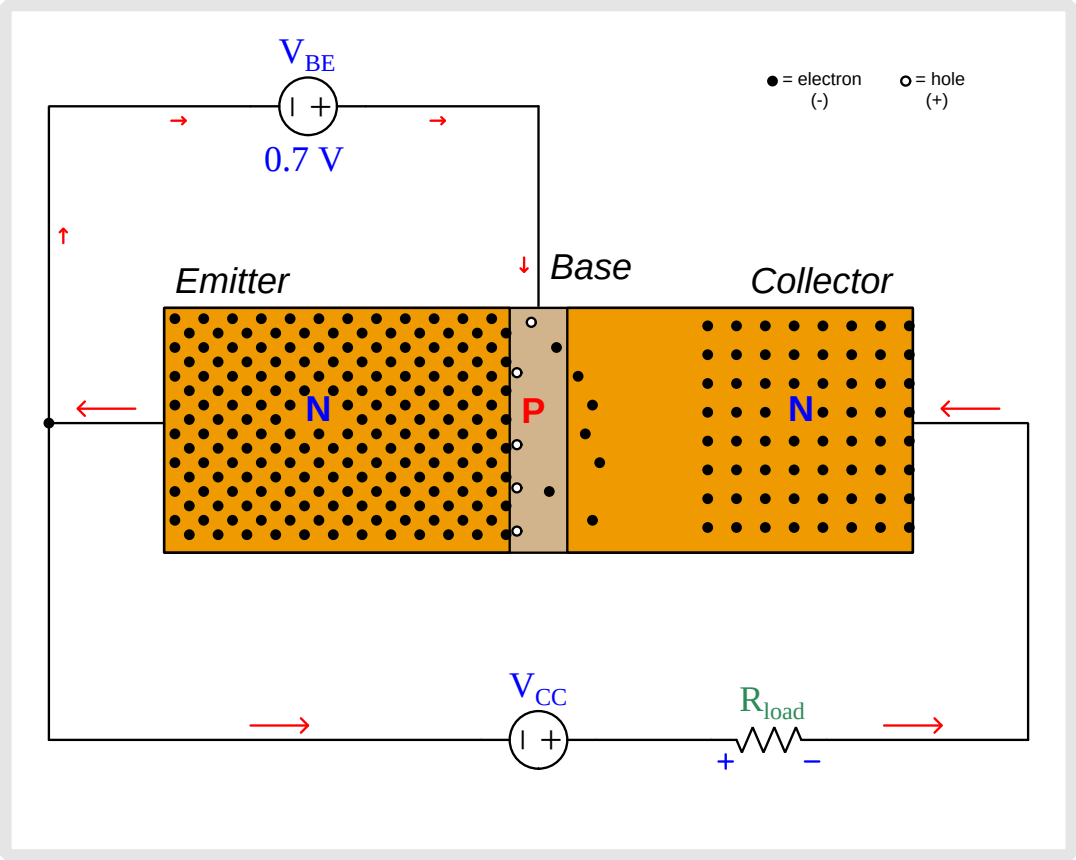
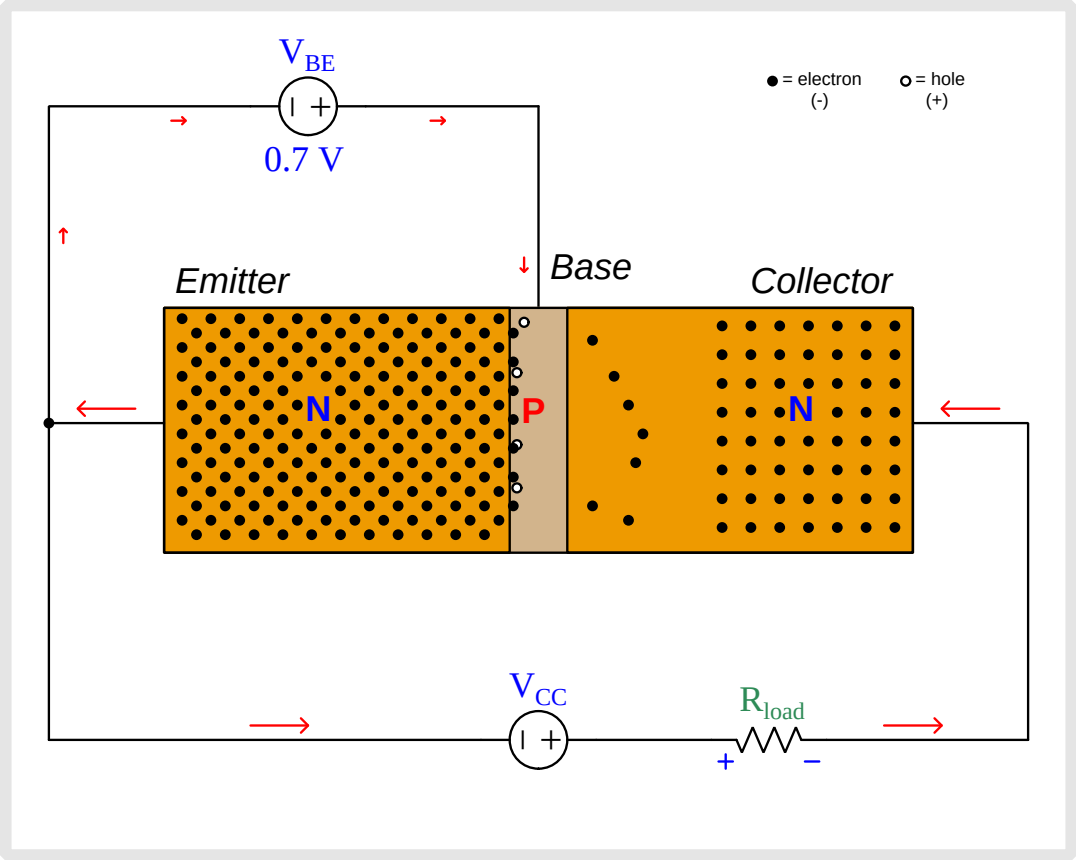


Now there is enough base-to-emitter voltage to fully collapse the base-emitter depletion region which allows base current to flow through the V_{BE} source. New holes enter into the base region from the base terminal to replenish any holes that have "re-combined" with electrons from the emitter region. Most of the emitter-injected electrons do *not* combine with holes, though, because the lightly-doped base region provides few holes to combine with. Therefore, most of the electrons injected into the base region from the emitter region begin to drift toward the collector.



The electric field imposed by V_{CC} across the base-collector PN junction quickly "sweeps" electrons toward the collector terminal, constituting current through the load resistor. A small number of electrons injected into the base "recombined" with holes there to constitute base current rather than collector current.



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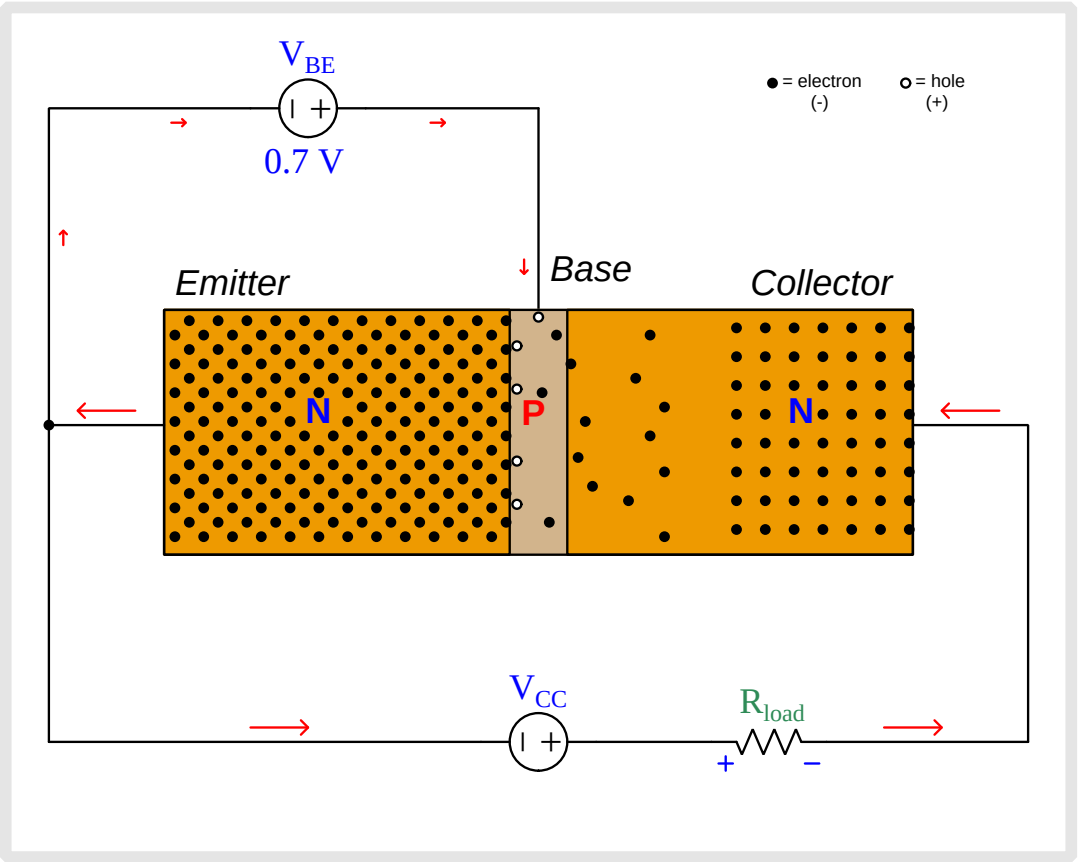
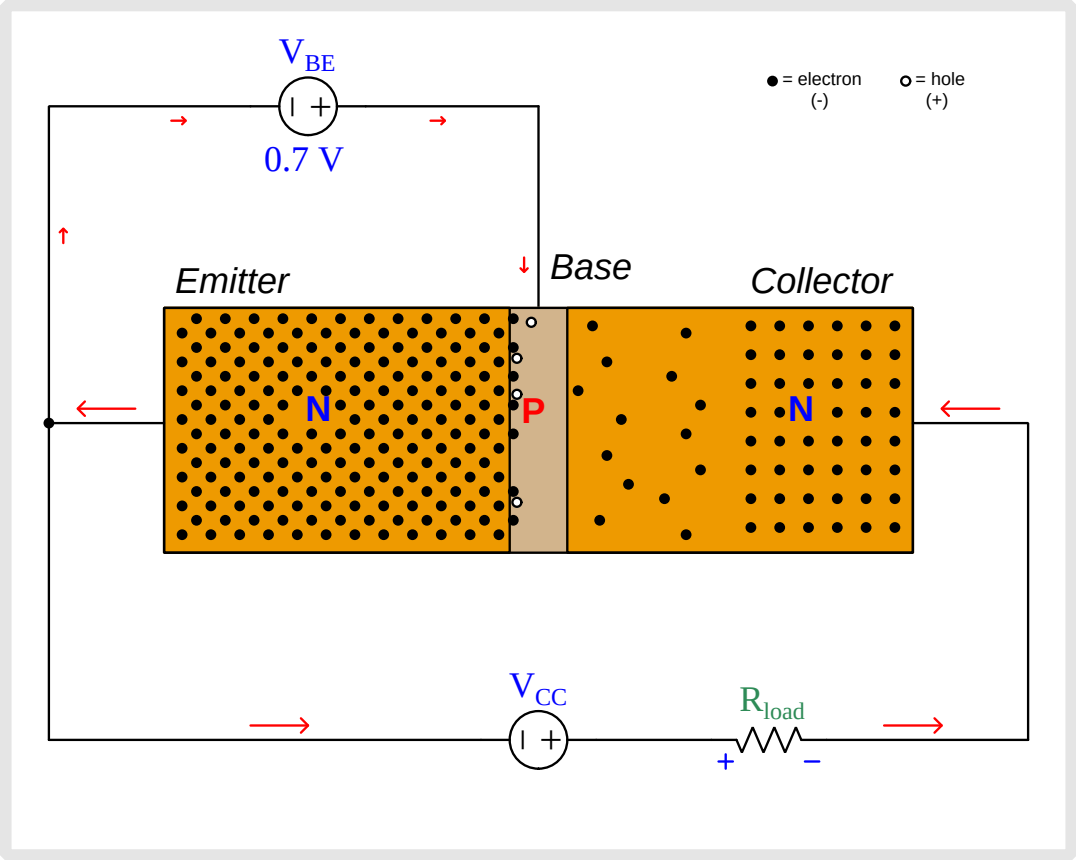


