ELTR 125 (Semiconductors 2), section 2

Recommended schedule

Day 1

Topics: *Load lines and amplifier bias calculations*
Questions: *1 through 15*
Lab Exercise: *Common-drain amplifier circuit (question 61)*

Day 2

Topics: *FET amplifier configurations*
Questions: *16 through 25*
Lab Exercise: *Common-source amplifier circuit (question 62)*

Day 3

Topics: *Push-pull amplifier circuits*
Questions: *26 through 35*
Lab Exercise: *Audio intercom circuit, push-pull output (question 63)*
Socratic Electronics animation: Push-pull transistor amplifier with crossover distortion

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Day 4

Topics: *Multi-stage and high-frequency amplifier designs*
Questions: *36 through 50*
Lab Exercise: *Audio intercom circuit, push-pull output (question 63, continued)*

Day 5

Topics: *Amplifier troubleshooting*
Questions: *51 through 60*
Lab Exercise: *Troubleshooting practice (oscillator/amplifier circuit – question 64)*

Day 6

Exam 2: *includes Amplifier circuit performance assessment*
Lab Exercise: *Troubleshooting practice (oscillator/amplifier circuit – question 64)*

General concept practice and challenge problems

Questions: *67 through the end of the worksheet*

Impending deadlines

Troubleshooting assessment (oscillator/amplifier) due at end of ELTR125, Section 3
Question 65: Troubleshooting log
Question 66: Sample troubleshooting assessment grading criteria

Skill standards addressed by this course section

EIA *Raising the Standard; Electronics Technician Skills for Today and Tomorrow*, June 1994

D Technical Skills – Discrete Solid-State Devices
D.12 Understand principles and operations of single stage amplifiers.
D.13 Fabricate and demonstrate single stage amplifiers.
D.14 Troubleshoot and repair single stage amplifiers.
E Technical Skills – Analog Circuits
E.01 Understand principles and operations of multistage amplifiers.
E.02 Fabricate and demonstrate multistage amplifiers.
E.03 Troubleshoot and repair multistage amplifiers.
E.14 Fabricate and demonstrate audio power amplifiers.
E.15 Troubleshoot and repair audio power amplifiers.

B Basic and Practical Skills – Communicating on the Job
B.01 Use effective written and other communication skills. *Met by group discussion and completion of labwork.*
B.03 Employ appropriate skills for gathering and retaining information. *Met by research and preparation prior to group discussion.*
B.04 Interpret written, graphic, and oral instructions. *Met by completion of labwork.*
B.06 Use language appropriate to the situation. *Met by group discussion and in explaining completed labwork.*
B.07 Participate in meetings in a positive and constructive manner. *Met by group discussion.*
B.08 Use job-related terminology. *Met by group discussion and in explaining completed labwork.*
B.10 Document work projects, procedures, tests, and equipment failures. *Met by project construction and/or troubleshooting assessments.*
C Basic and Practical Skills – Solving Problems and Critical Thinking
C.01 Identify the problem. *Met by research and preparation prior to group discussion.*
C.03 Identify available solutions and their impact including evaluating credibility of information, and locating information. *Met by research and preparation prior to group discussion.*
C.07 Organize personal workloads. *Met by daily labwork, preparatory research, and project management.*
C.08 Participate in brainstorming sessions to generate new ideas and solve problems. *Met by group discussion.*
D Basic and Practical Skills – Reading
D.01 Read and apply various sources of technical information (e.g. manufacturer literature, codes, and regulations). *Met by research and preparation prior to group discussion.*
E Basic and Practical Skills – Proficiency in Mathematics
E.01 Determine if a solution is reasonable.
E.02 Demonstrate ability to use a simple electronic calculator.
E.05 Solve problems and [sic] make applications involving integers, fractions, decimals, percentages, and ratios using order of operations.
E.06 Translate written and/or verbal statements into mathematical expressions.
E.09 Read scale on measurement device(s) and make interpolations where appropriate. *Met by oscilloscope usage.*
E.12 Interpret and use tables, charts, maps, and/or graphs.
E.13 Identify patterns, note trends, and/or draw conclusions from tables, charts, maps, and/or graphs.
E.15 Simplify and solve algebraic expressions and formulas.
E.16 Select and use formulas appropriately.
E.17 Understand and use scientific notation.

Common areas of confusion for students

Difficult concept: *Inverting nature of common-emitter amplifier.*

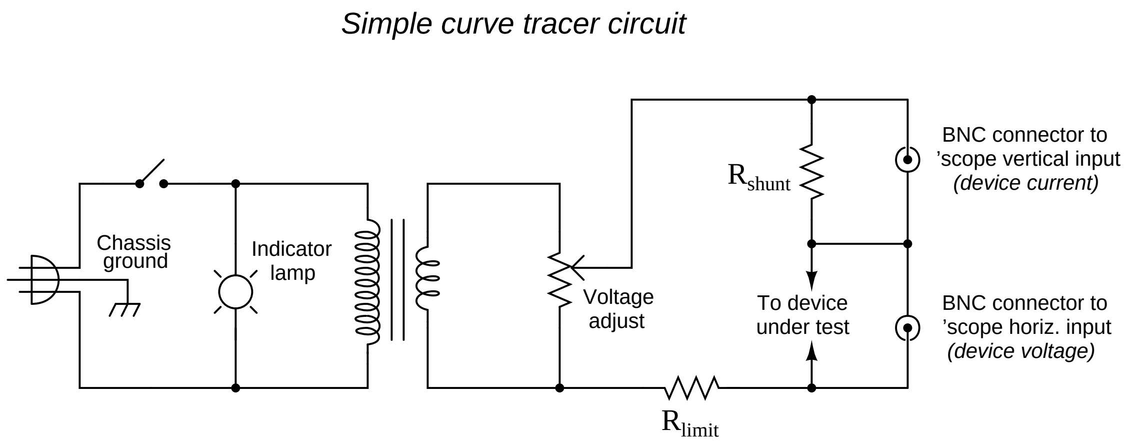
Some students find it quite difficult to grasp why the DC output voltage of a common-emitter amplifier *decreases* as the DC input voltage level increases. Step-by-step DC analysis of the circuit is the only remedy I have found to this conceptual block: getting students to carefully analyze what happens as voltages increase and decrease.

Difficult concept: *Crossover distortion.*

Crossover distortion is always a concern with class B amplifiers, because there is that point where one transistor "hands off" to the other near the zero-crossing point of the waveform. Ideally, the "hand off" is seamless, with one transistor beginning to conduct just as the other one cuts off, but this is difficult to achieve. One way to grasp the nature of the problem is to imagine a class-B amplifier with little or no bias trying to amplify a *very* small DC input voltage. Unless the input signal is enough to get one of the transistors conducting, there will be no resulting output! This is not good, as an amplifier should at least do *something* with any input signal, no matter how small.

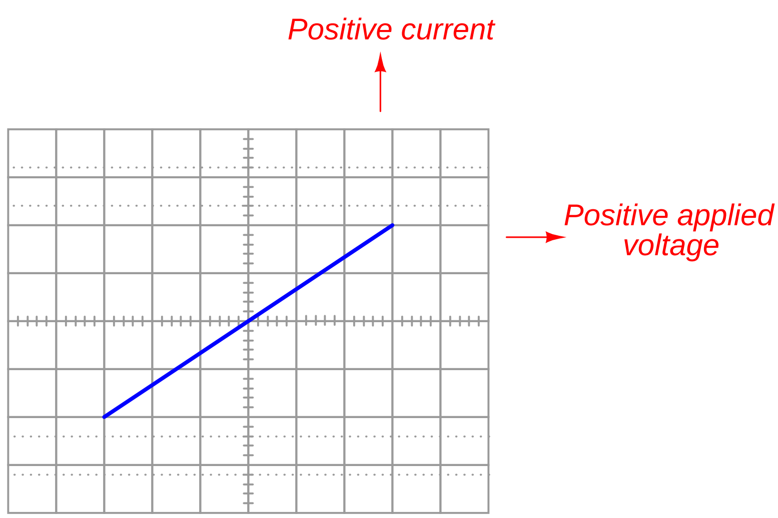
Question 1

The following schematic diagram is of a simple *curve tracer circuit*, used to plot the current/voltage characteristics of different electronic components on an oscilloscope screen:



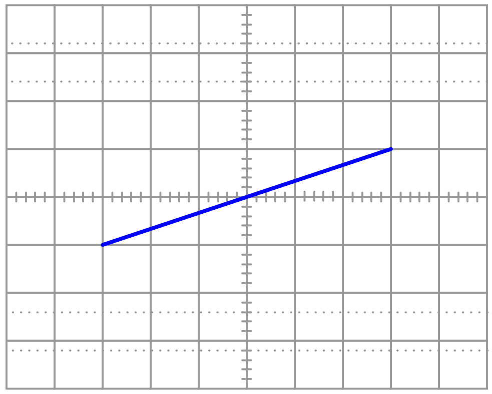
The way it works is by applying an AC voltage across the terminals of the device under test, outputting two different voltage signals to the oscilloscope. One signal, driving the horizontal axis of the oscilloscope, represents the voltage across the two terminals of the device. The other signal, driving the vertical axis of the oscilloscope, is the voltage dropped across the shunt resistor, representing current through the device. With the oscilloscope set for "X-Y" mode, the electron beam traces the device's characteristic curve.

For example, a simple resistor would generate this oscilloscope display:



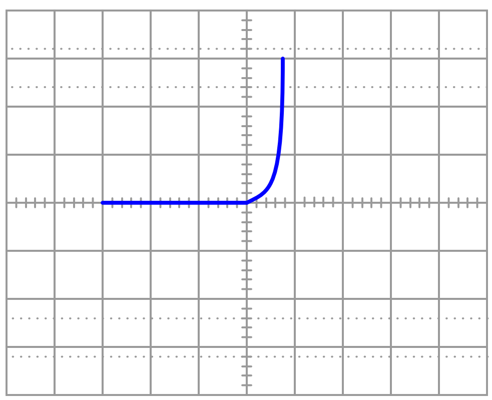
A resistor of greater value (more ohms of resistance) would generate a characteristic plot with a shallower slope, representing less current for the same amount of applied voltage:

Higher-valued resistor



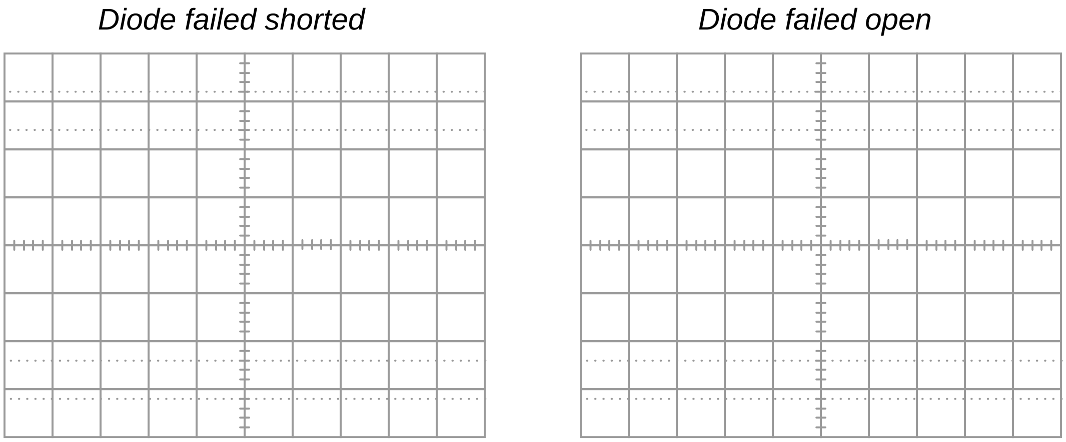
Curve tracer circuits find their real value in testing semiconductor components, whose voltage/current behaviors are nonlinear. Take for instance this characteristic curve for an ordinary rectifying diode:

Rectifying diode curve



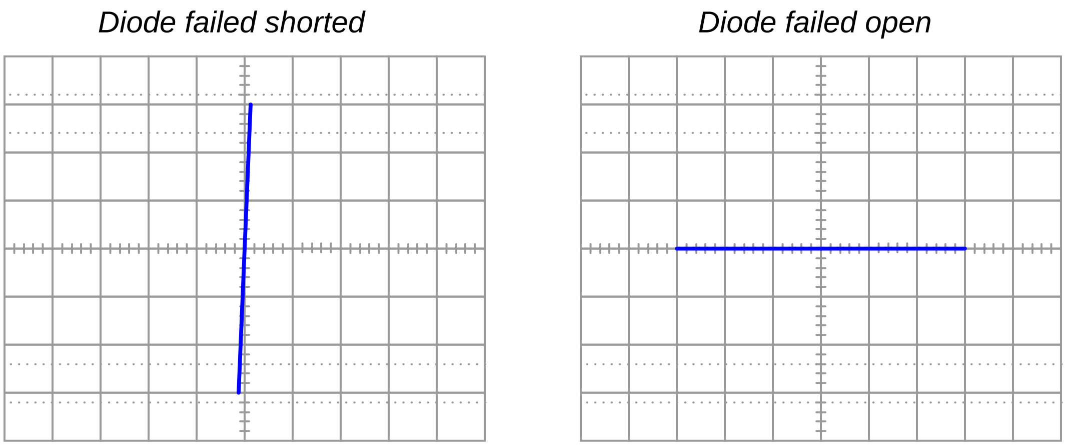
The trace is flat everywhere left of center where the applied voltage is negative, indicating no diode current when it is reverse-biased. To the right of center, though, the trace bends sharply upward, indicating exponential diode current with increasing applied voltage (forward-biased) just as the "diode equation" predicts.

On the following grids, plot the characteristic curve for a diode that is failed shorted, and also for one that is failed open:



file 02431

Answer 1



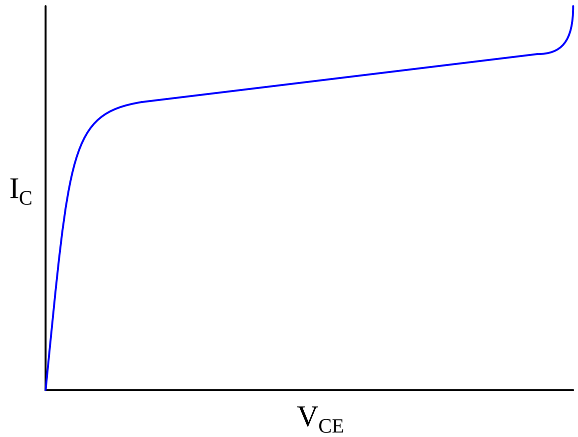
Notes 1

Characteristic curves are not the easiest concept for some students to grasp, but they are incredibly informative. Not only can they illustrate the electrical behavior of a nonlinear device, but they can also be used to diagnose otherwise hard-to-measure faults. Letting students figure out what shorted and open curves look like is a good way to open their minds to this diagnostic tool, and to the nature of characteristic curves in general.

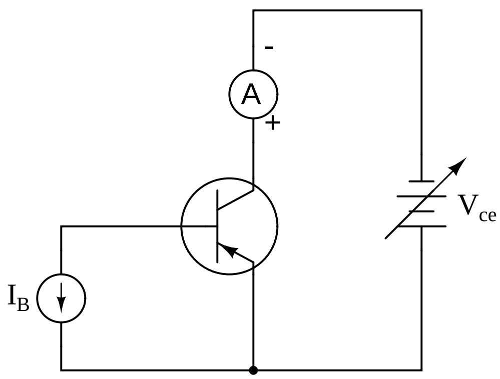
Although it is far from obvious, one of the oscilloscope channels will have to be "inverted" in order for the characteristic curve to appear in the correct quadrant(s) of the display. Most dual-trace oscilloscopes have a "channel invert" function that works well for this purpose. If engaging the channel invert function on the oscilloscope flips the wrong axis, you may reverse the connections of the test device to the curve tracer circuit, flipping both axes simultaneously. Between reversing device connections and reversing one channel of the oscilloscope, you can get the curve to plot any way you want it to!

Question 2

A very important measure of a transistor's behavior is its *characteristic curves*, a set of graphs showing collector current over a wide range of collector-emitter voltage drops, for a given amount of base current. The following plot is a typical curve for a bipolar transistor with a fixed value of base current:



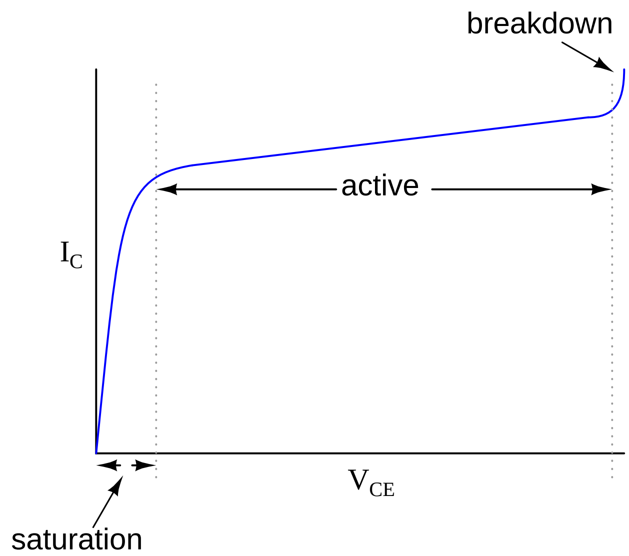
A "test circuit" for collecting data to make this graph looks like this:



Identify three different regions on this graph: *saturation*, *active*, and *breakdown*, and explain what each of these terms mean. Also, identify which part of this curve the transistor acts most like a current-regulating device.

file 00940

Answer 2



The transistor's best current-regulation behavior occurs in its "active" region.

Follow-up question: what might the characteristic curves look like for a transistor that is failed *shorted* between its collector and emitter terminals? What about the curves for a transistor that is failed *open*?

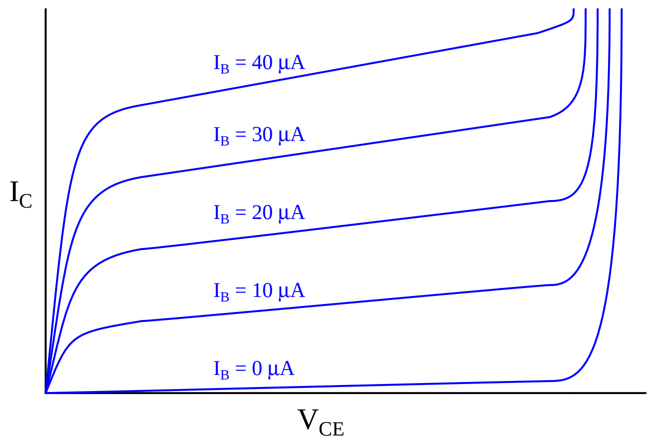
Notes 2

Ask your students what a perfect current-regulating curve would look like. How does this perfect curve compare with the characteristic curve shown in this question for a typical transistor?

A word of caution is in order: I do not recommend that a test circuit such as the one shown in the question be built for collecting curve data. If the transistor dissipates power for any substantial amount of time, it will heat up and its curves will change dramatically. Real transistor curves are generated by a piece of test equipment called a "curve tracer," which sweeps the collector-emitter voltage and steps the base current very rapidly (fast enough to "paint" all curves on an oscilloscope screen before the phosphor stops glowing).

Question 3

If a transistor is subjected to several different base currents, and the collector-emitter voltage (V_{CE}) "swept" through the full range for each of these base current values, data for an entire "family" of characteristic curves may be obtained and graphed:



What do these characteristic curves indicate about the base current's control over collector current? How are the two currents related?

file 00941

Answer 3

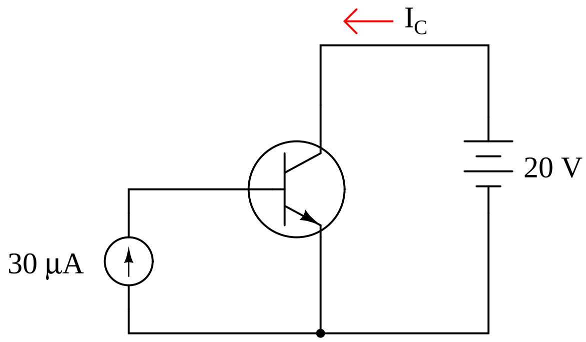
The collector current is (for the most part) directly proportional to base current while in the "active" region.

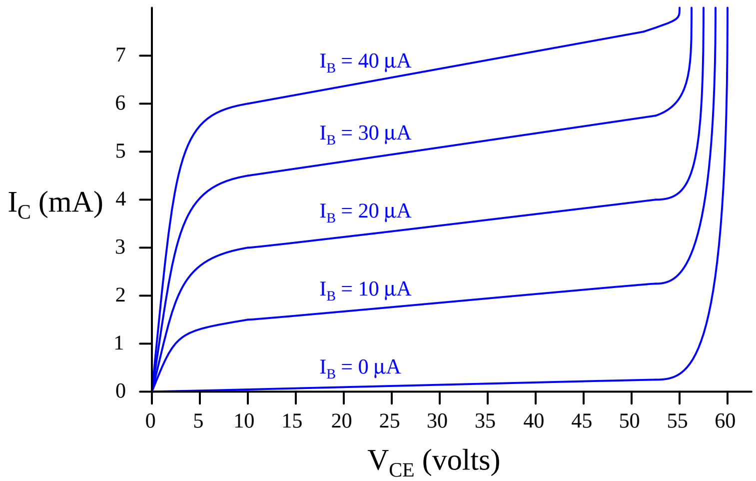
Notes 3

Ask your students what the characteristic curves would look like for a *perfect* transistor: one that was a perfect regulator of collector current over the full range of collector-emitter voltage.

Question 4

Determine the approximate amount of collector current for this transistor circuit, given the following characteristic curve set for the transistor:





file 02435

Answer 4

$I_C \approx 4.75$ mA

Follow-up question: how much will the collector current rise if the voltage source increases to 35 volts?

Notes 4

This question is nothing more than an exercise in interpreting characteristic curves.

Question 5

Explain why a bipolar junction transistor tends to regulate collector current over a wide range of collector-to-emitter voltage drops when its base current is constant. What happens internally that makes the BJT's collector current relatively independent of collector-to-emitter voltage and strongly dependent on base current?

file 02163

Answer 5

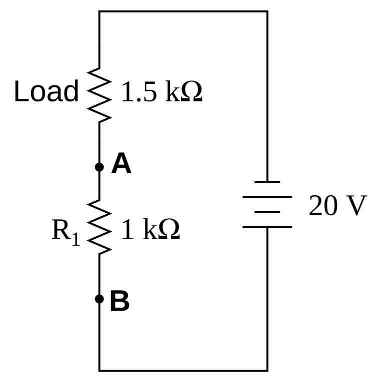
Because the BJT is a minority carrier device, the vast majority of collector current is the result of charge carriers injected from the emitter into the base region. Since this rate of charge carrier injection is a function of base-emitter junction excitation, base current (or more properly, base-to-emitter voltage) primarily determines collector current with collector-to-emitter voltage playing a relatively minor role.

Notes 5

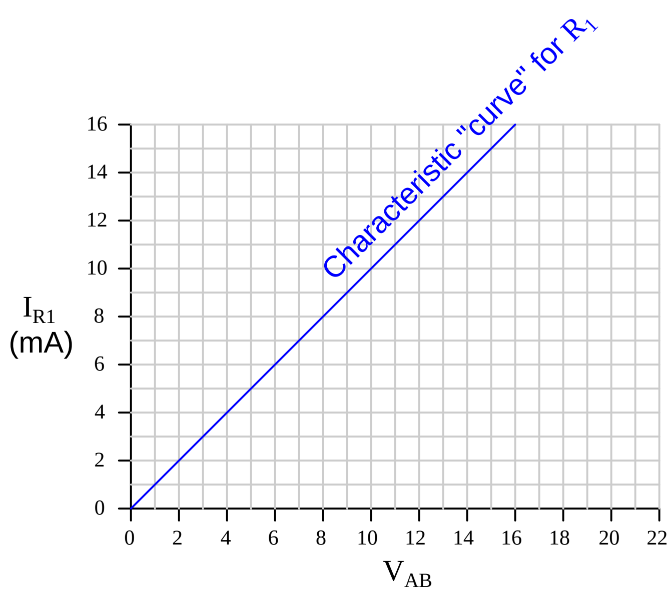
The current-regulating nature of a BJT is made more understandable by analyzing an energy band diagram of the transistor in active mode.

Question 6

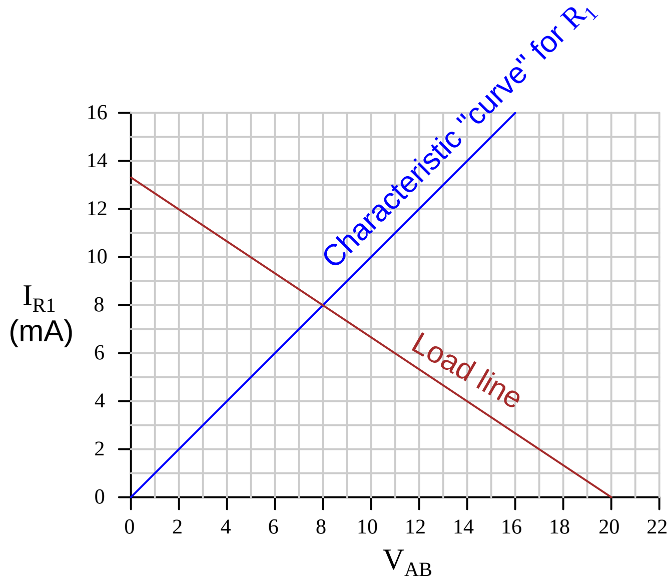
Load lines are useful tools for analyzing transistor amplifier circuits, but they may be hard to understand at first. To help you understand what "load lines" are useful for and how they are determined, I will apply one to this simple two-resistor circuit:



We will have to plot a load line for this simple two-resistor circuit along with the "characteristic curve" for resistor R_1 in order to see the benefit of a load line. Load lines really only have meaning when superimposed with other plots. First, the characteristic curve for R_1, defined as the voltage/current relationship between terminals **A** and **B**:



Next, I will plot the load line as defined by the 1.5 kΩ load resistor. This "load line" expresses the voltage available between the same two terminals (V_{AB}) as a function of the load current, to account for voltage dropped across the load:



At what value of current (I_{R1}) do the two lines intersect? Explain what is significant about this value of current.

file 00953

Answer 6

$I_R = 8$ mA is the same value of current you would calculate if you had analyzed this circuit as a simple series resistor network.

Follow-up question: you might be wondering, "what is the point of plotting a 'characteristic curve' and a 'load line' in such a simple circuit, if all we had to do to solve for current was add the two resistances and divide that total resistance value into the total voltage?" Well, to be honest, there is no point in analyzing such a simple circuit in this manner, except to illustrate *how* load lines work. My follow-up question to you is this: where would plotting a load line actually be helpful in analyzing circuit behavior? Can you think of any modifications to this two-resistor circuit that would require load line analysis in order to solve for current?

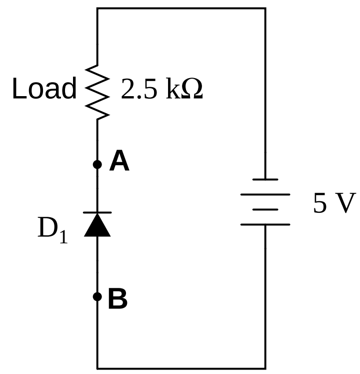
Notes 6

While this approach to circuit analysis may seem silly – using load lines to calculate the current in a two-resistor circuit – it demonstrates the principle of load lines in a context that should be obvious to students at this point in their study. Discuss with your students how the two lines are obtained (one for resistor R_1 and the other plotting the voltage available to R_1 based on the total source voltage and the load resistor's value).

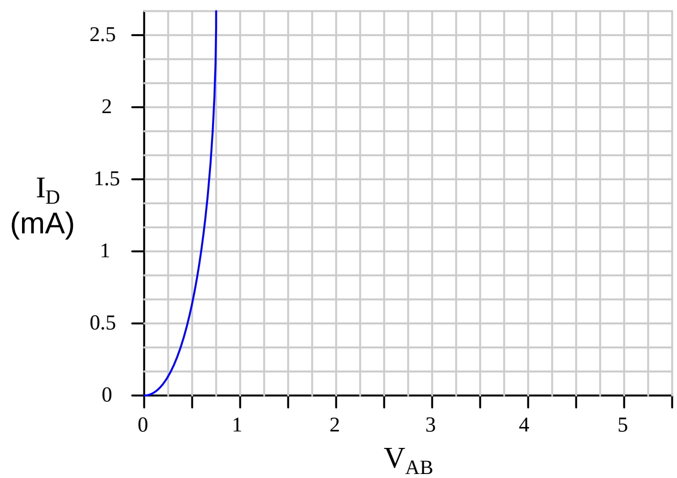
Also, discuss the significance of the two line intersecting. Mathematically, what does the intersection of two graphs mean? What do the coordinate values of the intersection point represent in a system of simultaneous functions? How does this principle relate to an electronic circuit?

Question 7

Load lines are useful tools for analyzing transistor amplifier circuits, but they may be applied to other types of circuits as well. Take for instance this diode-resistor circuit:



The diode's characteristic curve is already plotted on the following graph. Your task is to plot the load line for the circuit on the same graph, and note where the two lines intersect:

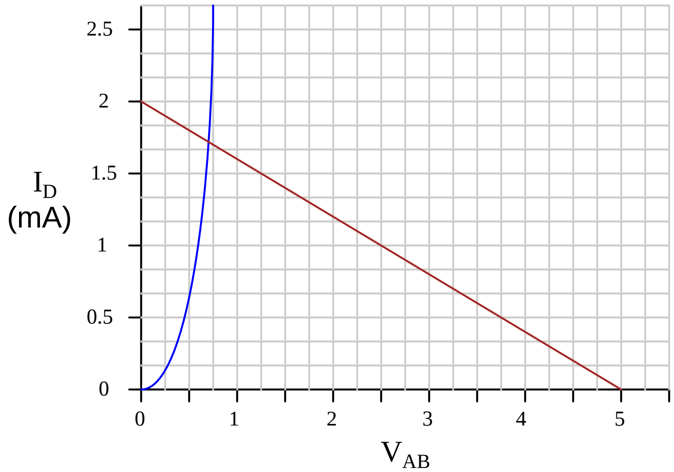


What is the practical significance of these two plots' intersection?

file 00954

Answer 7

The two lines intersect at a current of approximately 1.72 mA:



Follow-up question: explain why the use of a load line greatly simplifies the determination of circuit current in such a diode-resistor circuit.