The electric field imposed by V_{CC} across the base-collector PN junction quickly "sweeps" electrons toward the collector terminal, constituting current through the load resistor. A small number of electrons injected into the base "recombined" with holes there to constitute base current rather than collector current.



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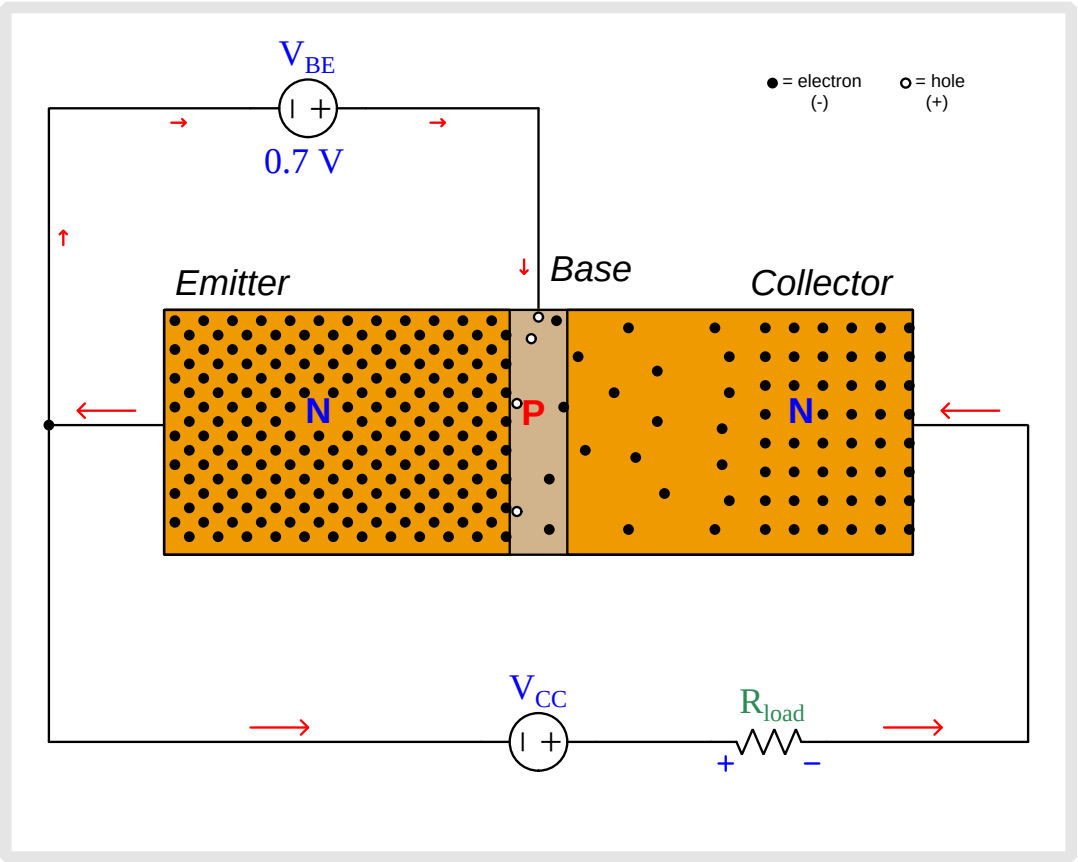
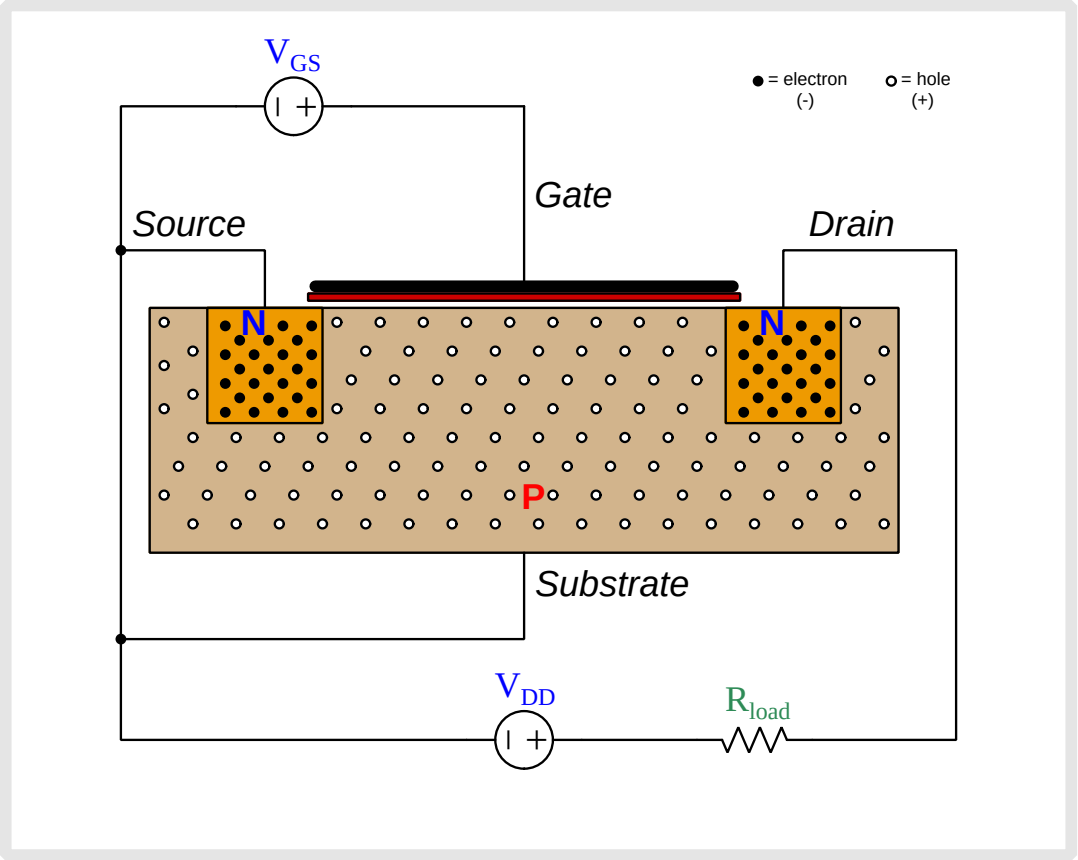


The electric field imposed by V_{CC} across the base-collector PN junction quickly "sweeps" electrons toward the collector terminal, constituting current through the load resistor. A small number of electrons injected into the base "recombined" with holes there to constitute base current rather than collector current.

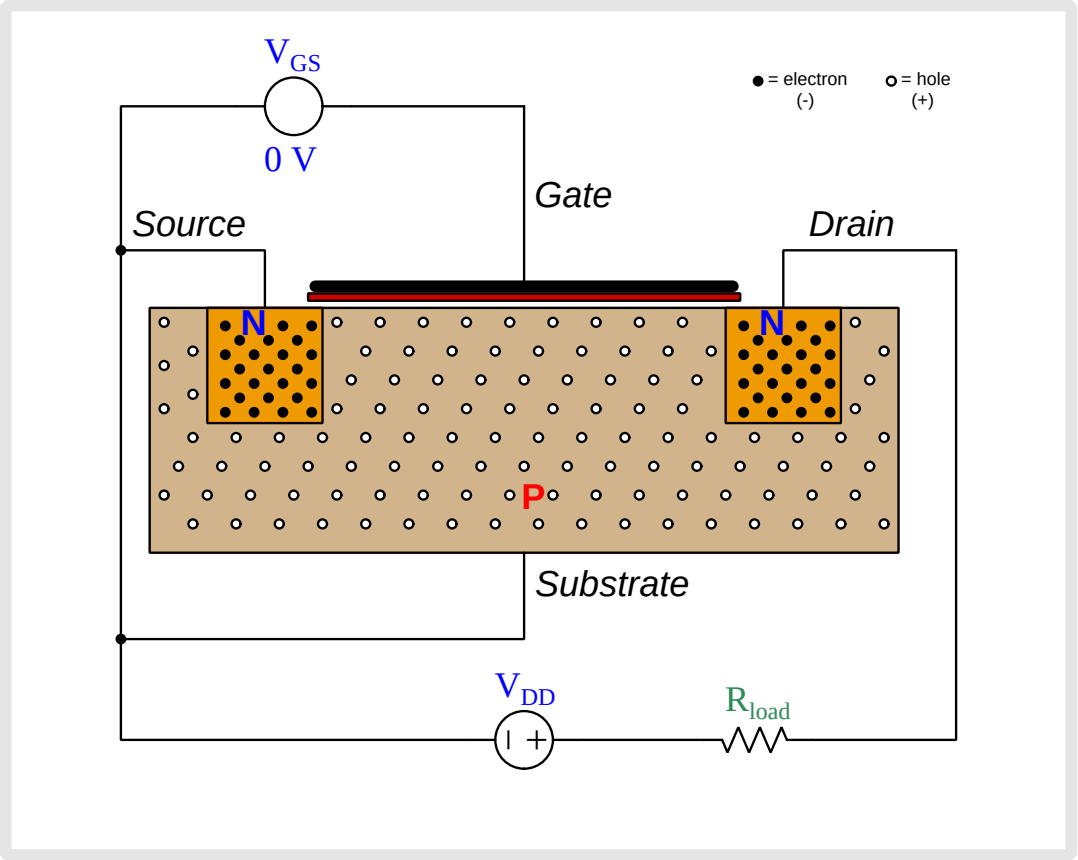
4.2 Animation of an E-type MOSFET turning on

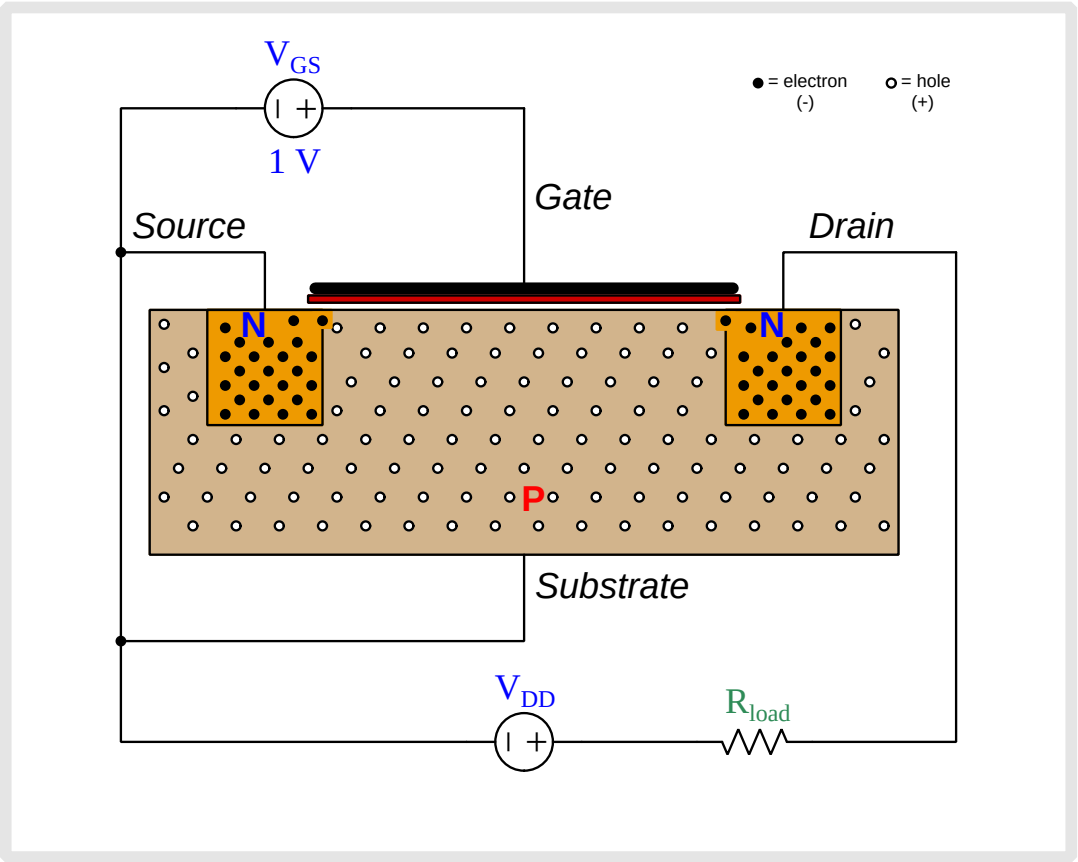
Enhancement-type (E-type) MOSFET transistors are naturally "off" devices, having no continuous channel of conductive semiconductor material joining source and drain by default the way D-type MOSFETs do. Instead the substrate semiconductor material, which is doped oppositely of the source and drain regions, interrupts that path with two series-opposed PN junctions. However, when a transverse electric field is applied between gate and substrate by an external voltage source, the surface-layer of the substrate in direct contact with the insulating metal-oxide layer converts to the opposite type of semiconductor. For an N-channel MOSFET with N-doped source and drain regions and with P-doped substrate, this means the surface of the P-doped substrate just beneath the gate effectively turns into N-type by the force of the electric field drawing free electrons from source and drain (and a few minority electrons existing within the substrate) to that surface region to form a thin film of free electrons capable of supporting source-drain conduction.



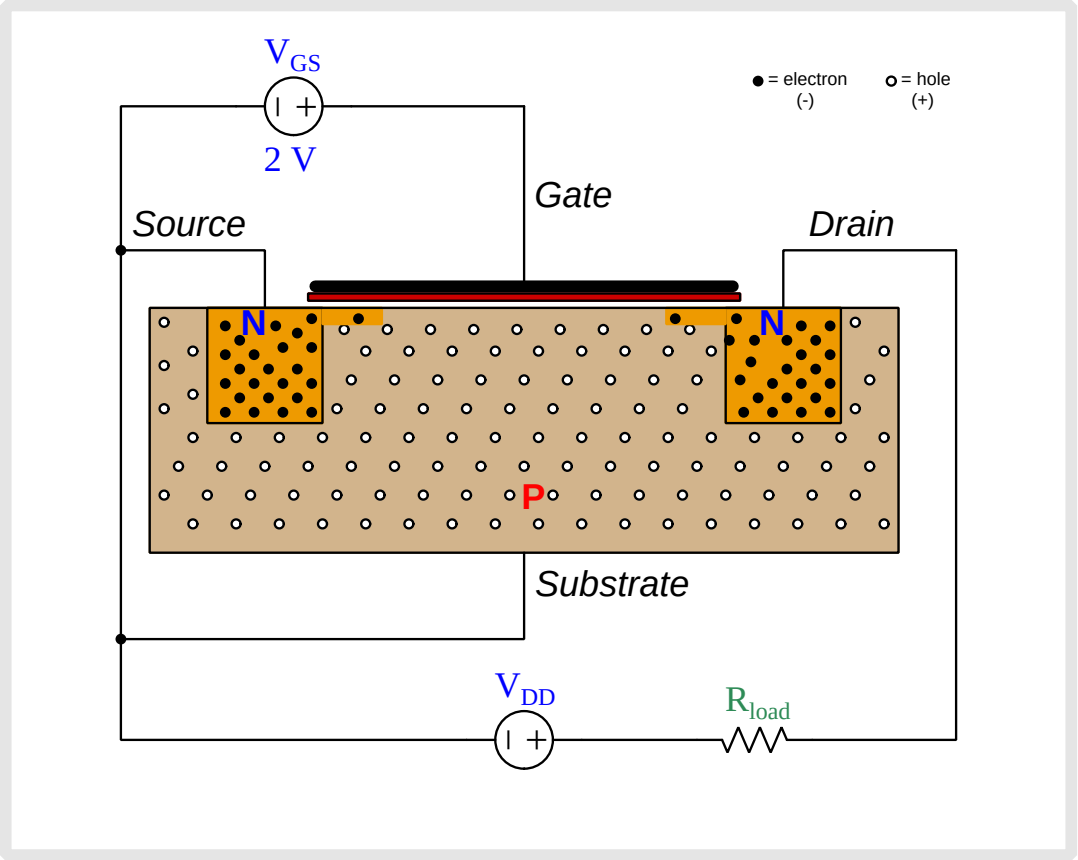
Above we see an N-channel, E-type MOSFET connected to two sources. V_{GS} applies a controlling voltage between the gate and the substrate, with the substrate connected to the source terminal to be one and the same. V_{DD} is the voltage source which will drive current through the load resistor once the transistor begins to conduct.

The N-doped source and drain regions have numerous free electrons (negatively-charged) as mobile charge carriers, while the P-doped substrate has holes (positively-charged). Note that when load current begins to flow, its direction will be shown in *conventional flow notation* which is the same direction in which holes move but is opposite to the direction free electrons move.

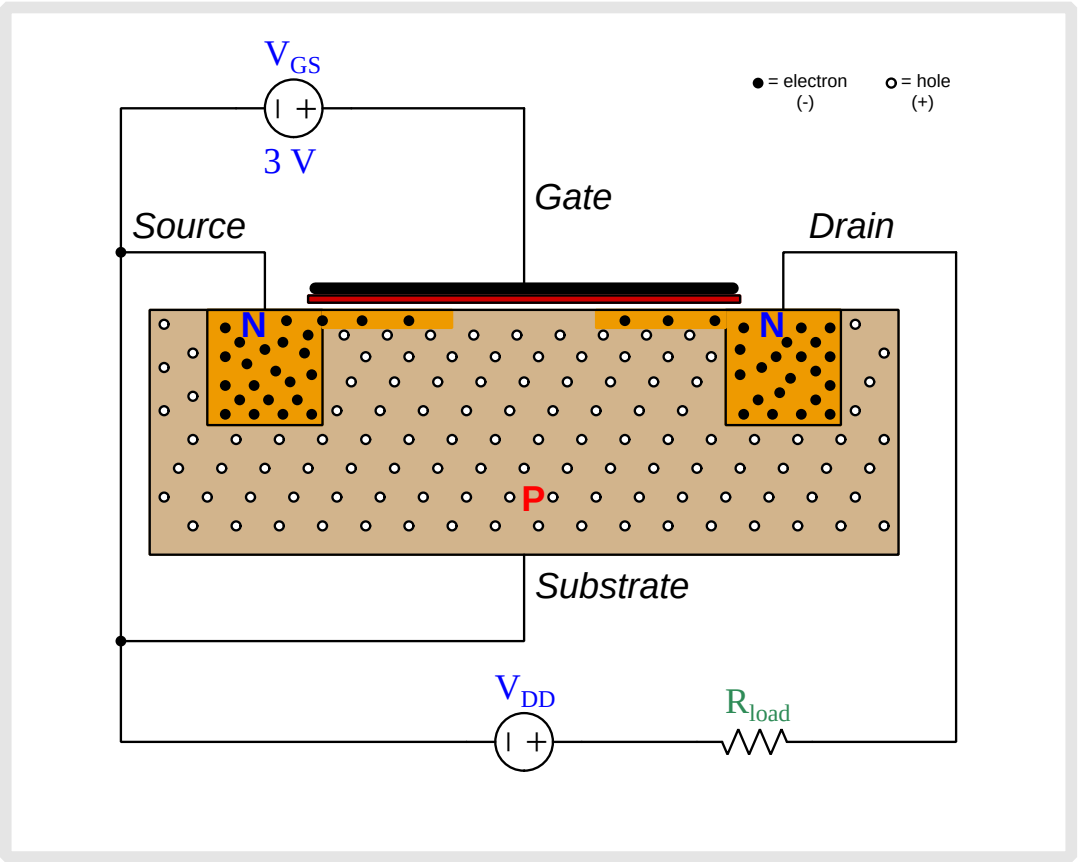

V_{GS}
0 V
● = electron (-)
○ = hole (+)
Gate
Source
Drain
N
N
P
Substrate
V_{DD}
R_{load}



As we begin to apply a gate-to-substrate voltage with the gate positive and substrate negative, negatively-charged free electrons from the source and drain regions are attracted toward the metal gate while positively-charged holes in the substrate are repelled from the gate and driven downward.