Challenge question: suppose the resistor value were increased from 2.5 kΩ to 10 kΩ. What difference would this make in the load line plot, and in the intersection point between the two plots?

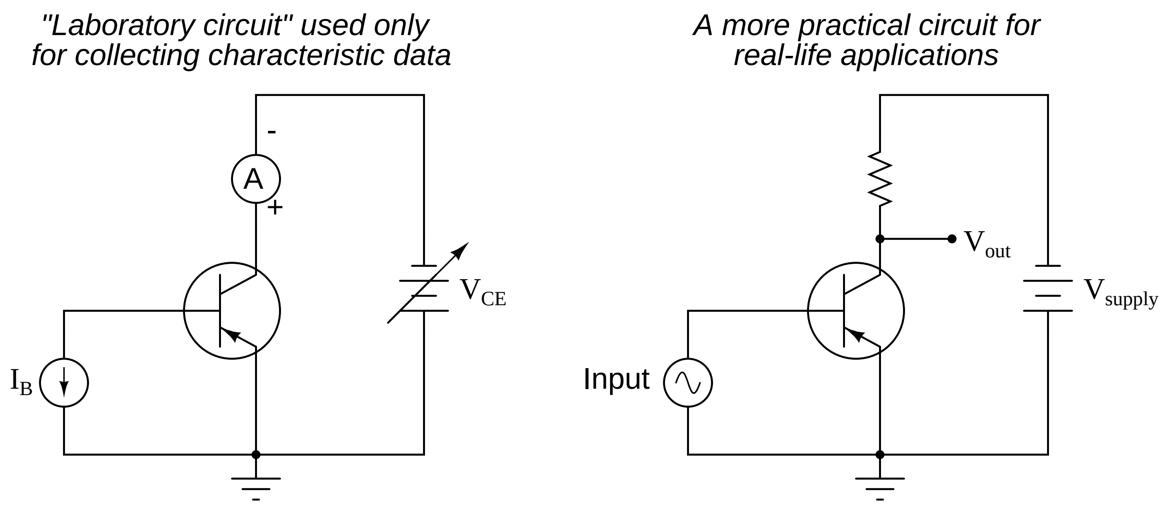
Notes 7

While this approach to circuit analysis may seem silly – using load lines to calculate the current in a diode-resistor circuit – it demonstrates the principle of load lines in a context that should be obvious to students at this point in their study. Discuss with your students how the load line is obtained for this circuit, and why it is straight while the diode's characteristic curve is not.

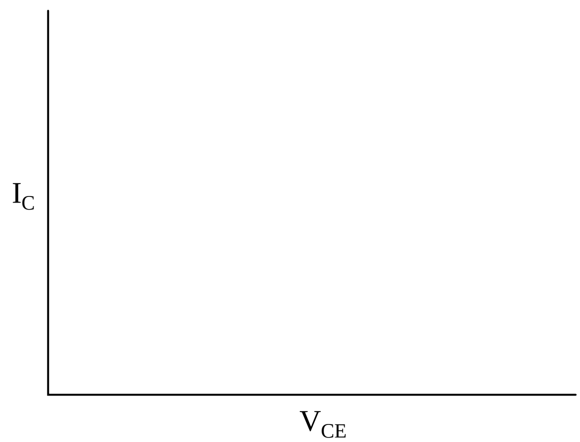
Also, discuss the significance of the two line intersecting. Mathematically, what does the intersection of two graphs mean? What do the coordinate values of the intersection point represent in a system of simultaneous functions? How does this principle relate to an electronic circuit?

Question 8

Though the characteristic curves for a transistor are usually generated in a circuit where base current is constant and the collector-emitter voltage (V_{CE}) is varied, this is usually not how transistor amplifier circuits are constructed. Typically, the base current varies with the input signal, and the collector power supply is a fixed-voltage source:



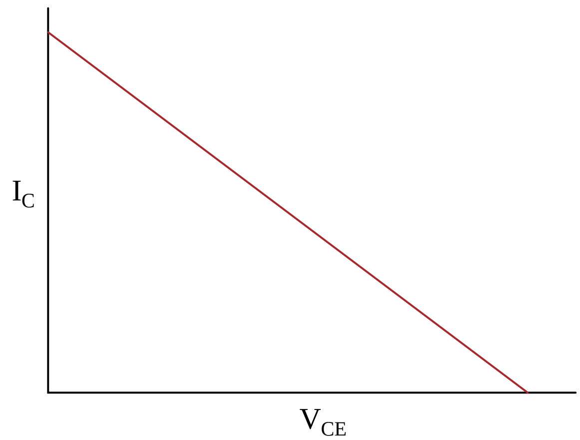
The presence of a load resistor in the circuit adds another dynamic to the circuit's behavior. Explain what happens to the transistor's collector-emitter voltage (V_{CE}) as the collector current increases (dropping more battery voltage across the load resistor), and qualitatively plot this *load line* on the same type of graph used for plotting transistor curves:



file 00943

Answer 8

Because there are no numbers along the axes of this graph, the best you can do is plot the general slope of the line, from upper-left to lower-right:

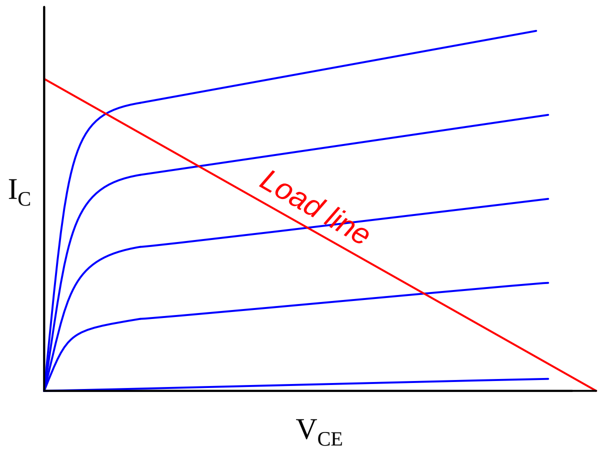


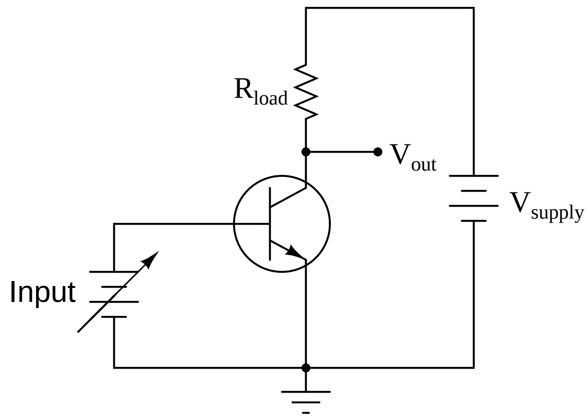
Notes 8

Ask your student why this plot is straight, and not curved like the transistor's characteristic function.

Question 9

Describe what a *load line* is, at it appears superimposed on this graph of characteristic transistor curves:



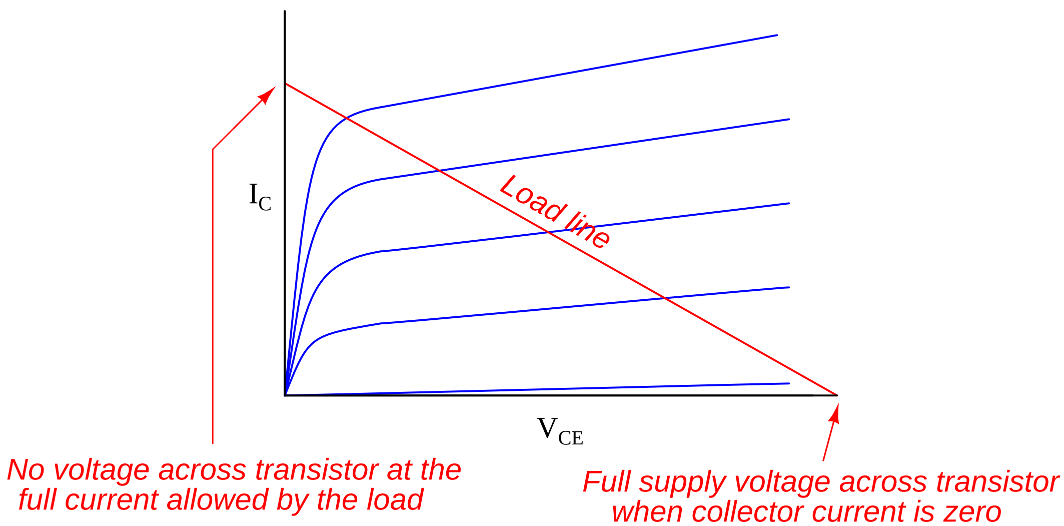


What exactly does the load line represent in the circuit?

file 01681

Answer 9

A *load line* is a plot showing the amount of collector-emitter voltage available to the transistor (V_{CE}) for any given collector current:



Follow-up question: why are load lines always straight, and not bent as the transistor characteristic curves are? What is it that ensures load line plots will always be linear functions?

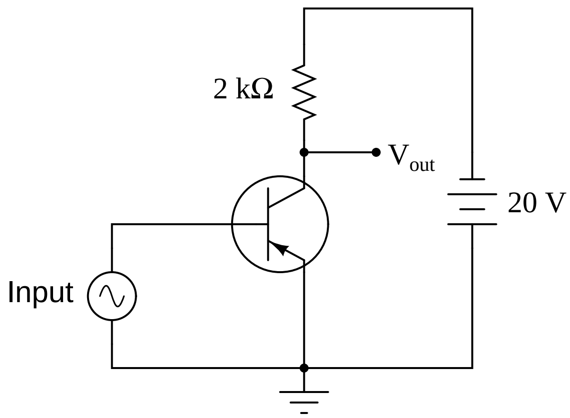
Notes 9

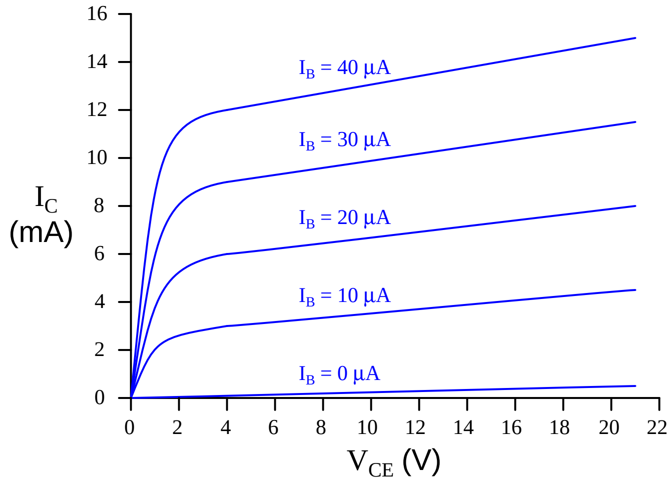
It is very important for students to grasp the ontological nature of load lines (i.e. *what they are*) if they are to use them frequently in transistor circuit analysis. This, sadly, is something often not grasped by students when they begin to study transistor circuits, and I place the blame squarely on textbooks (and instructors) who don't spend enough time introducing the concept.

My favorite way of teaching students about load lines is to have them plot load lines for non-transistor circuits, such as voltage dividers (with one of two resistors labeled as the "load," and the other resistor made variable) and diode-resistor circuits.

Question 10

Calculate and superimpose the *load line* for this circuit on top of the transistor's characteristic curves:



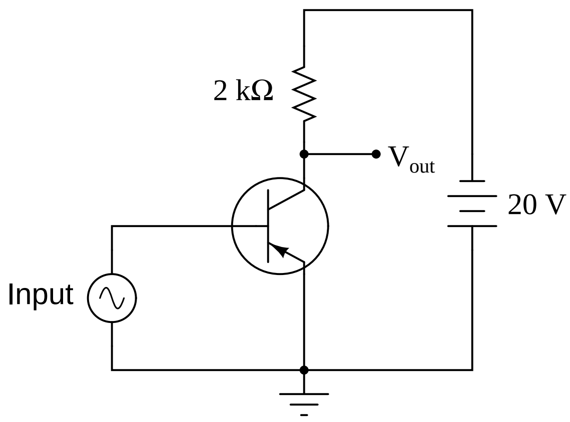


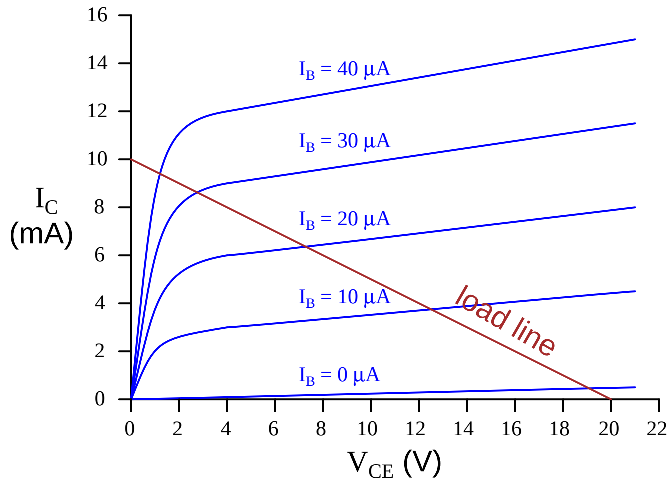
Then, determine the amount of collector current in the circuit at the following base current values:

- $I_B = 10\ \mu$A
- $I_B = 20\ \mu$A
- $I_B = 30\ \mu$A
- $I_B = 40\ \mu$A

file 00944

Answer 10





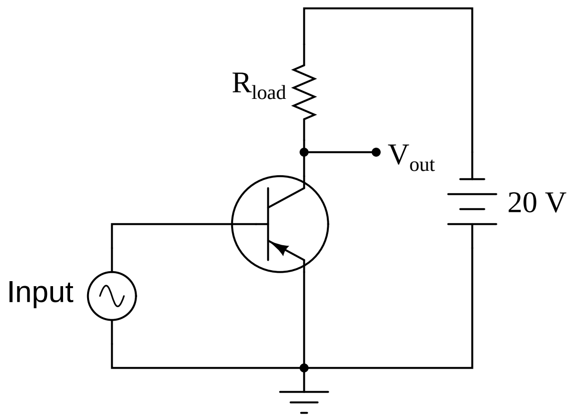
- $I_B = 10\ \mu$A ; $I_C = 3.75$ mA
- $I_B = 20\ \mu$A ; $I_C = 6.25$ mA
- $I_B = 30\ \mu$A ; $I_C = 8.5$ mA
- $I_B = 40\ \mu$A ; $I_C = 9.5$ mA

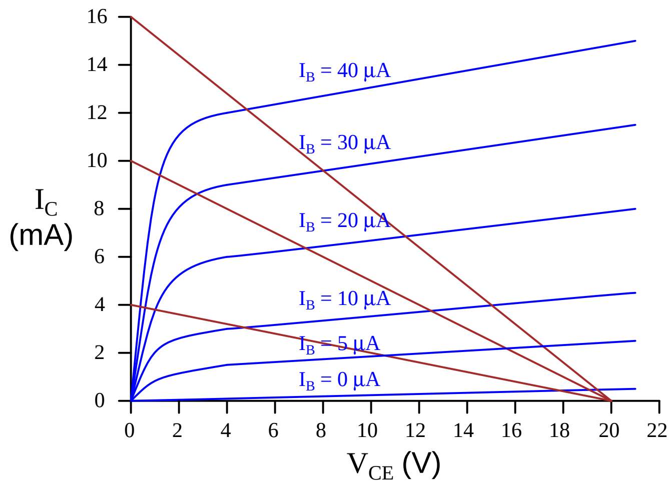
Notes 10

It would be good to point out something here: superimposing a linear function on a set of nonlinear functions and looking for the intersection points allows us to solve for multiple variables in a nonlinear mathematical system. Normally, only *linear* systems of equations are considered "solvable" without resorting to very time-consuming arithmetic computations, but here we have a powerful (graphical) tool for approximating the values of variables in a nonlinear system. Since approximations are the best we can hope for in transistor circuits anyway, this is good enough!

Question 11

In this graph you will see three different load lines plotted, representing three different values of load resistance in the amplifier circuit:





Which one of the three load lines represents the largest value of load resistance (R_{load})? Which of the three load lines will result in the greatest amount of change in voltage drop across the transistor (ΔV_{CE}) for any given amount of base current change (ΔI_B)? What do these relationships indicate about the load resistor's effect on the amplifier circuit's *voltage gain*?

file 00955

Answer 11

The load line closest to horizontal represents the largest value of load resistance, and it also represents the condition in which V_{CE} will vary the most for any given amount of base current (input signal) change.

Notes 11

This question challenges students to relate load resistor values to load lines, and both to the practical measure of voltage gain in a simple amplifier circuit. As an illustration, ask the students to analyze changes in the circuit for an input signal that varies between 5 μA and 10 μA for the three different load resistor values. The difference in ΔV_{CE} should be very evident!

Question 12

An important parameter of transistor amplifier circuits is the *Q point*, or *quiescent operating point*. The "Q point" of a transistor amplifier circuit will be a single point somewhere along its load line.

Describe what the "Q point" actually means for a transistor amplifier circuit, and how its value may be altered.

file 00952

Answer 12

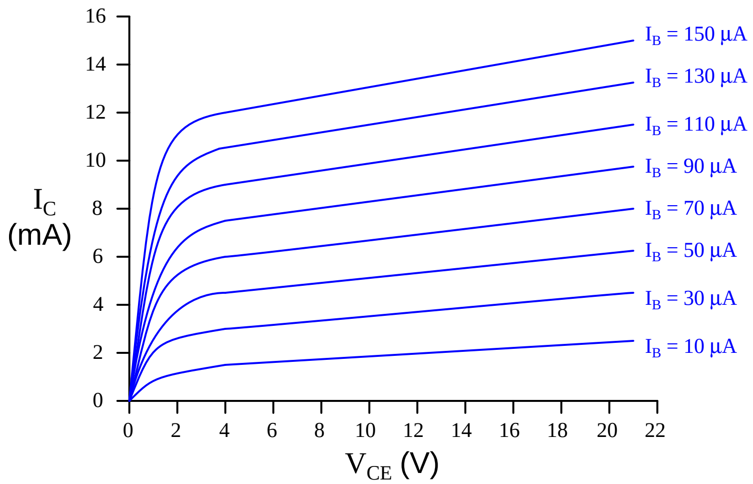
The "Q point" for a transistor amplifier circuit is the point along its operating region in a "quiescent" condition: when there is no input signal being amplified.

Notes 12

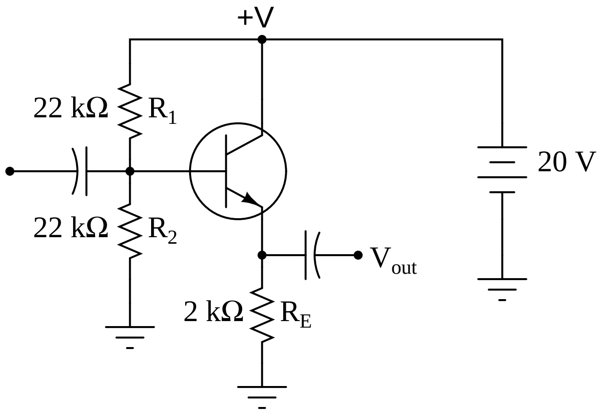
Q points are very important in the design process of transistor amplifiers, but again students often seem to fail to grasp the actual meaning of the concept. Ask your students to explain how the load line formed by the load resistance, and characteristic curves of the transistor, describe all the possible operating conditions of collector current and V_{CE} for that amplifier circuit. Then discuss how the status of that circuit is defined *at any single point in time* along those graphs (by a line, a curve, or a point?).

Question 13

The following graph is a family of characteristic curves for a particular transistor:

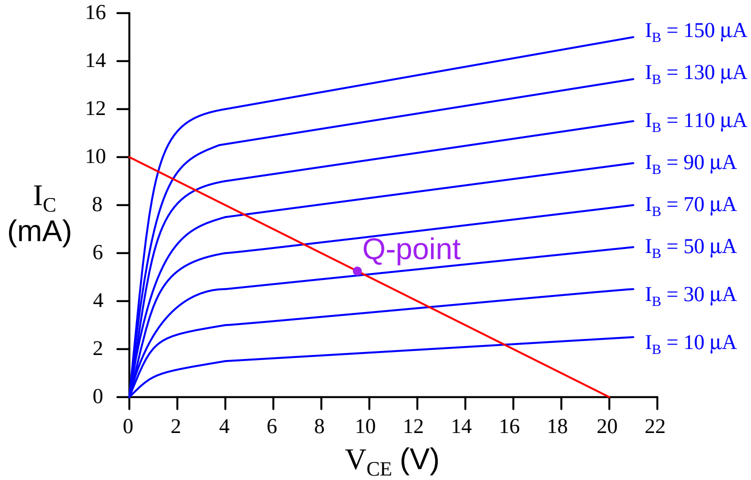


Draw the load line and identify the Q-point on that load line for a common-collector amplifier circuit using this transistor:



file 02244

Answer 13



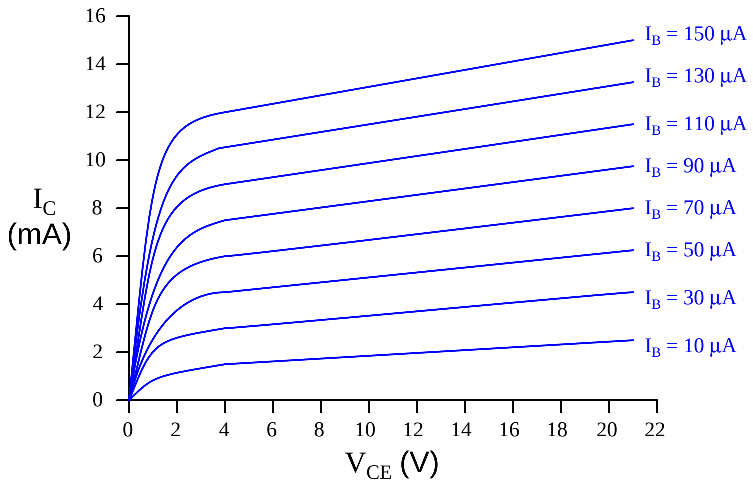
Follow-up question: the position of this circuit's Q-point is approximately mid-way along the load line. Would you say this is indicative of an amplifier biased for Class A operation, or for some other class of operation? Explain your answer.

Notes 13

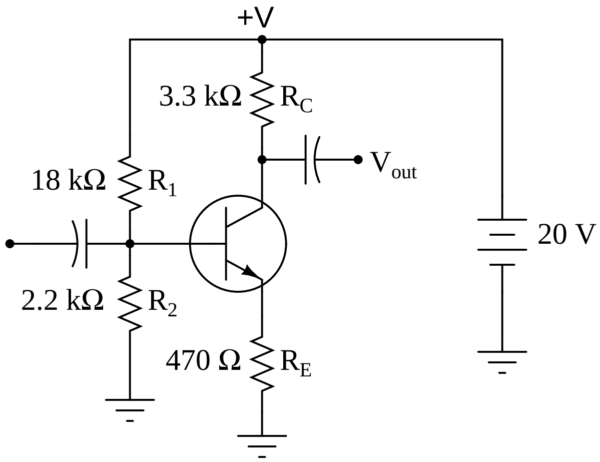
The purpose of this question is to get students to relate their existing knowledge of common-collector circuit DC analysis to the concept of load lines and Q-points. Ask your students to share their analysis techniques with the whole class.

Question 14

The following graph is a family of characteristic curves for a particular transistor:

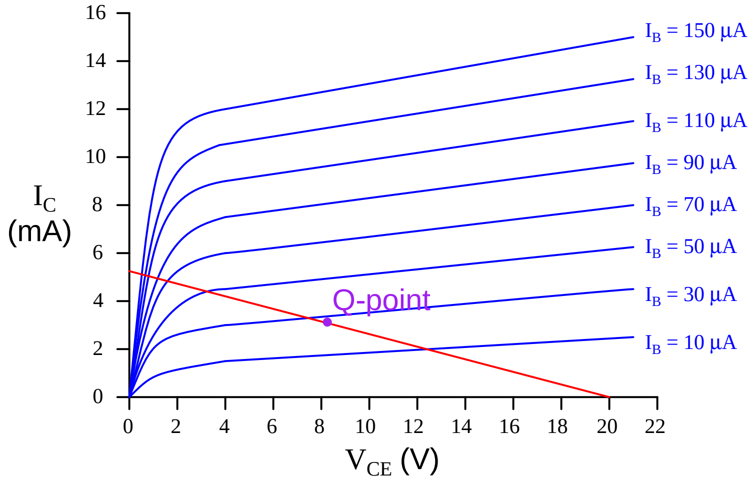


Draw the load line and identify the Q-point on that load line for a common-emitter amplifier circuit using this transistor:



file 02245

Answer 14



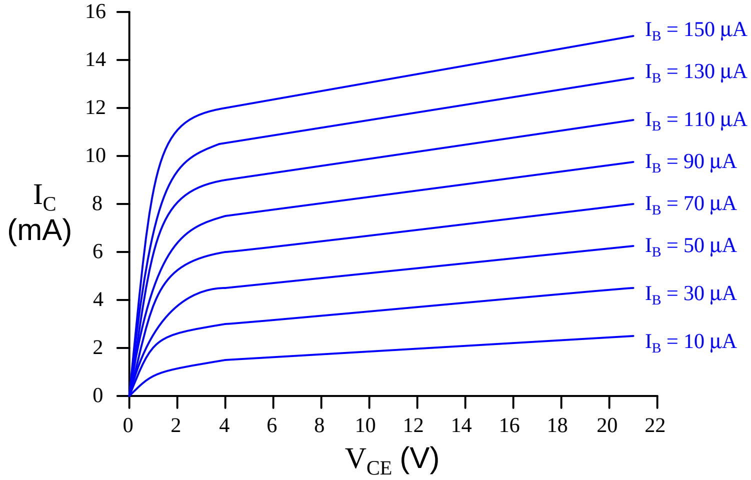
Follow-up question: determine what would happen to the Q-point if resistor R_2 (the 2.2 kΩ biasing resistor) were to fail open.

Notes 14

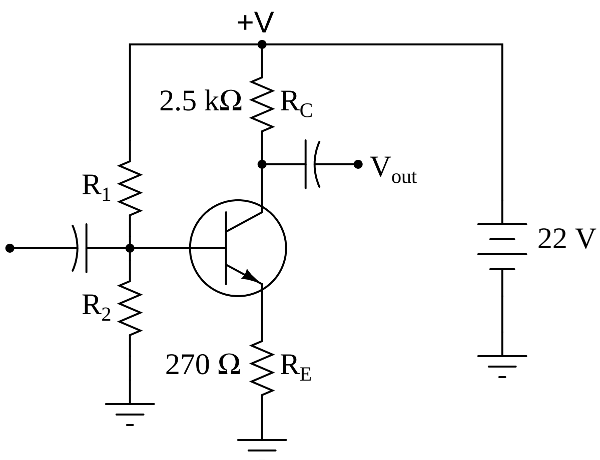
The purpose of this question is to get students to relate their existing knowledge of common-emitter circuit DC analysis to the concept of load lines and Q-points. Ask your students to share their analysis techniques with the whole class.

Question 15

The following graph is a family of characteristic curves for a particular transistor:



Superimpose on that graph a load line for the following common-emitter amplifier circuit using the same transistor:

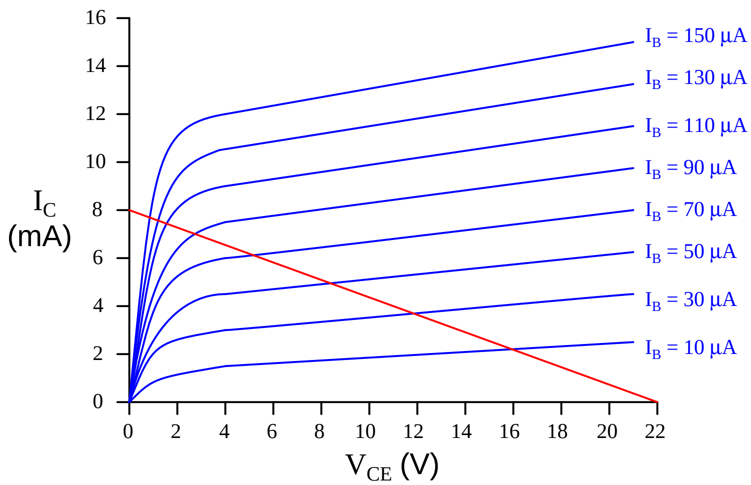


Also determine some bias resistor values (R_1 and R_2) that will cause the Q-point to rest approximately mid-way on the load line.

R_1 = R_2 =

file 02246

Answer 15



There are several pairs of resistor values that will work adequately to position the Q-point at the center of the load line. I leave this an an exercise for you to work through and discuss with your classmates!

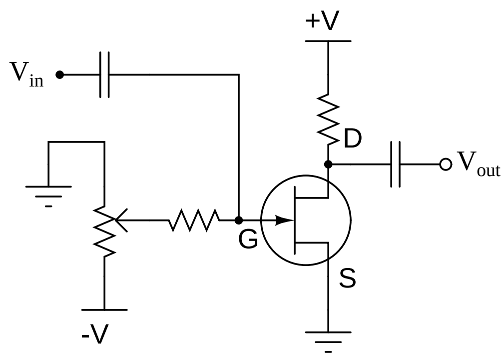
Follow-up question: determine what would happen to the Q-point if resistor R_2 (the 2.2 kΩ biasing resistor) were to fail open.