As this V_{GS} voltage increases, a thin film of free electrons begins to form beneath the gate, effectively turning what used to be P-type semiconductor material into N-type. This is called an *inversion layer*.



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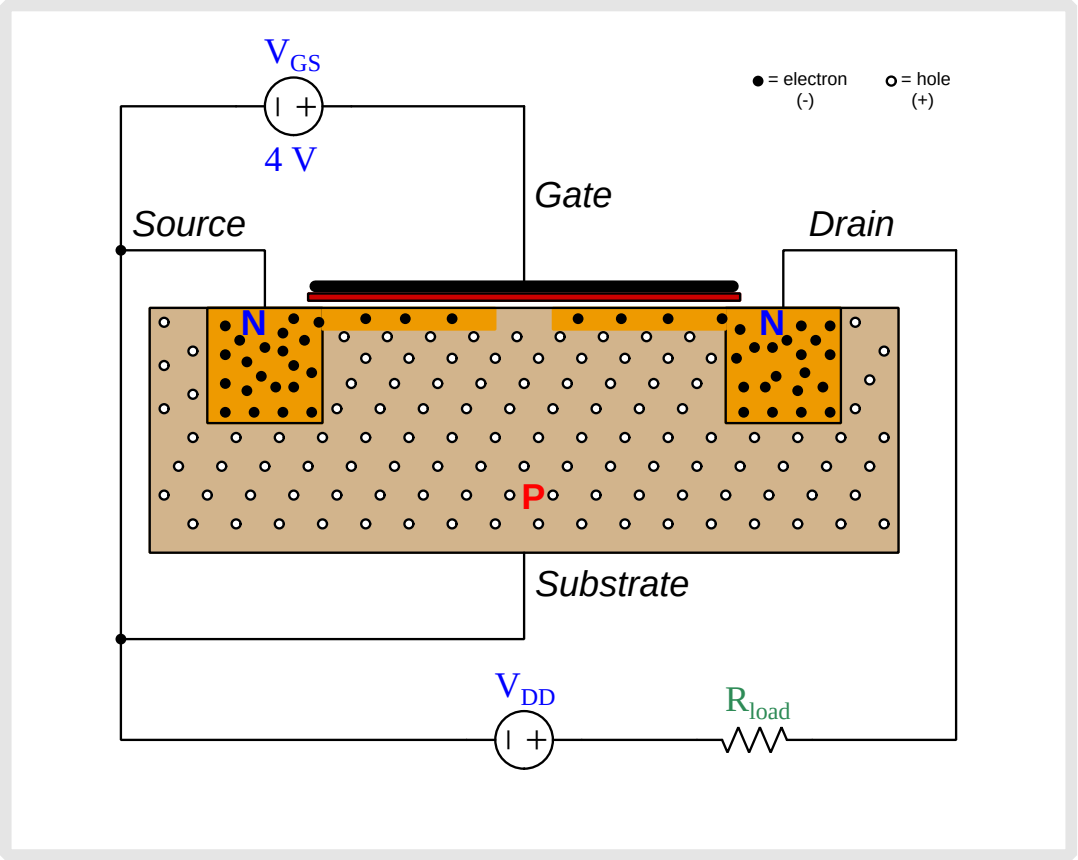

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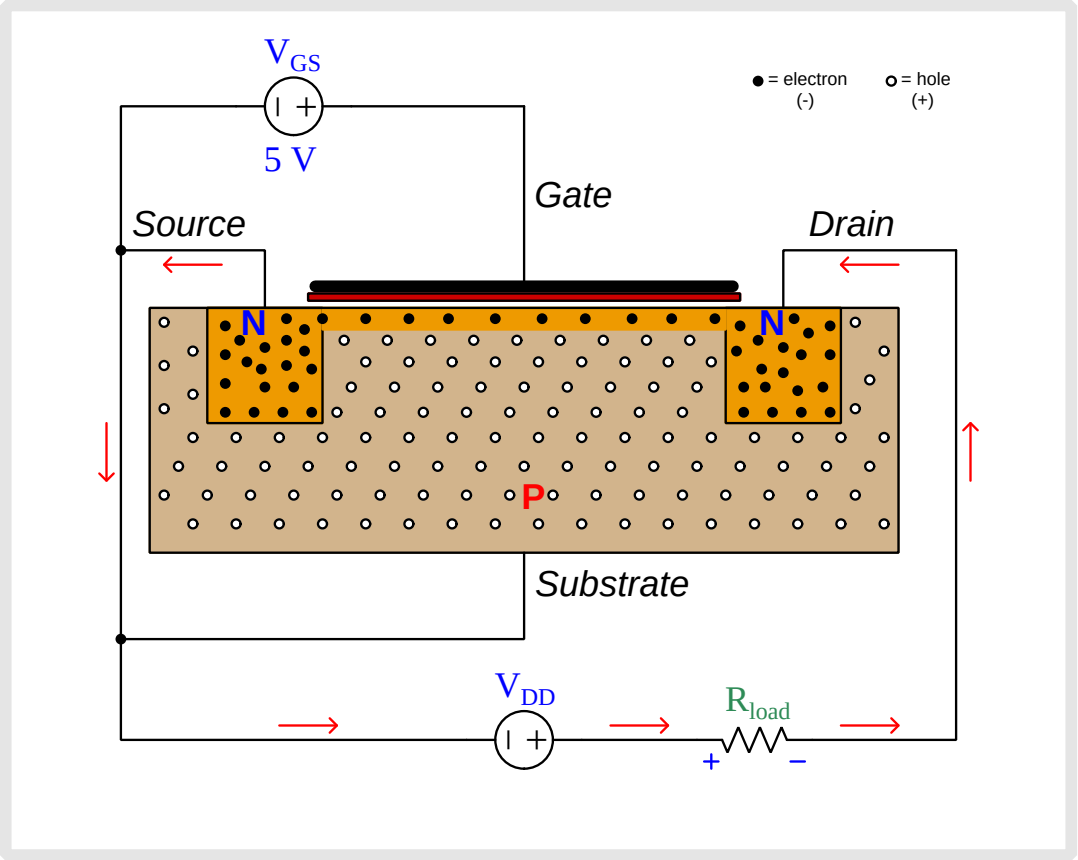
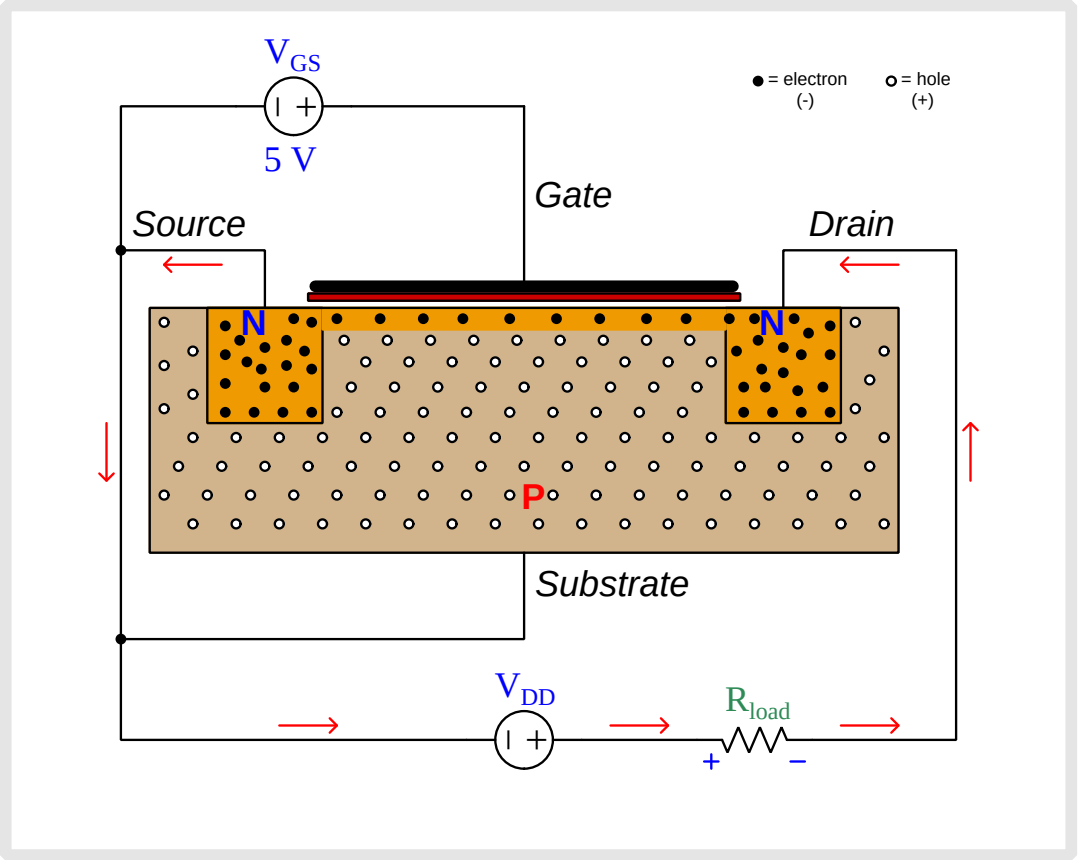
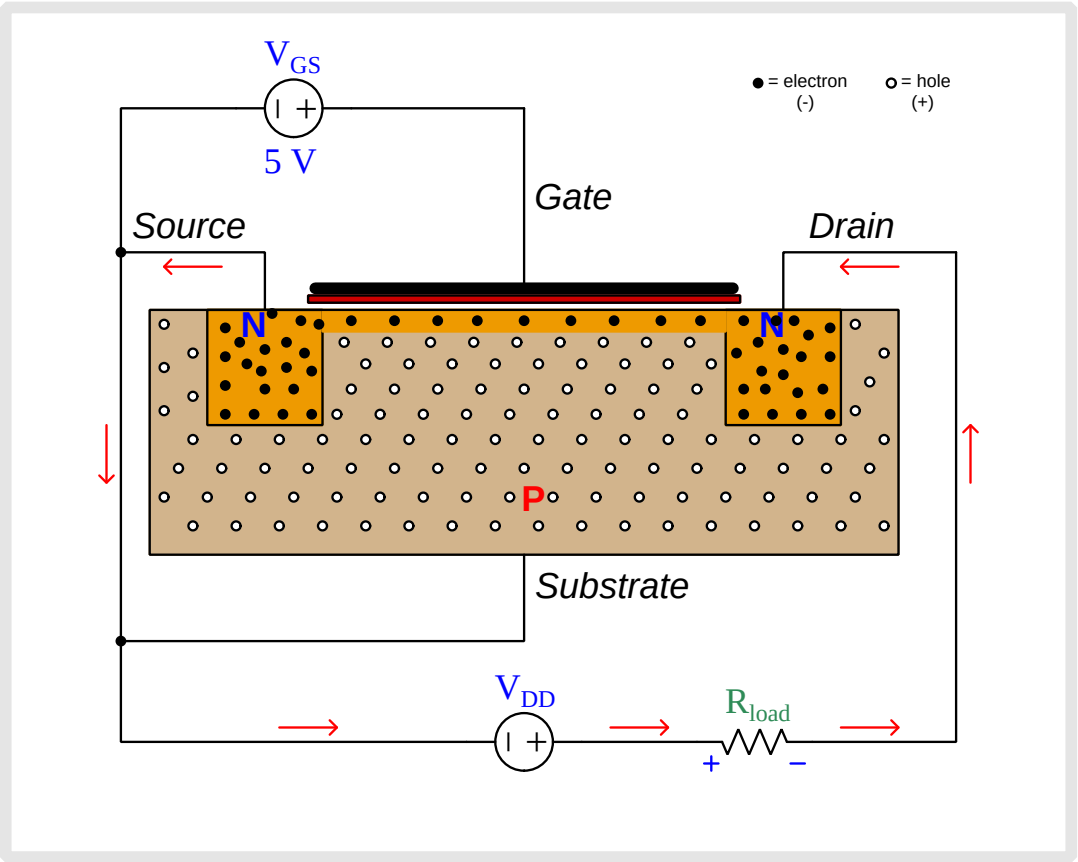


Once V_{GS} reaches the threshold or "turn-on" level, this inversion layer completely connects drain and source to form a new N-type channel permitting conduction between source and drain. The V_{DD} source is now able to promote a current through the MOSFET.