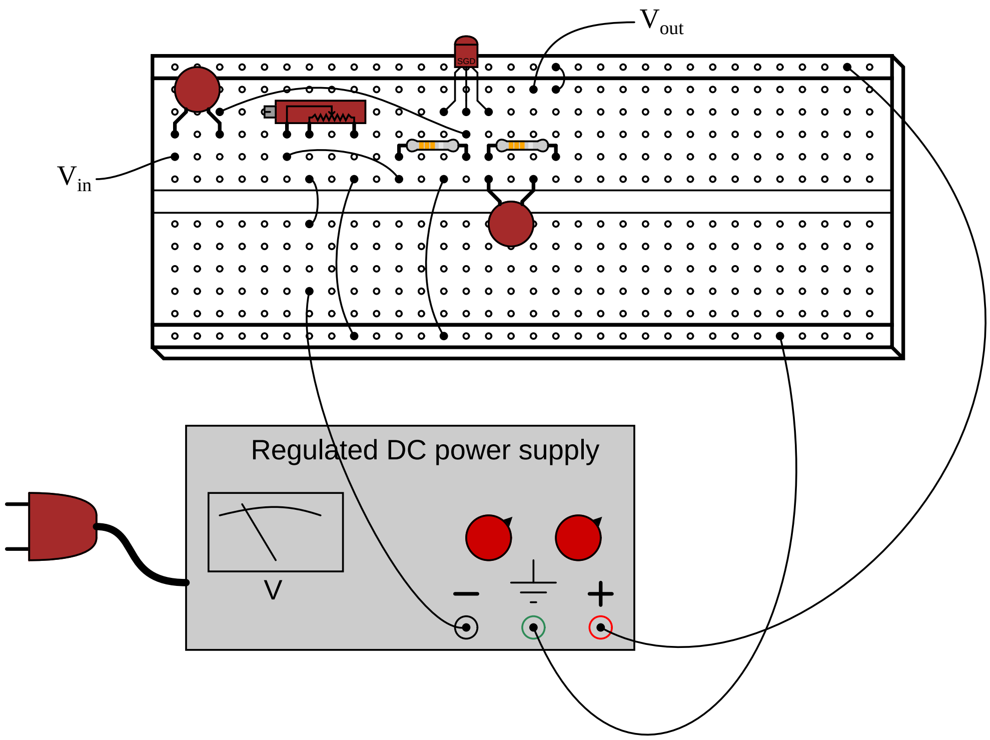
Notes 15

This is a very practical question, as technicians and engineers alike need to choose proper biasing so their amplifier circuits will operate in the intended class (A, in this case). There is more than one proper answer for the resistor values, so be sure to have your students share their solutions with the whole class so that many options may be explored.

Question 16

A student builds this transistor amplifier circuit on a solderless "breadboard":





The purpose of the potentiometer is to provide an adjustable DC bias voltage for the transistor, so it may be operated in Class-A mode. After some adjustment of this potentiometer, the student is able to obtain good amplification from the transistor (signal generators and oscilloscopes have been omitted from the illustration for simplicity).

Later, the student accidently adjusts the power supply voltage to a level beyond the JFET's rating, destroying the transistor. Re-setting the power supply voltage back where the student began the experiment and replacing the transistor, the student discovers that the biasing potentiometer must be re-adjusted to achieve good Class-A operation.

Intrigued by this discovery, the student decides to replace this transistor with a third (of the same part number, of course), just to see if the biasing potentiometer needs to be adjusted again for good Class-A operation. It does.

Explain why this is so. Why must the gate biasing potentiometer be re-adjusted every time the transistor is replaced, even if the replacement transistor(s) are of the exact same type?

file 01180

Answer 16

This amplifier circuit uses *gate bias*, which is a notoriously unstable method of biasing a JFET amplifier circuit.

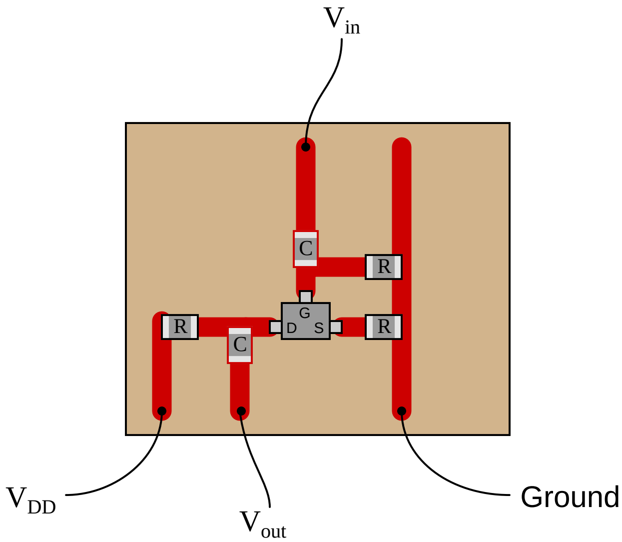
Notes 16

Ask your students to explain exactly what it is that causes the Q point of this amplifier circuit to change with each new transistor. Is it something in the transistor itself, or in some other part of the circuit?

Given the instability of gate biasing, should this method be used in mass-produced amplifier circuits? Ask your students to elaborate on why or why not.

Question 17

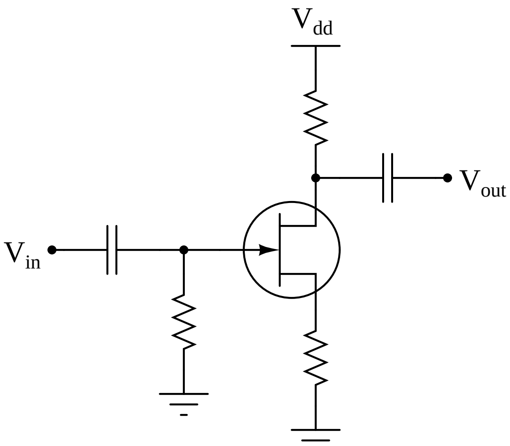
The simple JFET amplifier circuit shown here (built with surface-mount components) employs a biasing technique known as *self-biasing*:



Self-biasing provides much greater Q-point stability than gate-biasing. Draw a schematic diagram of this circuit, and then explain how self-biasing works.

file 01181

Answer 17



Self-biasing uses the negative feedback created by a source resistor to establish a "natural" Q-point for the amplifier circuit, rather than having to supply an external voltage as is done with gate biasing.

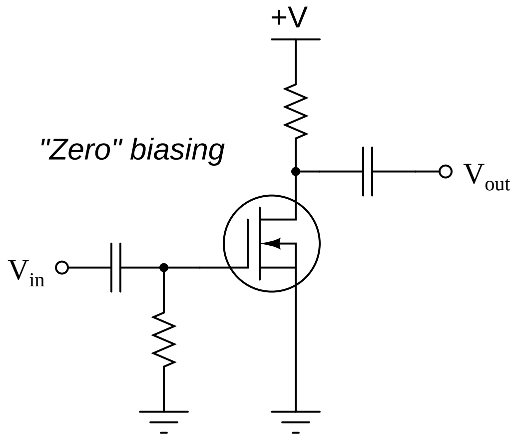
Notes 17

The concept of negative feedback is extremely important in electronic circuits, but it is not easily grasped by all. Self-biasing of JFET transistors is a relatively easy-to-understand application of negative feedback, so be sure to take advantage of this opportunity to explore the concept with your students.

Ask your students to explain why Q-point stability is a desirable feature for mass-produced amplifier circuits, as well as circuits subject to component-level repair.

Question 18

A common means of biasing a depletion-type IGFET is called *zero biasing*. An example circuit is shown below:



This may appear similar to *self-biasing* as seen with JFET amplifier circuits, but it is not. Zero biasing only works with IGFET amplifier circuits. Explain why this is so.

file 01193

Answer 18

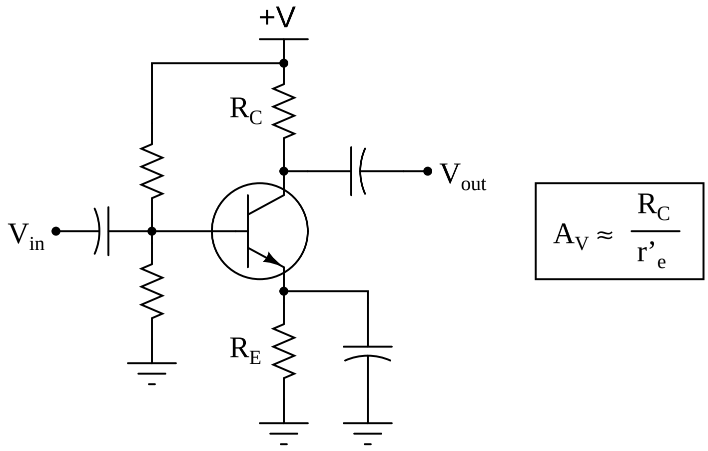
The natural Q-point of a depletion-type IGFET occurs with a gate-to-source voltage of 0 volts. This is very different from either bipolar junction (BJT) or junction field-effect (JFET) transistors.

Follow-up question: will "zero" biasing work with enhancement-mode IGFETs as well? Explain why or why not.

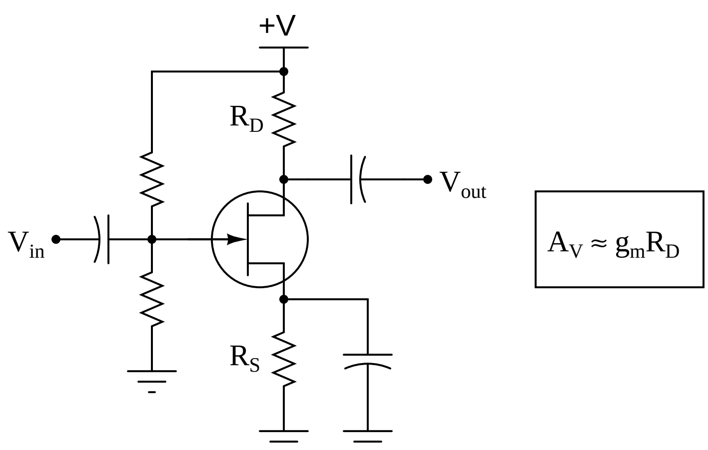
Notes 18

This question provides students with an opportunity to review IGFET theory, and to differentiate between depletion-mode and enhancement-mode types, which is a subject of much confusion among students new to the topic.

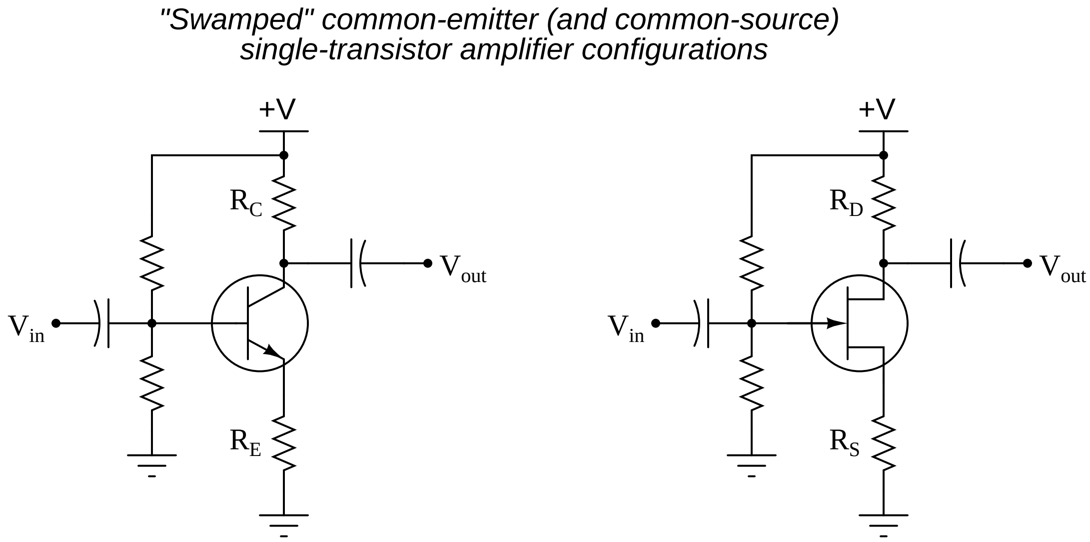
The voltage gain for a "bypassed" common-emitter BJT amplifier circuit is as follows:



Common-source JFET amplifier circuits are very similar:



One of the problems with "bypassed" amplifier configurations such as the common-emitter and common-source is voltage gain variability. It is difficult to keep the voltage gain stable in either type of amplifier, due to changing factors within the transistors themselves which cannot be tightly controlled (r'_e and g_m, respectively). One solution to this dilemma is to "swamp" those uncontrollable factors by not bypassing the emitter (or source) resistor. The result is greater A_V stability at the expense of A_V magnitude:



Write the voltage gain equations for both "swamped" BJT and JFET amplifier configurations, and explain why they are similar to each other.

file 02250

Answer 19

$$A_V \approx \frac{R_C}{R_E} \qquad \text{Common-emitter BJT amplifier}$$

$$A_V \approx \frac{R_D}{R_S} \qquad \text{Common-source JFET amplifier}$$

I'll let you explain why these two voltage gain approximations share the same form. Hint: it has something to do with the magnitudes of the currents through each transistor terminal!

Follow-up question: explain mathematically why the emitter/source resistances succeed in "swamping" r'_e and g_m, respectively, in these more precise formulae. You should provide typical values for r'_e and g_m as part of your argument:

$$A_V = \frac{R_C}{R_E + r'_e} \qquad \text{Common-emitter BJT amplifier}$$

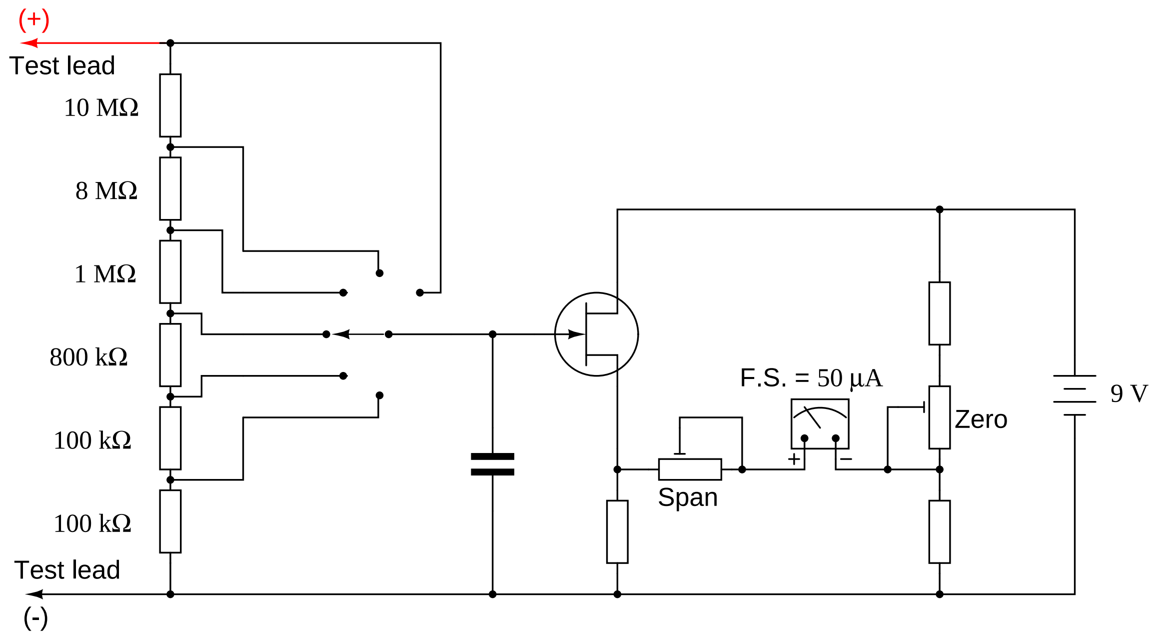
$$A_V = \frac{R_D}{R_S + \frac{1}{g_m}} \qquad \text{Common-source JFET amplifier}$$

Notes 19

Swamping is a common engineering practice, and one that students would do well to understand. It is unfortunate that parameters such as dynamic emitter resistance (r'_e) and transconductance (g_m) are so variable, but this does not have to be the end of the story. To be able to work around practical limitations such as these is the essence of engineering practice, in my opinion.