Note how the mobile charge carriers within the inversion layer are electrons, which flow opposite the direction of "conventional flow" as notated by the red arrows. Notice also how new electrons enter the inversion layer from the source region of the MOSFET, which is why that region is so-named (because that is the "source" of fresh charge carriers entering the inversion layer).



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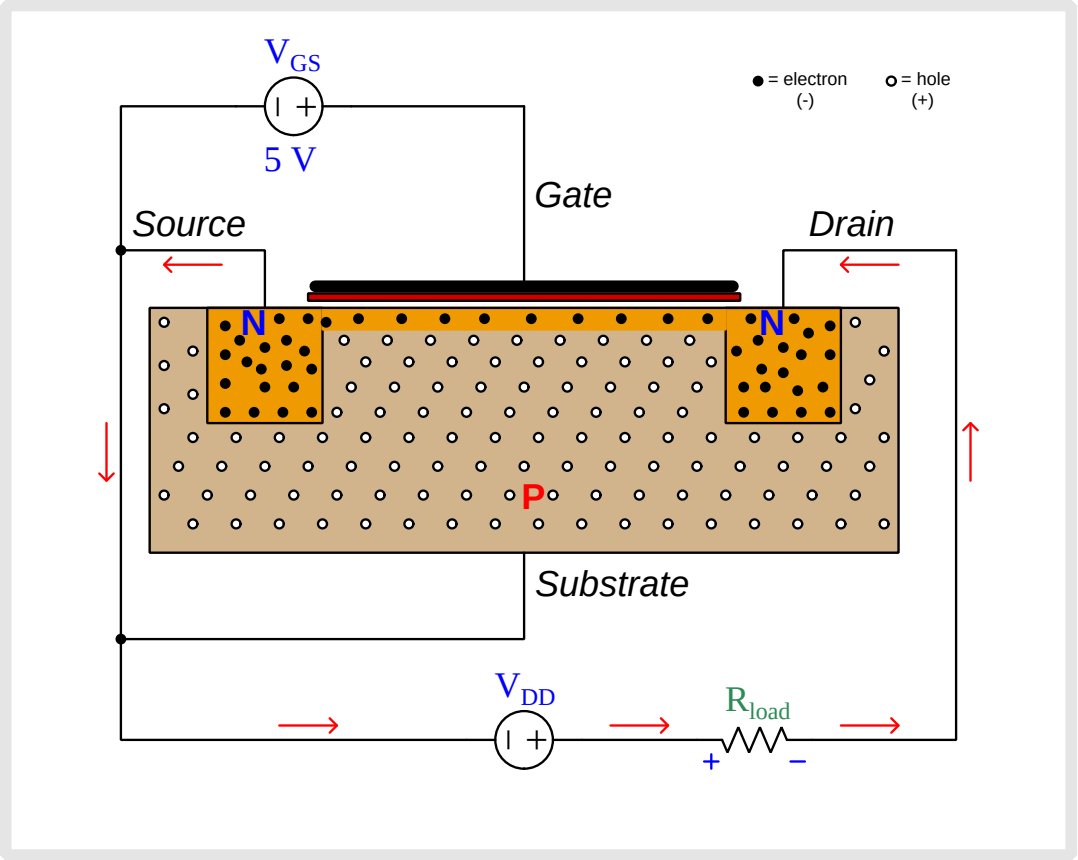

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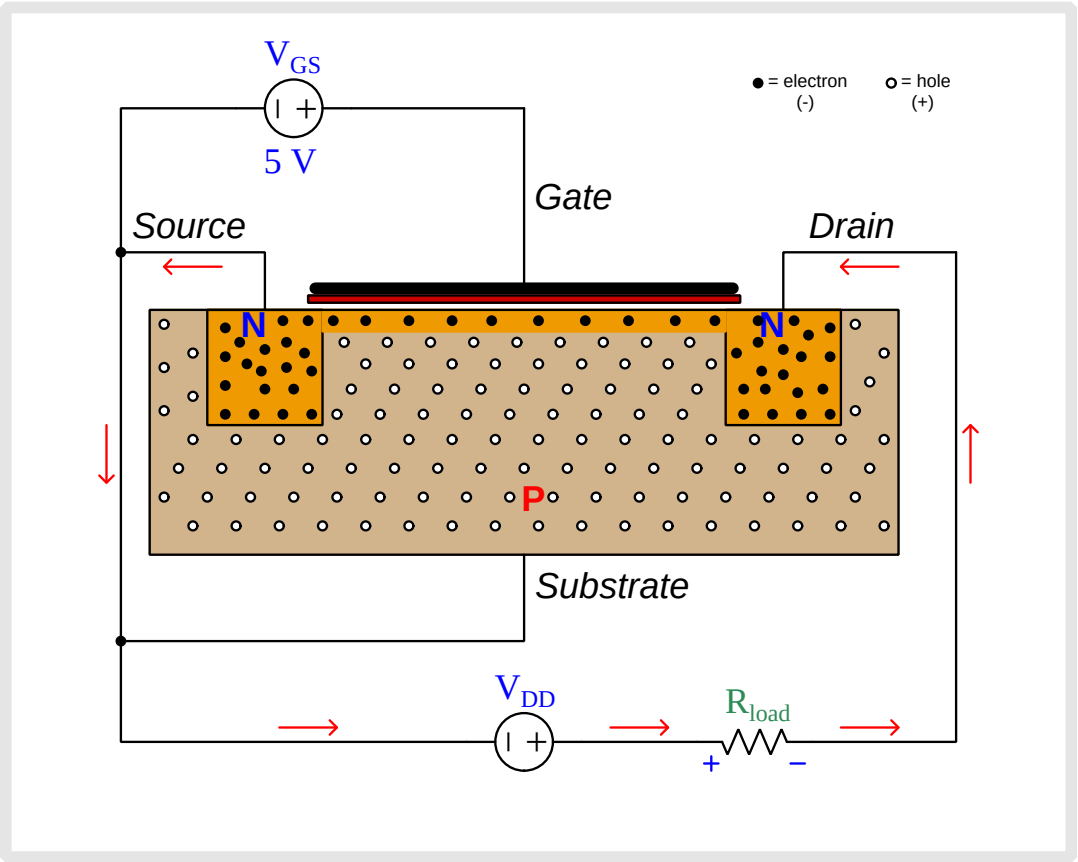

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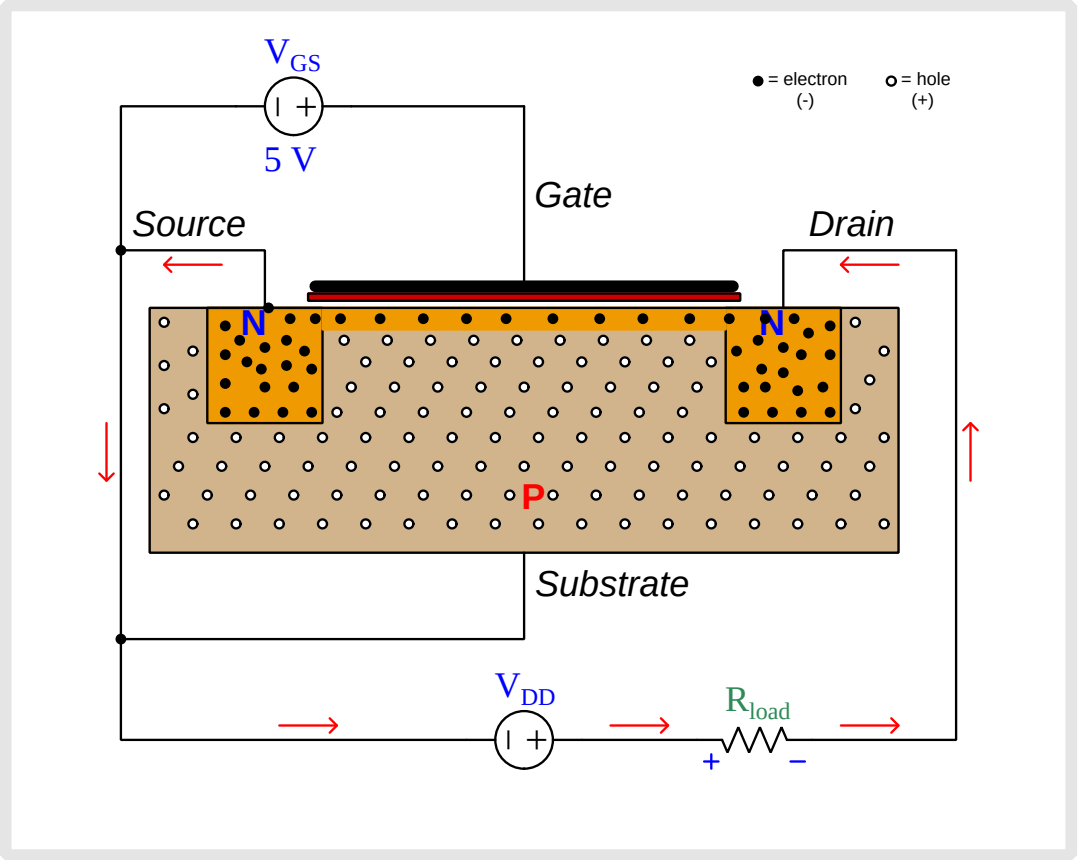