Question 20

The circuit shown here is a precision DC voltmeter:



Explain why this circuit design requires the use of a field-effect transistor, and not a bipolar junction transistor (BJT).

Also, answer the following questions about the circuit:

- Explain, step by step, how an increasing input voltage between the test probes causes the meter movement to deflect further.
- If the most sensitive range of this voltmeter is 0.1 volts (full-scale), calculate the other range values, and label them on the schematic next to their respective switch positions.
- What type of JFET configuration is this (common-gate, common-source, or common-drain)?
- What purpose does the capacitor serve in this circuit?
- What detrimental effect would result from installing a capacitor that was too large?
- Estimate a reasonable value for the capacitor's capacitance.
- Explain the functions of the "Zero" and "Span" calibration potentiometers.

file 01184

Answer 20

The voltage ranges for this meter are as follows:

- 0.1 volts
- 0.2 volts
- 1.0 volts
- 2.0 volts
- 10 volts
- 20 volts

The JFET is being used in the *common drain* configuration. A reasonable value for the capacitor would be 0.01 μF.

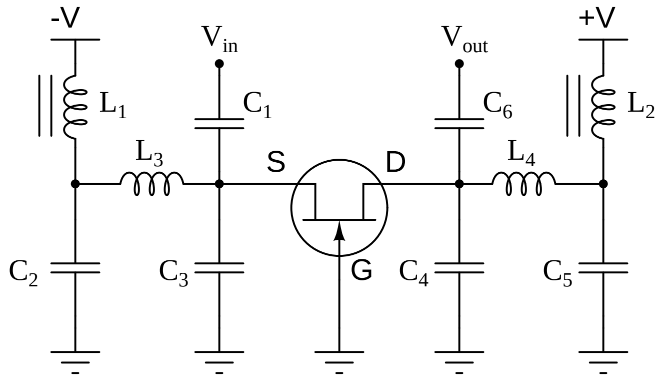
Notes 20

This relatively simple DC voltage amplifier circuit provides a wealth of educational value, both for understanding the function of the JFET, and also for review on past electrical/electronics concepts.

Note: John Markus' Guidebook of Electronic Circuits, first edition, page 469, provided the inspiration for this circuit.

Question 21

This is a schematic of an RF amplifier using a JFET as the active element:



What configuration of JFET amplifier is this (common drain, common gate, or common source)? Also, explain the purpose of the two iron-core inductors in this circuit. Hint: inductors L_1 and L_2 are often referred to as *RF chokes*.

file 01178

Answer 21

This is a common-gate amplifier. The iron-core inductors block ("choke") the high-frequency AC signals from getting to the DC power supply.

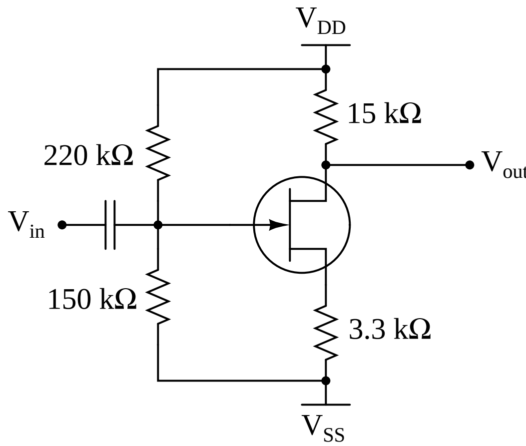
Notes 21

Be sure to ask your students *why* it would not be good for the RF signals to find their way to the DC power supply. There is more than one possible answer to this question!

This schematic was derived from an evaluation amplifier schematic shown in an ON Semiconductor J308/J309/J310 transistor datasheet.

Question 22

Calculate the approximate input impedance of this JFET amplifier circuit:



Explain why it is easier to calculate the Z_{in} of a JFET circuit like this than it is to calculate the Z_{in} of a similar bipolar transistor amplifier circuit. Also, explain how calculation of this amplifier's *output* impedance compares with that of a similar BJT amplifier circuit – same approach or different approach?

file 01177

Answer 22

$Z_{in} = 89.2$ kΩ

Notes 22

Ask your students to explain why input impedance is an important factor in amplifier design. Why should we care how much input impedance an amplifier has?

Also, ask your students to explain why such high-value bias resistors (150 kΩ and 220 kΩ) would probably not be practical in a BJT amplifier circuit.

Question 23

Define what a *common-source* transistor amplifier circuit is. What distinguishes this amplifier configuration from the other single-FET amplifier configurations, namely *common-drain* and *common-gate*? What configuration of BJT amplifier circuit does the common-source FET circuit most resemble in form and behavior?

Also, describe the typical voltage gains of this amplifier configuration, and whether it is *inverting* or *noninverting*.

file 02247

Answer 23

The common-source amplifier configuration is defined by having the input and output signals referenced to the gate and drain terminals (respectively), with the source terminal of the transistor typically having a low AC impedance to ground and thus being "common" to one pole of both the input and output voltages.

The common-source amplifier configuration most resembles the common-emitter BJT amplifier configuration in both form and behavior.

Common-source amplifiers are characterized by moderate voltage gains, and an inverting phase relationship between input and output.

Notes 23

The answers to the question may be easily found in any fundamental electronics text, but it is important to ensure students know *why* these characteristics are such. I always like to tell my students, "Memory *will* fail you, so you need to build an understanding of *why* things are, not just *what* things are."

One exercise you might have your students do is come up to the board in front of the room and draw an example of this circuit, then everyone may refer to the drawn image when discussing the circuit's characteristics.

Question 24

Define what a *common-gate* transistor amplifier circuit is. What distinguishes this amplifier configuration from the other single-FET amplifier configurations, namely *common-drain* and *common-source*? What configuration of BJT amplifier circuit does the common-gate FET circuit most resemble in form and behavior?

Also, describe the typical voltage gains of this amplifier configuration, and whether it is *inverting* or *noninverting*.

file 02248

Answer 24

The common-gate amplifier configuration is defined by having the input and output signals referenced to the source and drain terminals (respectively), with the gate terminal of the transistor typically having a low AC impedance to ground and thus being "common" to one pole of both the input and output voltages.

The common-gate amplifier configuration most resembles the common-base BJT amplifier configuration in both form and behavior.

Common-gate amplifiers are characterized by moderate voltage gains, and a noninverting phase relationship between input and output.

Notes 24

The answers to the question may be easily found in any fundamental electronics text, but it is important to ensure students know *why* these characteristics are such. I always like to tell my students, "Memory *will* fail you, so you need to build an understanding of *why* things are, not just *what* things are."

One exercise you might have your students do is come up to the board in front of the room and draw an example of this circuit, then everyone may refer to the drawn image when discussing the circuit's characteristics.

Question 25

Define what a *common-drain* transistor amplifier circuit is. What distinguishes this amplifier configuration from the other single-FET amplifier configurations, namely *common-source* and *common-gate*? What configuration of BJT amplifier circuit does the common-drain FET circuit most resemble in form and behavior?

Also, describe the typical voltage gains of this amplifier configuration, and whether it is *inverting* or *noninverting*.

file 02249

Answer 25

The common-drain amplifier configuration is defined by having the input and output signals referenced to the gate and source terminals (respectively), with the drain terminal of the transistor typically having a low AC impedance to ground and thus being "common" to one pole of both the input and output voltages.

The common-drain amplifier configuration most resembles the common-collector BJT amplifier configuration in both form and behavior.

Common-drain amplifiers are characterized by low voltage gains (less than unity), and a noninverting phase relationship between input and output.

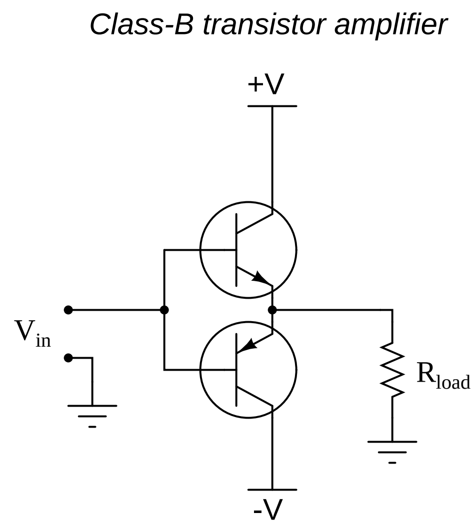
Notes 25

The answers to the question may be easily found in any fundamental electronics text, but it is important to ensure students know *why* these characteristics are such. I always like to tell my students, "Memory *will* fail you, so you need to build an understanding of *why* things are, not just *what* things are."

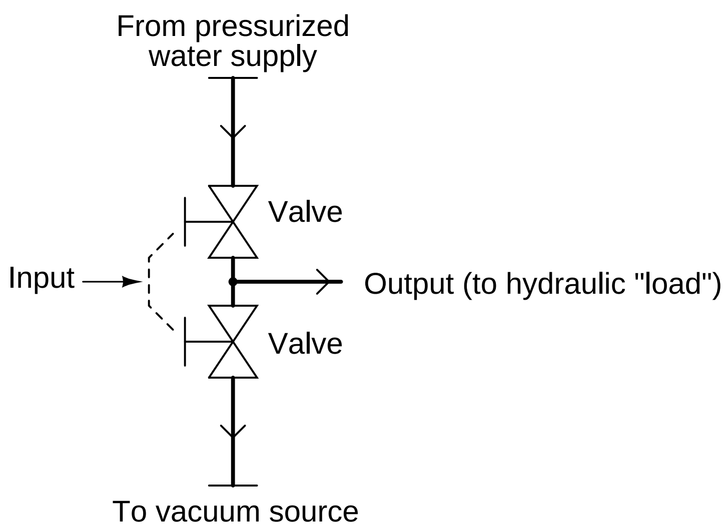
One exercise you might have your students do is come up to the board in front of the room and draw an example of this circuit, then everyone may refer to the drawn image when discussing the circuit's characteristics.

Question 26

A *class-B* transistor amplifier (sometimes called a *push-pull amplifier*) uses a pair of transistors to generate an output signal to a load. The circuit shown here has been simplified for the sake of illustrating the basic concept:



An analogue for this electronic circuit is this water-pressure control, consisting of two variable valves. One valve connects the output pipe to a supply of pressurized water, and the other connects the output pipe to a source of vacuum (suction):



The "input" to this amplifier is the positioning of the valve control handle. The "output" of this amplifier is water pressure measured at the end of the horizontal "output" pipe. Valve action is synchronized such that only one valve is open at any given time, just as no more than one transistor will be "on" at any given time in the class-B electronic circuit.

Explain how either of these "circuits" meets the criteria of being an amplifier. In other words, explain how *power* is boosted from input to output in both these systems. Also, describe how efficient each of these amplifiers is, "efficiency" being a measure of how much current (or water) goes to the load device, as compared to how much just goes straight from one supply "rail" to the other (from pressure to vacuum).

file 00868

Answer 26

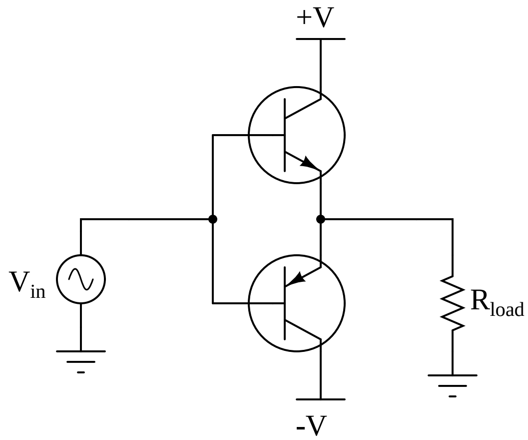
In both systems, a small amount of energy (current through the "base" terminal of the transistor, mechanical motion of the valve handle) exerts control over a larger amount of energy (current to the load, water to the load). Both systems are very energy efficient, with little flow wasted by flowing from supply to vacuum (from +V to -V) and bypassing the load.

Notes 26

Push-pull amplifiers are a bit more difficult to understand than simple class-A (single-ended), so be sure to take whatever time is necessary to discuss this concept with your students. Ask them to trace current through the load resistor for different input voltage conditions. Your students need not know any details of transistor operation, except that a positive input voltage turns on the upper transistor, and a negative input voltage turns on the lower transistor.

Question 27

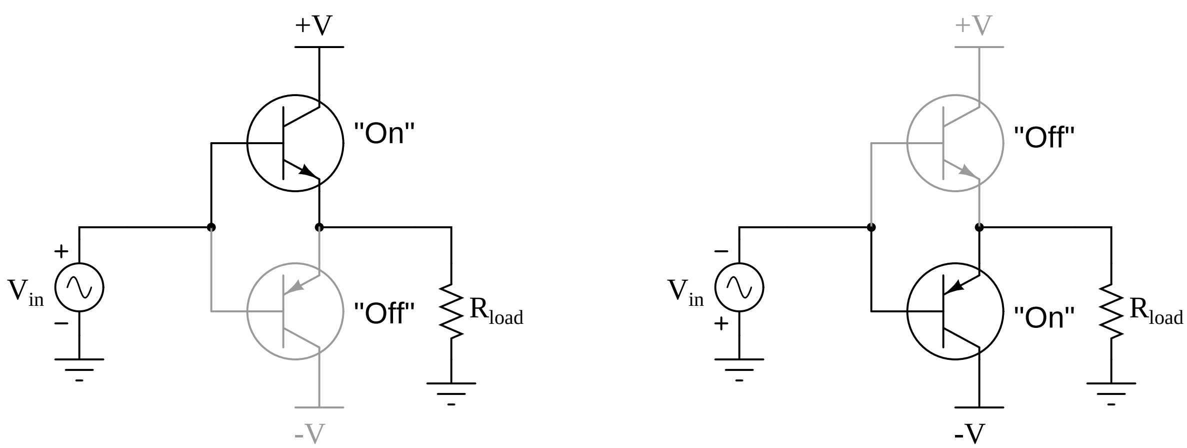
The circuit shown here is a standard *push-pull* amplifier, comprised of a complementary pair of bipolar junction transistors:



Trace current in this circuit during periods of time when the instantaneous voltage of the signal source (V_{in}) is positive, and for those periods when it is negative. Determine at which times each of the transistors is "on" (conducting current).

file 00968

Answer 27



Follow-up question: would you classify this amplifier circuit as common-emitter, common-collector, or common-base? What kind of voltage gain would you expect this amplifier circuit to have?

Notes 27

Have your students trace current in the circuit on a diagram drawn on the whiteboard, so all can see the analysis. After analyzing its operation, ask them why they think this amplifier is called "push-pull."

Another way to approach this circuit is from the perspective of current *sourcing* and current *sinking*. Which transistor sources current to the load resistor, and which transistor sinks current from the load resistor?

Question 28

Class B amplifiers are greatly preferred over Class A designs for high-power applications such as audio power amplifiers. Explain why this is.

file 00970

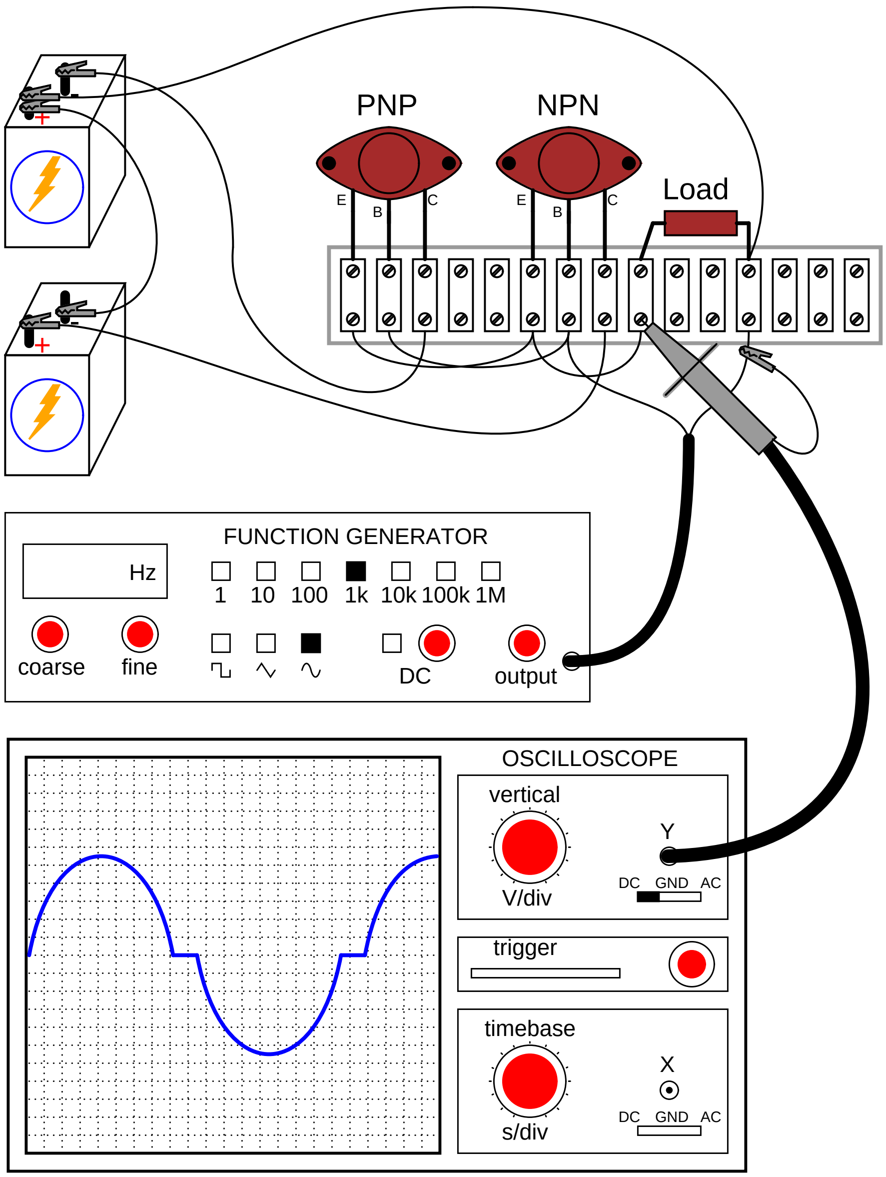
Answer 28

Class B amplifiers are much more efficient than Class A amplifiers, meaning that they do not waste as much energy in the form of heat dissipation.

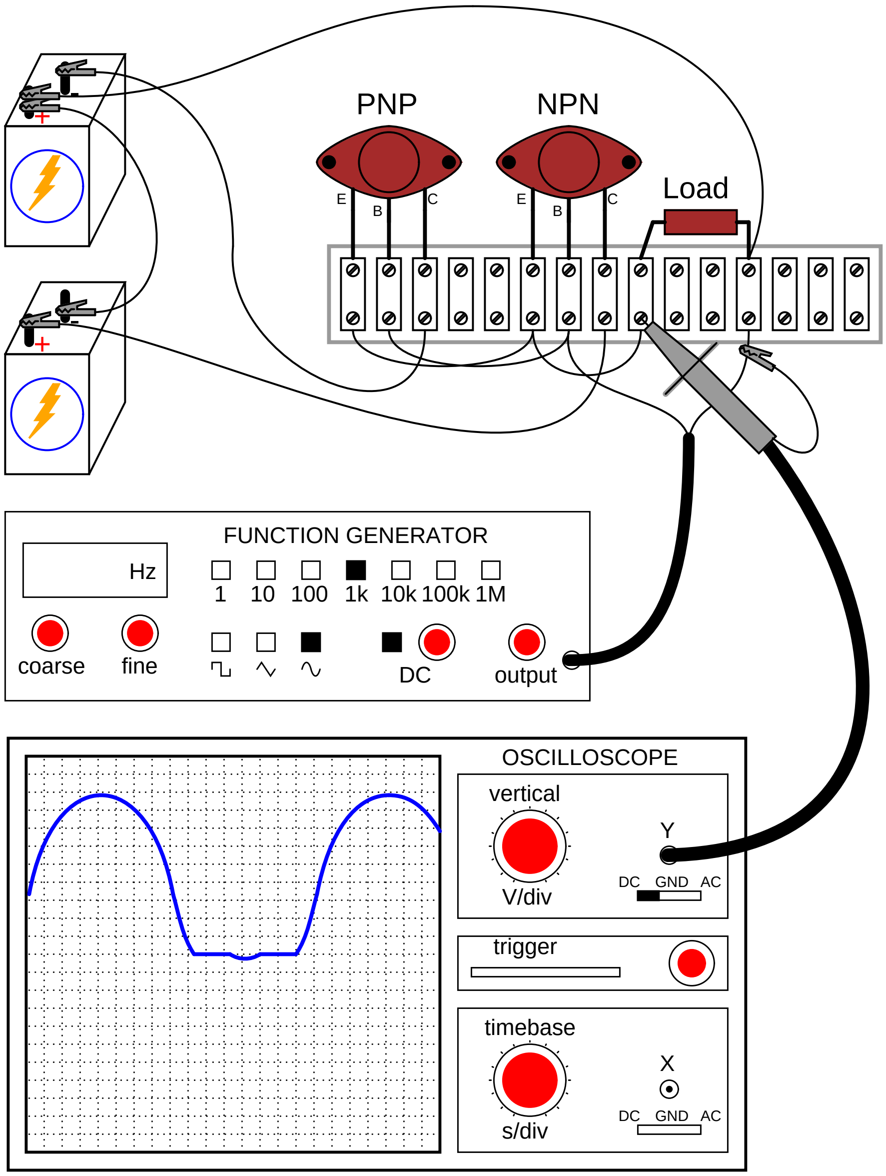
Notes 28

Discuss *why* Class B amplifiers are more efficient than Class A amplifiers with your students. What is it about a Class A amplifier that makes it so inefficient for high-power applications?

A student builds the following push-pull amplifier circuit, and notices that the output waveform is distorted from the original sine-wave shape output by the function generator:



Thinking that perhaps this circuit requires DC biasing, just like Class A amplifier circuits, the student turns on the "DC offset" feature of the function generator and introduces some DC voltage to the input signal. The result is actually worse:



Obviously, the problem will not be fixed by biasing the AC input signal, so what causes this distortion in the output waveform?

file 00969

Answer 29

I'll give you a hint: this type of distortion is called *crossover distortion*, and it is the most prevalent type of distortion in Class B amplifier designs.

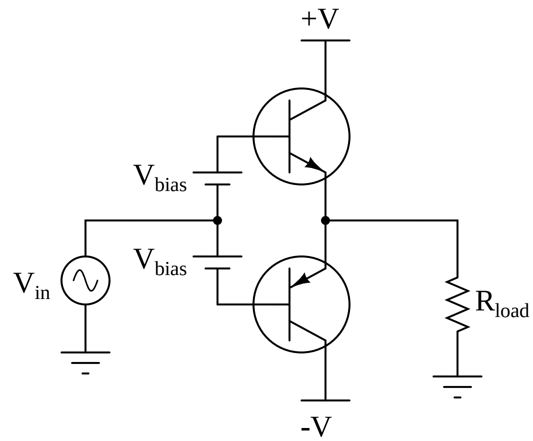
Challenge question: since this type of transistor amplifier is often referred to as a "push-pull" design, describe the cause of this distortion in terms of the transistors "pushing" and "pulling".

Notes 29

Crossover distortion is fairly easy to understand, but more difficult to fix than the one-sided "clipping" distortion students are used to seeing in Class A amplifier designs. If you think it might help your students understand better, ask them how a push-pull amplifier circuit would respond to a *slowly changing* DC input voltage: one that started negative, went to zero volts, then increased in the positive direction. Carefully monitor the transistors' status as this input signal slowly changes from negative to positive, and the reason for this form of distortion should be evident to all.

Question 30

A simple yet impractical way to eliminate crossover distortion in a Class B amplifier is to add two small voltage sources to the circuit like this:



Explain why this solution works to eliminate crossover distortion.

Also, explain what practical purpose this push-pull amplifier circuit might serve, since its voltage gain is only 1 (0 dB).

file 00972

Answer 30

Each voltage source biases its respective transistor to be at the brink of turning on when the instantaneous voltage of the input (V_{in}) is 0 volts.

Such amplifier circuits are typically used as *voltage buffers*: effectively diminishing the output impedance of the source (boosting its current sourcing/sinking capability) so that it may supply more current to a load.

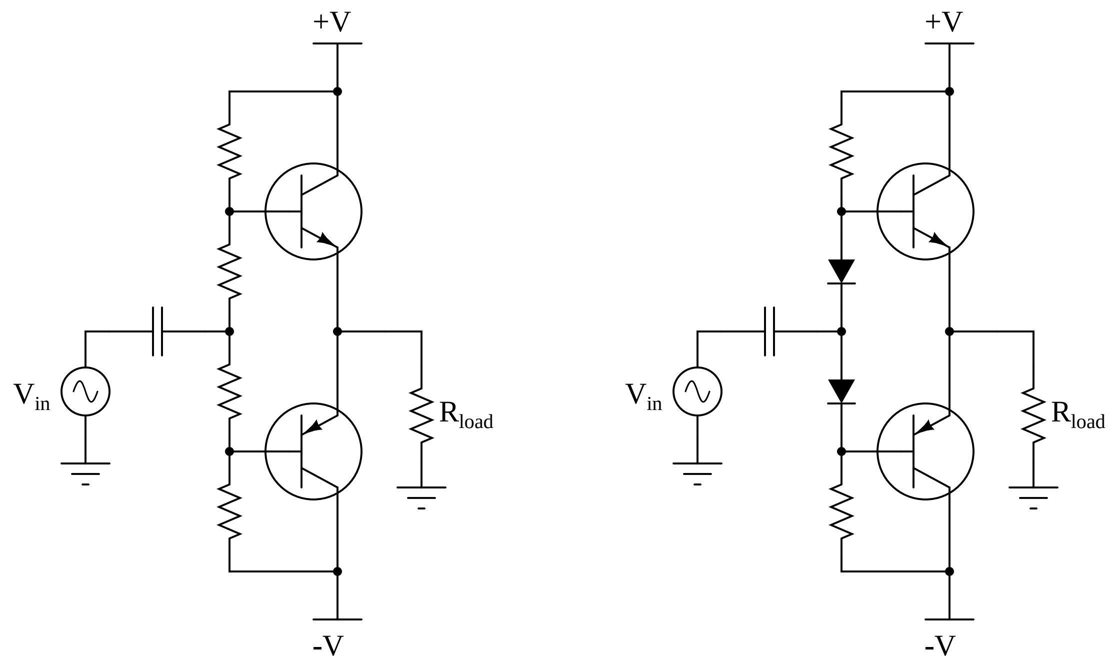
Challenge question: how would you estimate the output impedance of such an amplifier circuit?

Notes 30

Ask your students to relate these bias voltage sources to the DC bias voltages previously seen in Class A amplifier designs. How much voltage do they think would be necessary to properly bias each transistor?

Question 31

Two methods of biasing push-pull transistor pairs are shown here:



Which of these two methods is preferred, and why?

file 00973

Answer 31

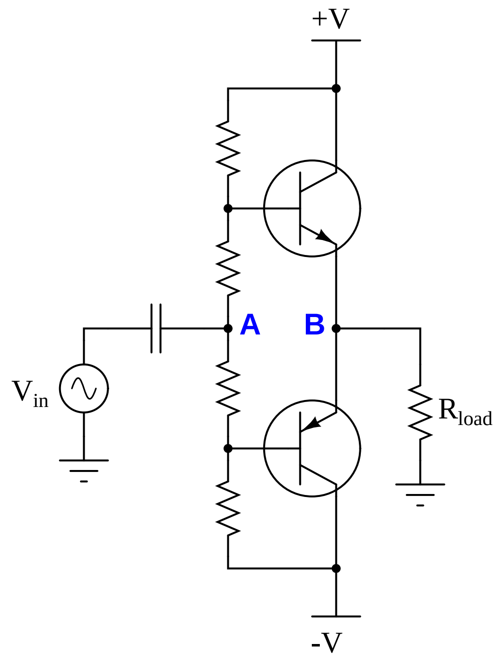
Biasing with diodes is preferred, because the bias voltage remains stable despite fluctuations in power supply rail voltages.

Notes 31

Ask your students what is special about a *diode* that provides just the right amount of bias voltage for the transistors.

Question 32

In a properly biased Class B amplifier circuit, how much voltage should be between the points **A** and **B**?



file 00977

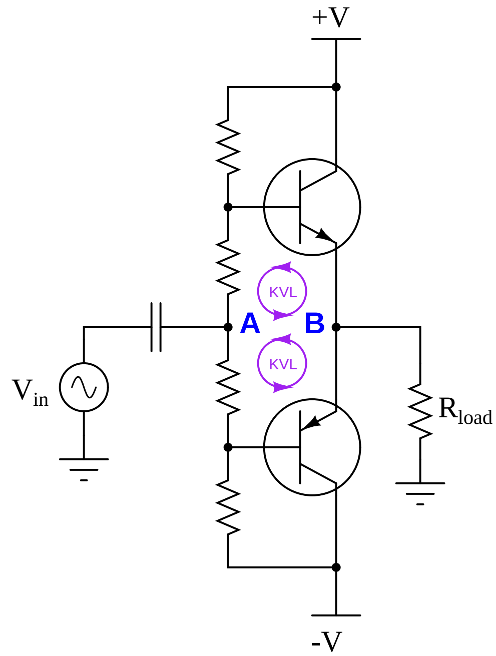
Answer 32

0 volts, at all moments in time!

Follow-up questions: explain how this fact may be useful in troubleshooting push-pull amplifier circuits, and also explain how this fact proves the amplifier has a voltage gain of unity (1).