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Chapter 5

Questions

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

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

5.1 Conceptual reasoning

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

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

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

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

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

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

5.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

5.1.2 Foundational concepts

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

Amplification

Energy

Conservation of Energy

BJT principles

FET principles

Biasing

Reactance

Superposition

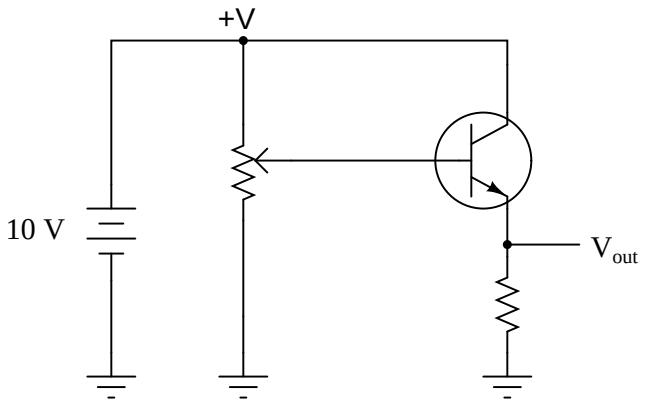
Voltage divider

Filter

Transformer

5.1.3 BJT behavior with slow-changing DC input

Describe what the output voltage of this transistor circuit will do (measured with reference to ground), if the potentiometer wiper begins at the full-down position (common with ground), and is slowly moved in the *upward* direction (closer to +V):

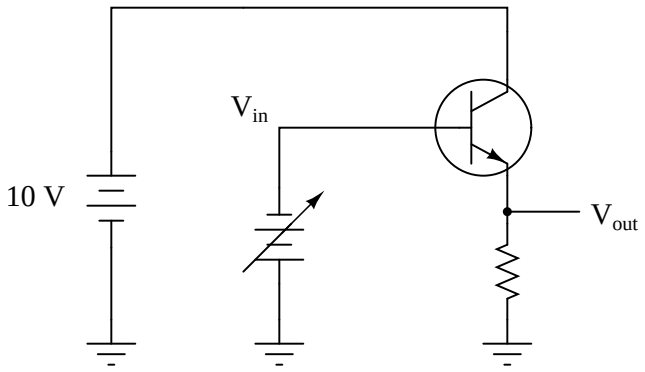


Challenges

- Explain how the "limiting cases" method of problem-solving could be applied here.
- Based on this result, would you be inclined to call this amplifier an *inverting* or a *noninverting* circuit?
- If an AC voltage signal were substituted for the potentiometer, would an AC voltage signal appear at V_{out} (with respect to ground)?

5.1.4 BJT behavior with negative input signal

Describe what the output voltage of this transistor circuit will do (measured with reference to ground), if the input voltage ramps from 0 Volts to −10 Volts (measured with respect to ground):

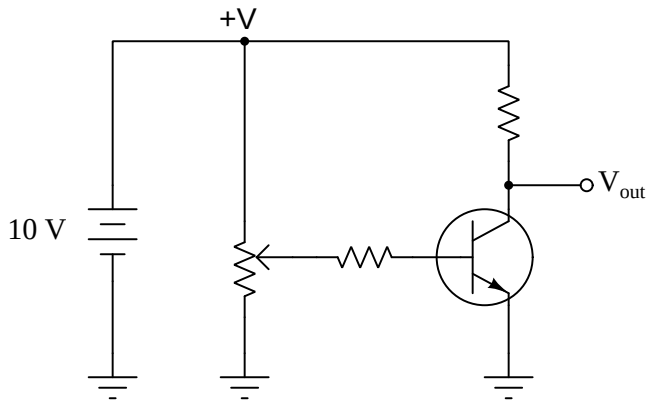


Challenges

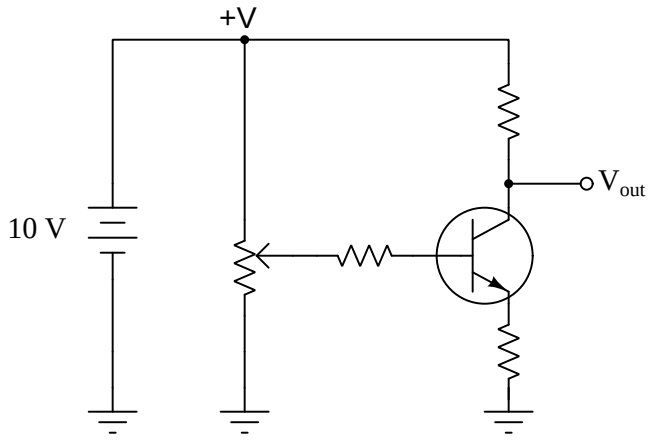
- If an AC voltage signal were substituted for the potentiometer, would an AC voltage signal appear at V_{out} (with respect to ground)?

5.1.5 Another BJT with slow-changing DC input

Describe what the output voltage of this transistor circuit will do (measured with reference to ground), if the potentiometer wiper begins at the full-down position (common with ground), and is slowly moved in the *upward* direction (closer to +V):



Now suppose we add another resistor to the circuit. Will this affect the results, or will the circuit behave the same as before?

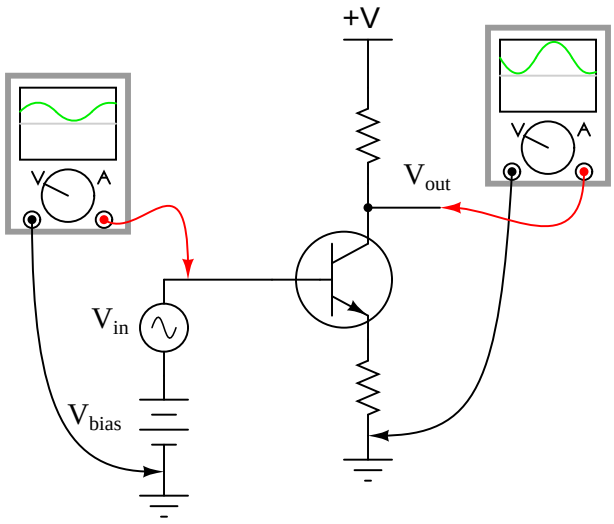


Challenges

- Explain how the "limiting cases" method of problem-solving could be applied here.
- Based on this result, would you be inclined to call this amplifier an *inverting* or a *noninverting* circuit?
- If an AC voltage signal were substituted for the potentiometer, would an AC voltage signal appear at V_{out} (with respect to ground)?

5.1.6 Inverting amplifier circuit

This amplifier's behavior may be generally classified as *inverting*. Based on the oscilloscope displays, why do you suppose this is so?



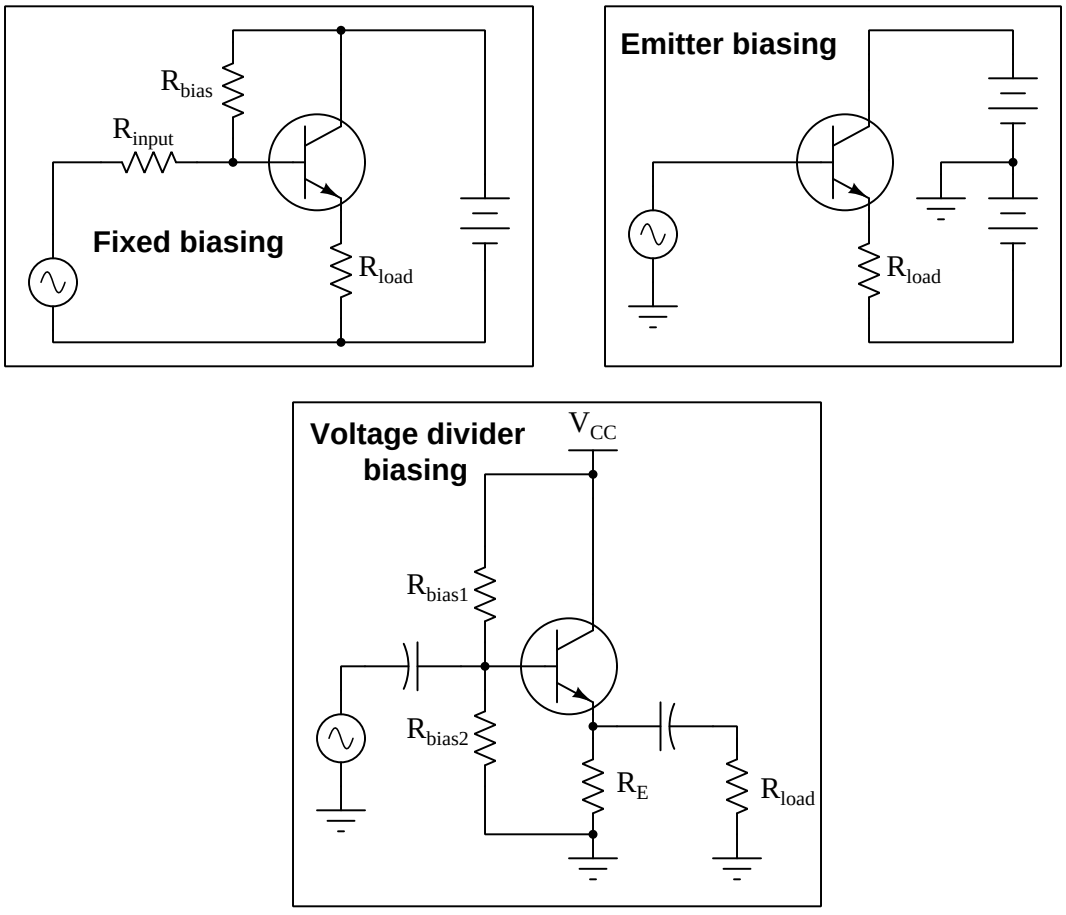
Also, explain why this amplifier inverts the input signal.

Challenges

- Identify where in this circuit we might be able to measure a non-inverted output signal.

5.1.7 BJT amplifier biasing strategies

Explain how the following bias networks function:



Each one has the same basic purpose, but works in a different way to accomplish it. Describe the purpose of any biasing network in an AC signal amplifier, and comment on the different means of accomplishing this purpose employed by each of the three circuits. *Hint:* imagine if the AC signal source in each circuit were turned off (replaced with a short). Explain how each biasing network maintains the transistor in a partially "on" state at all times even with no AC signal input.

Next, identify how to make each circuit's bias level user-adjustable. *Note:* this is highly recommended as you build your first transistor amplifier, making the bias level adjustable so you may fine-tune your circuit to have proper bias as well as seeing first-hand the effects of improper biasing.

Also identify which foundational concepts (e.g. **Ohm's Law**, **Kirchhoff's Voltage Law**,

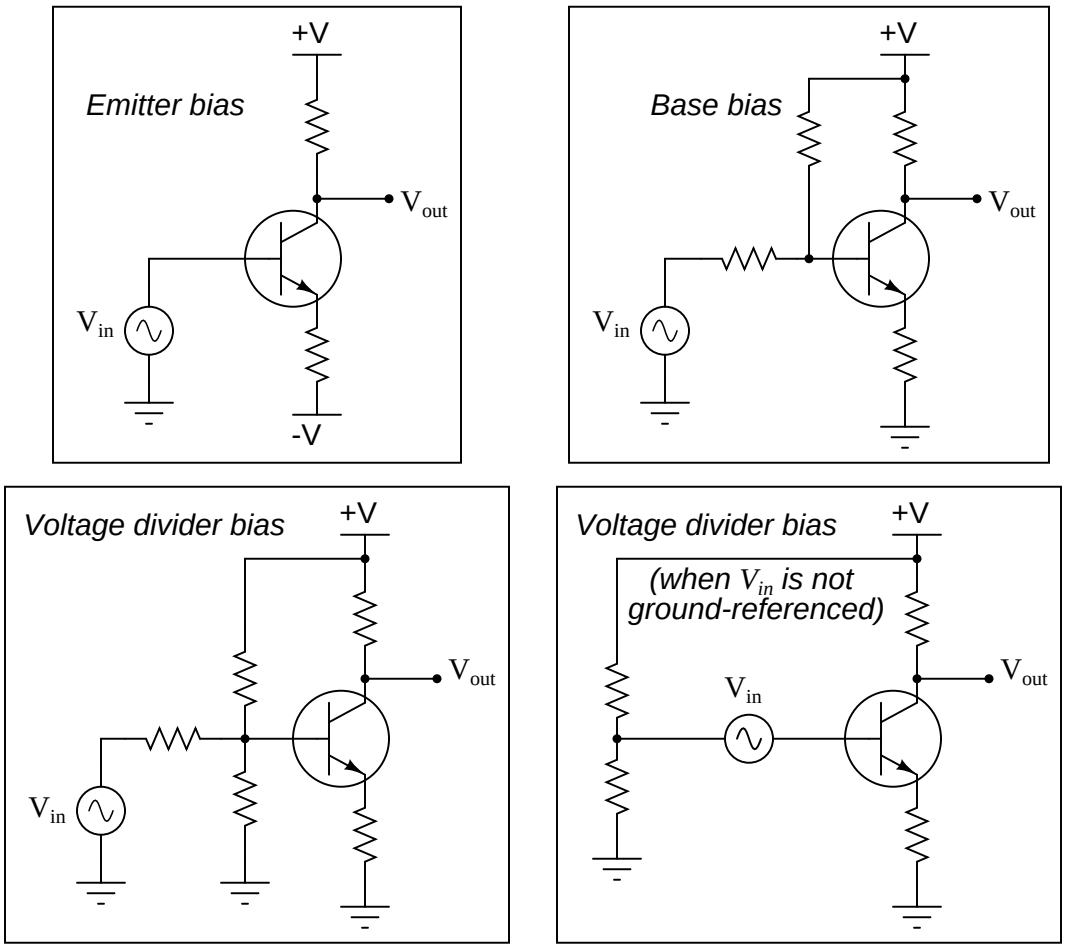
Kirchhoff's Current Law, properties of **series** versus **parallel** networks, the **Superposition Theorem**, etc.) could be applied to the calculation of bias currents in each circuit.

Challenges

- What fundamental principle of circuit analysis allows us to simply replace these AC voltage sources with *shorts* to determine the DC bias?
- Explain what you would alter in each of these circuits to *increase* the amount of DC biasing presented to each transistor.
- Calculate approximate quiescent values for V_{load} for circuits where every resistor is 1 kΩ and the total power supply voltage is 18 Volts.

5.1.8 More BJT amplifier biasing strategies

Explain how the following bias networks function:



Each one has the same basic purpose, but works in a different way to accomplish it. Describe the purpose of any biasing network in an AC signal amplifier, and comment on the different means of accomplishing this purpose employed by each of the three circuits.

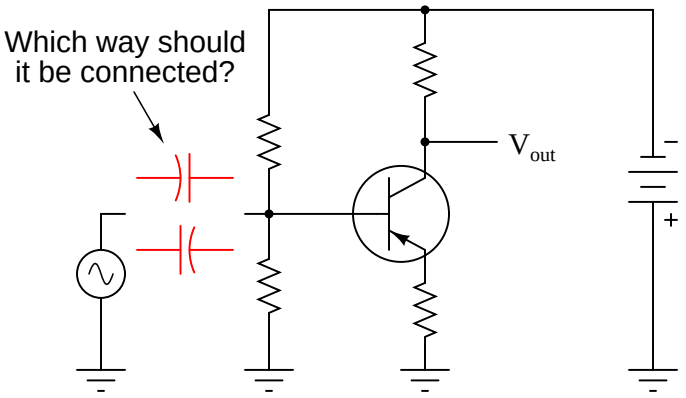
Hint: imagine if the AC signal source in each circuit were turned off (replaced with a short). Explain how each biasing network maintains the transistor in a partially "on" state at all times even with no AC signal input.

Challenges

- Calculate approximate quiescent values for V_{load} for circuits where every resistor is 1 kΩ and the total power supply voltage is 18 Volts.

5.1.9 Coupling capacitor polarity

When inserting a signal coupling capacitor into the bias network for this transistor amplifier, which way should the (polarized) capacitor go? (Hint: the AC signal source outputs pure AC, with a time-averaged DC value of 0 Volts).



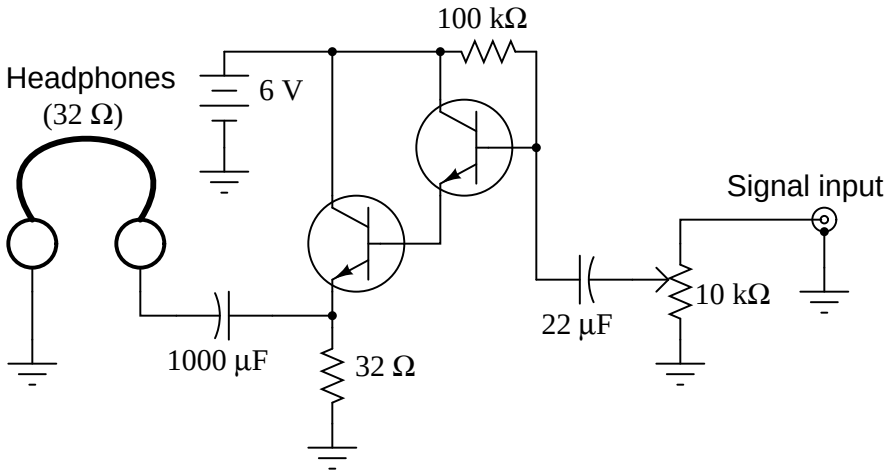
Explain why the orientation of this capacitor matters, and what might happen if it is connected the wrong way.

Challenges

- Sketch a load connected to the output of this amplifier through another coupling capacitor, and show the proper orientation of that capacitor.

5.1.10 Headphone amplifier circuit

Describe how proper biasing is accomplished in this headphone amplifier circuit (suitable for amplifying the audio output of a small radio):



Also, describe the functions of the 10 kΩ potentiometer and the 22 μF capacitor.

Challenges

- There is a name used to describe the dual-transistor configuration used in this circuit, where a pair of PNP or NPN transistors is cascaded, with the emitter of one going to the base of the other. What is this name, and what advantage does this configuration provide over a single transistor?

5.2 Quantitative reasoning

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

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

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

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

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

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

5.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.2.2 Introduction to spreadsheets

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

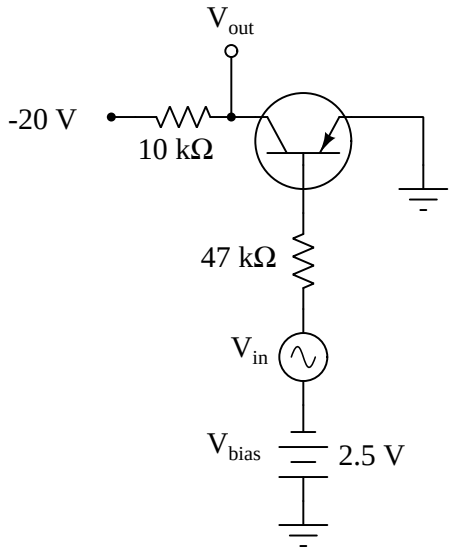
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference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

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

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

5.2.3 Quiescent base current

Calculate the approximate quiescent (DC) base current for this transistor circuit, assuming an AC input voltage of 0 Volts, and a silicon transistor:



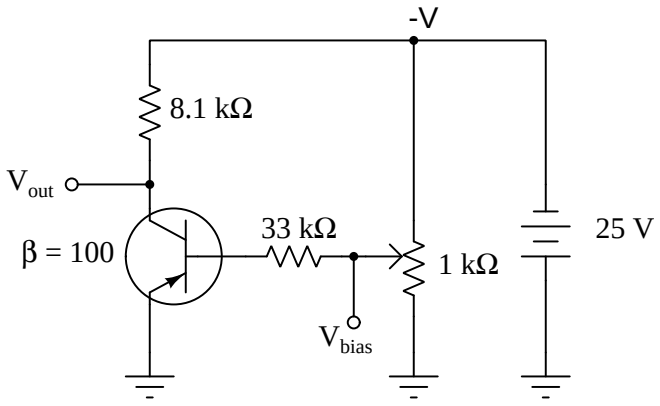
Be sure to explain each of your analytical steps by appealing to foundational concepts such as **Ohm's Law**, **Kirchhoff's Voltage Law**, **Kirchhoff's Current Law**, properties of **series** versus **parallel** networks, the **Superposition Theorem**, etc.

Challenges

- Explain why completing the schematic diagram so that it shows the power supply as a voltage source could be helpful in analyzing this circuit.
- Explain why we cannot calculate the quiescent collector current without more information.
- What would happen if we reversed the polarity of V_{bias}?

5.2.4 Potentiometer-adjusted bias

Calculate the potentiometer wiper voltage (V_{bias}) required to maintain the transistor right at the threshold between cutoff and active mode. Then, calculate the input voltage required to drive the transistor right to the threshold between active mode and saturation. Assume ideal silicon transistor behavior, with a constant β of 100:

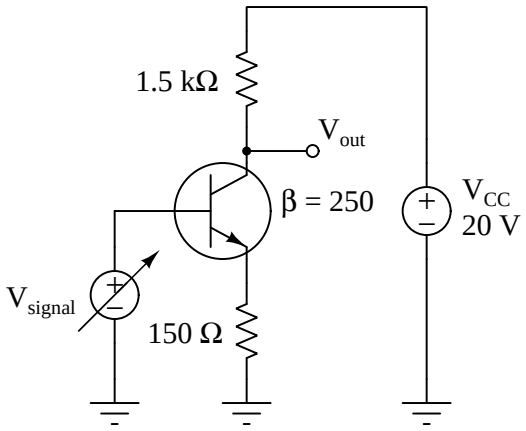


Challenges

- If we were using the potentiometer to establish a bias voltage for an AC signal, what amount of DC bias voltage would place the transistor directly between these two extremes of operation (cutoff versus saturation), so as to allow the AC input signal to "swing" equal amounts positive and negative at the distortion limit?

5.2.5 DC signal sweep simulation program

This BJT amplifier circuit has an adjustable DC input signal source (V_{signal}) and an output terminal where the output voltage signal (V_{out}) is measured with reference to ground:



A bipolar transistor connected in this particular configuration is called a *common-emitter amplifier*, its purpose generally to amplify a small AC voltage into a larger AC voltage. Here, though, we will use a computer program to simulate "sweeping" the DC voltage source V_{signal} and analyze how the amplifier's output voltage responds, in order to better understand the circuit's fundamental characteristics.

Transistor amplifiers tend to be daunting for students initially encountering them, especially the topic of biasing which is intended to "fool" a transistor into amplifying an AC signal when it can only naturally handle currents in one direction. An important key in understanding how amplifier biasing works is to explore how basic amplifier circuits respond to changing DC signal voltages. Here we will do exactly that, using a computer program written to simulate the circuit's operation when tested by a varying DC signal voltage.

The following computer program written in C performs this simulated voltage sweep:

```
#include <stdio.h>

int main (void)
{
  float Vcc=20.0, Beta=250, Rload=1.5e3, Re=150, Vsignal, Vout, Vce, Ic, Ie;

  printf("Vsignal , Vce , Voutput \n");

  for (Vsignal = 0.0 ; Vsignal <= 3.0 ; Vsignal = Vsignal + 0.2)
  {
    if (Vsignal > 0.7)
      Ie = (Vsignal - 0.7) / Re;

    else
      Ie = 0.0;

    Ic = Ie * (Beta / (Beta + 1));
    Vce = Vcc - ((Rload * Ic) + (Re * Ie));

    if (Vce > 0.3)
      Vout = Vcc - (Rload * Ic);

    else
    {
      Vce = 0.3;
      Vout = Vsignal - 0.7 + Vce;
    }

    printf("%f , %f , %f \n", Vsignal, Vce, Vout);
  }

  return 0;
}
```

Compile and run this program, taking the comma-separated variable text output and plotting it using a spreadsheet application, then answering the following questions:

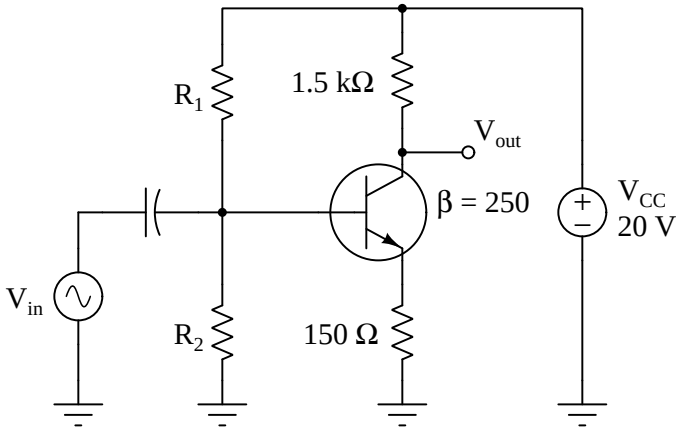
Explain how each line of code works in this program.

Where along the "sweep" test results do we see the amplifier responding to changes in V_{signal}? Where do we see the amplifier unresponsive to changes in input voltage? *Why* is the amplifier more or less responsive to V_{signal}?

Choose a value for V_{signal} that appears to be half-way between the unresponsive regions apparent in the table, and then explain why this voltage value would be a good choice for *bias voltage* if we intended to use this amplifier to amplify an AC signal (i.e. where the AC signal to be amplified was its own AC voltage source connected in series with a DC "bias" voltage source). Revise the schematic diagram to show where these AC and DC signal sources would connect.

Voltage gain for an amplifier is most broadly defined as the amount its output voltage changes for a given change in its input voltage (Gain = $\frac{\Delta V_{out}}{\Delta V_{in}}$). Take any pair of test conditions found in the table and use these to calculate the amplifier's voltage gain.

Explain how the following alteration to the amplifier circuit's design is capable of providing DC bias voltage without requiring the addition of another DC voltage source, and choose appropriate values for resistors R_1 and R_2 for creating the DC bias voltage you previously calculated:

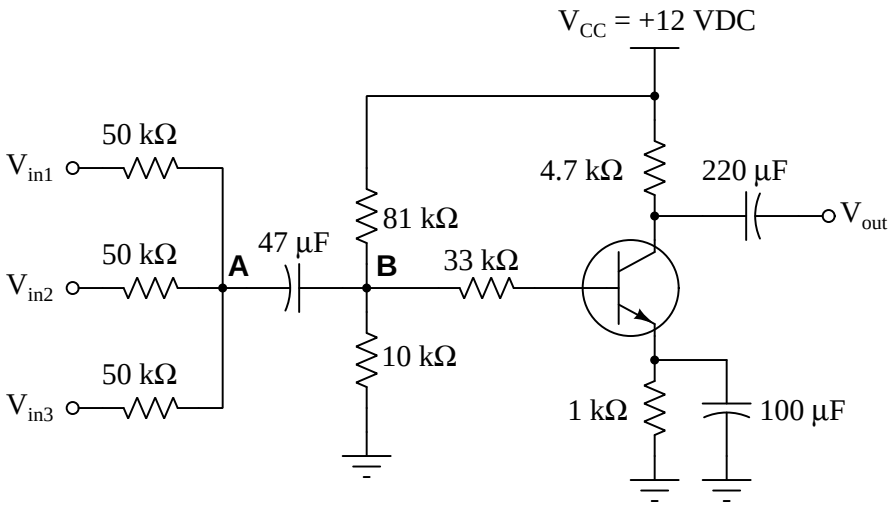


Challenges

- Is the exhibited voltage gain of this amplifier related at all to its component values?
- Modify the C code to simulate a full amplifier circuit with constant DC bias, so that the full AC wave-shape gets amplified by the transistor.

5.2.6 Three-channel mixer circuit

The following circuit is a three-channel audio *mixer* circuit, used to blend and amplify three different audio signals (coming from microphones or other signal sources):



Suppose we measured a 9 kHz sinusoidal voltage of 0.5 Volts (peak) at point **A** in the diagram, using an oscilloscope. Determine the voltage at point **B** in the circuit, after this AC signal voltage "passes through" the voltage divider biasing network.

The voltage at point **B** will be a mix of AC and DC, so be sure to express both quantities! Ignore any "loading" effects of the transistor's base current on the voltage divider.

Challenges

- What purpose does the 47 μF capacitor serve?

5.3 Diagnostic reasoning

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

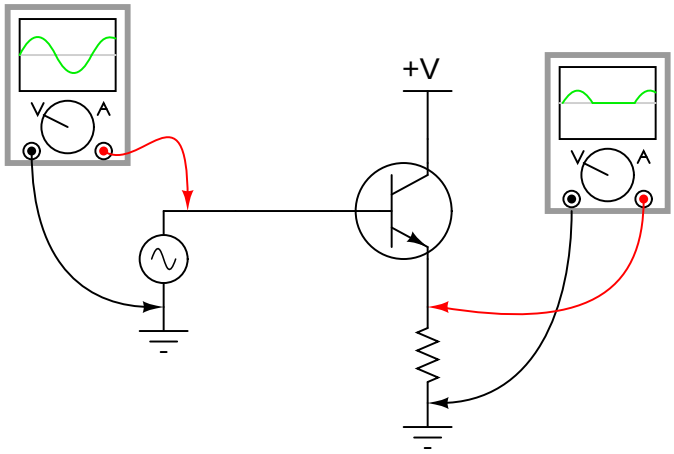
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

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

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

5.3.1 Fixing a bad amplifier design

Examine this transistor amplifier's schematic diagram as well as the oscilloscope displays, and then implement a remedy to avoid the "clipping" seen in the output signal:



Challenges

- Identify more than one solution to this problem.
- How much biasing is necessary to make this amplifier circuit reproduce the input wave-shape.
- Based on this result, would you be inclined to call this amplifier an *inverting* or a *noninverting* circuit?

5.3.2 Detecting clipping without an oscilloscope

Suppose you were building a simple transistor amplifier for audio frequency use, but did not have an oscilloscope available to check the output waveform for the presence of "clipping" caused by improper biasing. You do, however, have a pair of audio headphones you may use to *listen* to the signals.

Explain how you would use loudspeakers or headphones to check for the presence of clipping in a waveform.

Challenges

- Explain how to equip the loudspeaker or headphone with a rudimentary volume control in case it is too loud to comfortably hear.

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

References

Pilliod, James J. "Philadelphia-Pittsburgh Section of the New York-Chicago Cable", pages 60-87, *Bell System Technical Journal*, volume 1, 1922.

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 September 2025 – added a new sub-question to the "BJT amplifier biasing strategies" Conceptual Reasoning question, having students identify how to modify the circuits to make the bias adjustable.

10-11 September 2025 – added a new section title to the introductory portion of the Tutorial chapter, and made minor additions to the text of the Tutorial. Also made minor edits to the one Historical References section on vacuum tube amplifier biasing, and also added some instructor notes.

6 February 2025 – added two animations: one for an NPN BJT and another for an N-channel MOSFET showing how each type of transistor turns on. Also added a bit more introductory explanation of biasing to the Tutorial.

12 September 2024 – minor edits to the Tutorial.

10 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 April 2024 – modified the "DC signal sweep simulation program" Qualitative Reasoning question to employ a swamped-emitter CE amplifier and to have students identify the quiescent point for Class-A operation.

8 February 2024 – edited some instructor notes, and also added "negative" symbols to the voltage-sweep limit values in the "DC signal sweep simulation program" Qualitative Reasoning question.

14 September 2023 – fixed a typo courtesy of Nolan Call.

19 May 2023 – added a new Quantitative Reasoning question, this one focused on simulating an input signal sweep of a common-emitter BJT amplifier.

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.

10 February 2022 – added some Challenge questions, and fixed a grammatical error in the Tutorial chapter spotted by Jacob Stormes.

20 September 2021 – minor grammatical error correction in the Tutorial chapter.

11 September 2021 – divided the Tutorial into sections, and added more explanatory text.

5 September 2021 – added foundational concept review to the "BJT amplifier biasing strategies" Conceptual Reasoning question.

10 May 2021 – commented out or deleted empty chapters.

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

28 April 2020 – expanded upon the "Another BJT with slow-changing DC input" Conceptual problem to include an added (emitter) resistor in the circuit.

26 April 2020 – added labels to diagrams for "BJT amplifier biasing strategies" Conceptual problem.

21 April 2020 – replaced some incorrect quotation marks (" and " instead of " and "), and capitalized every instance of the word "Volt".

29 January 2020 – added Foundational Concepts to the list in the Conceptual Reasoning section.

12 January 2020 – elaborated on the loading caused by the transistor on the biasing voltage divider.

28 October 2019 – added some more content to the Tutorial chapter, plus questions from the SELEC (Socratic Electronics) project.

24 October 2019 – document first created.

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