Notes 32

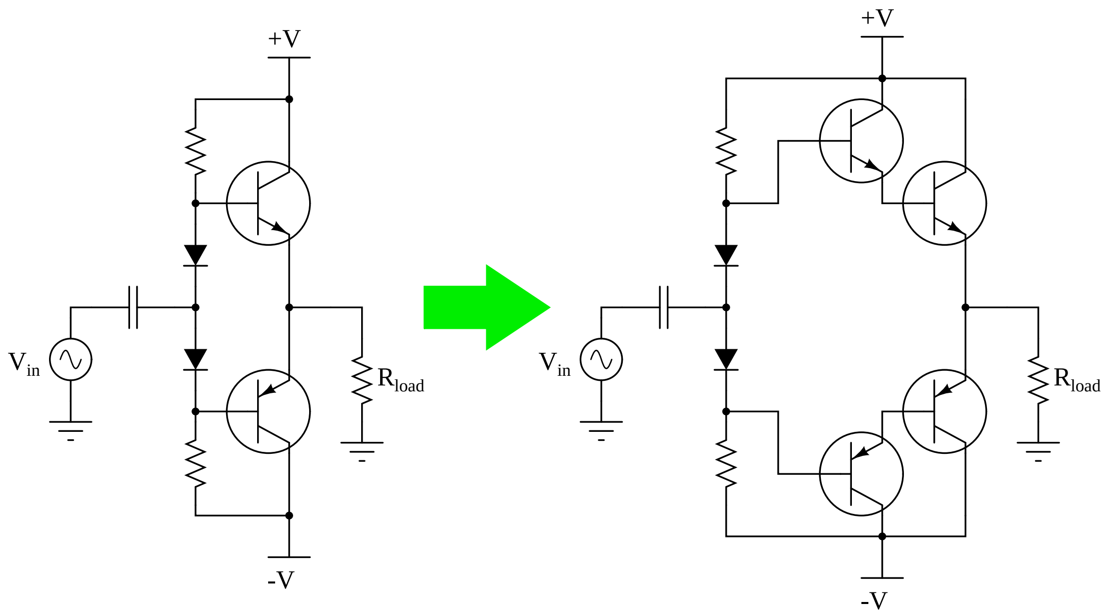
Challenge your students to apply Kirchhoff's Voltage Law to the "loops" around these two points, as such:



Knowing that the voltage between points **A** and **B** is zero, ask your students what the voltage drops *must* be across the biasing resistors. This question foreshadows the concept of a "virtual ground" in operational amplifier circuits. It is the idea that two or more points in a circuit may be held at the same potential without actually being connected together. In other words, the points are *virtually common* rather than being *actually common* with one another.

Question 33

One way to greatly boost the current gain (A_I) of a Class B push-pull amplifier is to use *Darlington pairs* instead of single transistors:

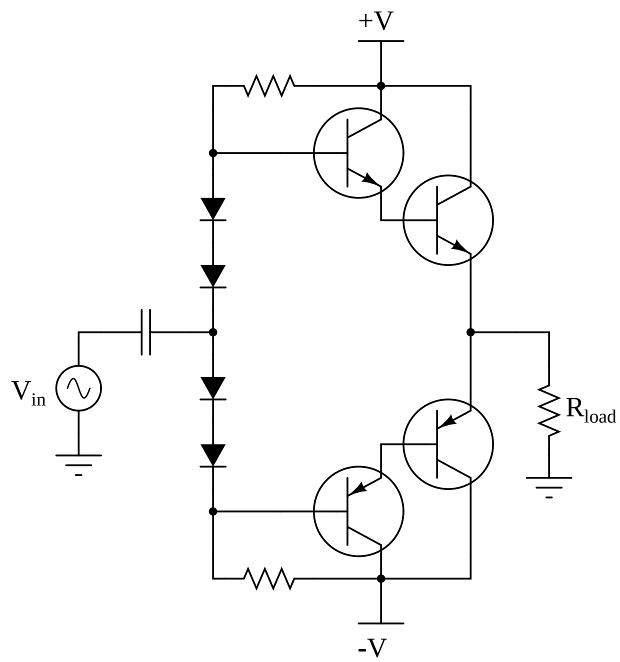


The only problem with the Darlington pair amplifier circuit shown is that the original biasing network will no longer be sufficient. Unless something else is changed in this circuit, the amplifier will exhibit some crossover distortion.

Draw the necessary modifications to the circuit to properly bias the new transistors, and explain why these modifications are necessary.

file 00974

Answer 33

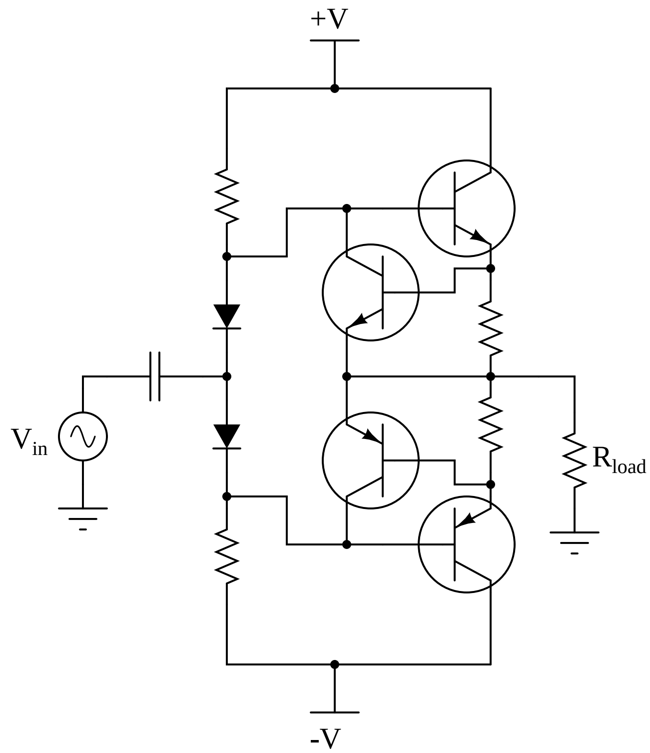


Notes 33

Ask your students to estimate the additional biasing voltage necessary with the two (new) transistors added to the circuit. How much biasing voltage, per transistor, was necessary with just two transistors in the circuit? Now that four transistors are in the circuit, how much more biasing voltage is necessary to avoid crossover distortion?

Question 34

An interesting addition to the basic Class B push-pull amplifier circuit is *overcurrent protection*, in the form of two more transistors and two more resistors added to the circuit:



This form of overcurrent protection is common in voltage-regulated DC power supply circuitry, but it works well in amplifier circuitry, too. Explain how the additional transistors and resistors work together to protect the main power transistors from damage in the event of an overload.

file 00978

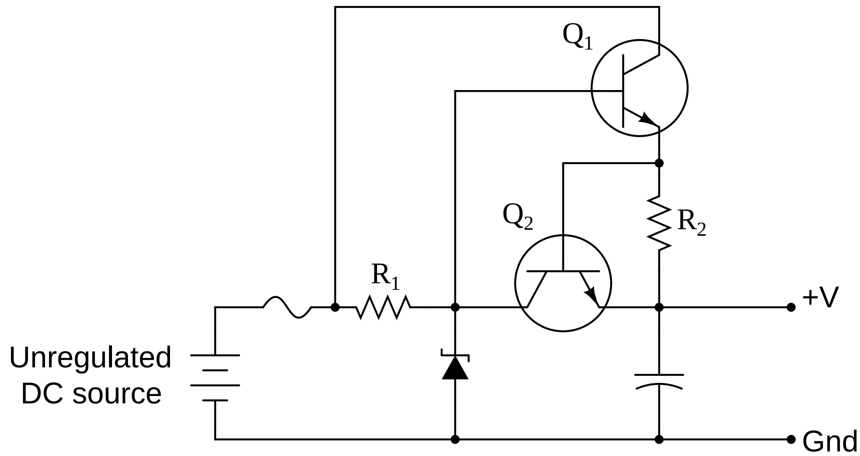
Answer 34

If there happens to be excessive current going through a power transistor, the voltage drop across that emitter resistor will be enough to turn on the auxiliary transistor, which then "shunts" the overloaded power transistor's base current to the load.

Challenge question: what mathematical procedure would you use to size the emitter resistors? How much resistance is appropriate in this application?

Notes 34

If students are having difficulty understanding how this circuitry works, it might be worthwhile to show them this circuit (from a regulated DC power supply):



Ask them how transistor Q2 in this circuit works to protect transistor Q1 from overload.

An interesting way to explain the operation of this form of overcurrent protection is to say that when the auxiliary transistor begins to conduct (shorting base current away from the main power transistor), it effectively decreases the β of the main power transistor. By suddenly making the main power transistor less effective at amplifying, the signal source "feels" more of the load. This causes the signal source's voltage to sag, ultimately limiting load current in the process.

Question 35

A popular variation of the Class B amplifier is the *Class AB* amplifier, designed to eliminate any trace of crossover distortion. What makes the difference between a Class B and a Class AB amplifier? Why do Class AB amplifiers have less crossover distortion than Class B amplifiers? And, is there any disadvantage to changing from Class B to Class AB operation?

file 00975

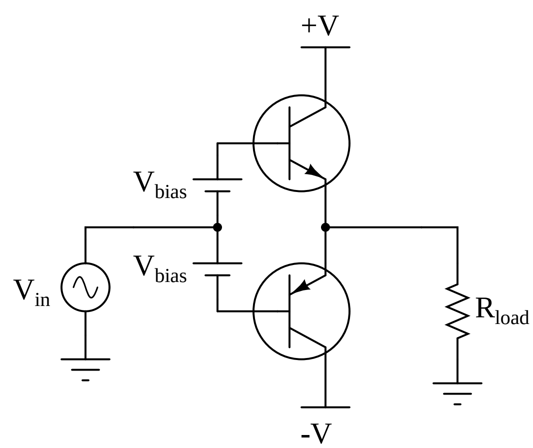
Answer 35

The fundamental difference between Class B and Class AB operation is biasing: both transistors are "on" for a brief moment in time around the zero-crossover point in a Class AB circuit, where only one transistor is supposed to be on at any given time in a Class B circuit.

Amplifiers operating in Class AB mode are less power-efficient than pure Class B operation.

Notes 35

Ask your students to specifically identify the change(s) that would have to be made in the following Class B circuit to make it operate as a Class AB amplifier:



Discuss why the name "Class AB" is given to this mode of operation. How does Class AB operation differ from pure Class A or pure Class B?

Question 36

Why is it common for amplifier circuits to use multiple stages of transistors, rather than just one transistor (or two transistors in a push-pull circuit)? Describe some of the benefits of using multiple transistor stages.

file 01120

Answer 36

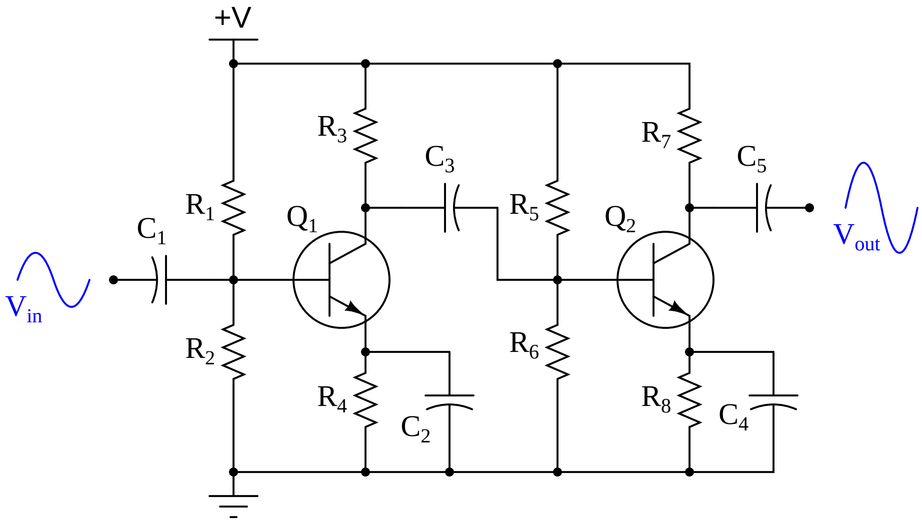
I'll let you research the answer(s) to this question on your own!

Notes 36

A fairly simple question, but useful to discuss nevertheless.

Question 37

Describe the function of each component in this two-stage amplifier circuit:



Also, be prepared to explain what the effect of any one component's failure (either open or shorted) will have on the output signal.

file 01117

Answer 37

- R_1 = Q_1 biasing
- R_2 = Q_1 biasing
- R_3 = Q_1 load
- R_4 = Q_1 stability (prevents thermal runaway)
- R_5 = Q_2 biasing
- R_6 = Q_2 biasing
- R_7 = Q_2 load
- R_8 = Q_2 stability (prevents thermal runaway)

- C_1 = Input signal coupling to Q_1
- C_2 = AC bypass for Q_1
- C_3 = Coupling between amplifier stages
- C_4 = AC bypass for Q_2
- C_5 = Output signal coupling to load

- Q_1 = First-stage amplification
- Q_2 = Second-stage amplification

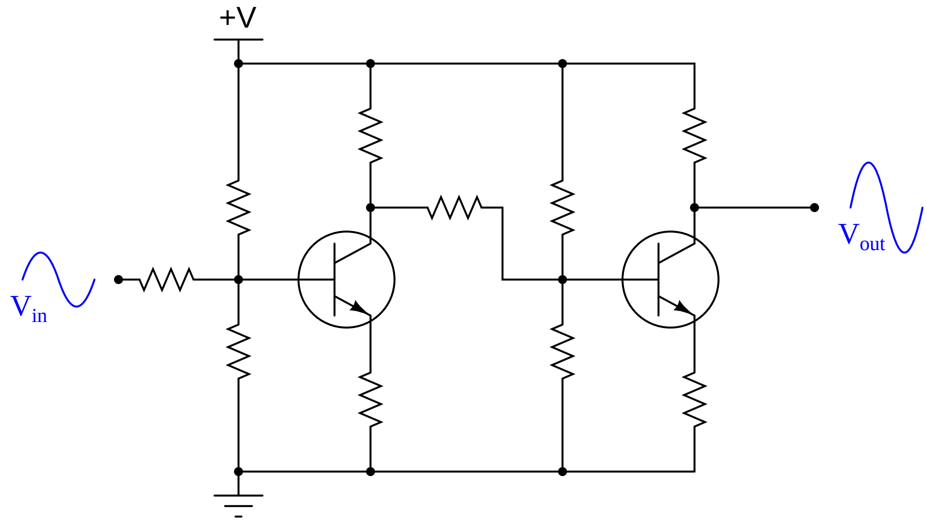
Notes 37

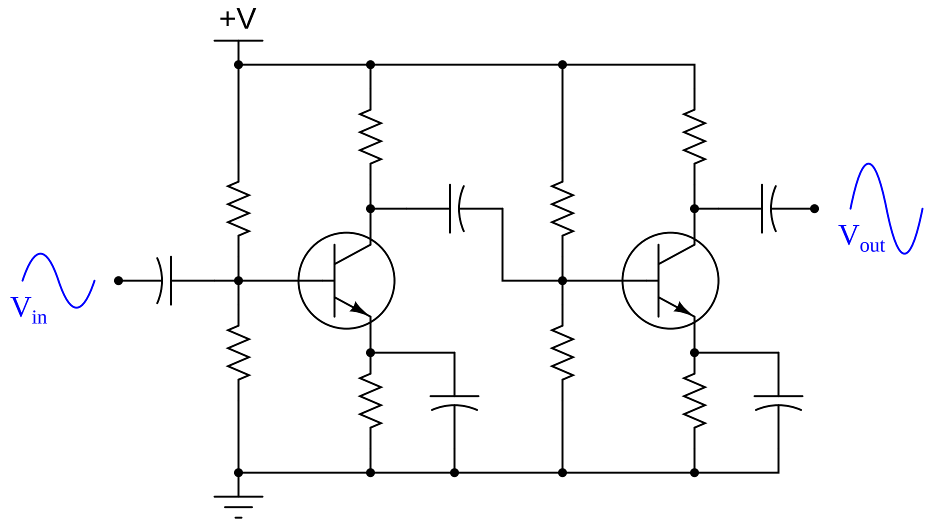
The answers given in the "Answers" section are minimal: just enough to help students who may be struggling with the concepts. During discussion, I would expect more detail than these short phrases.

Be sure to challenge your students with hypothetical component failures in this circuit. Make sure they comprehend each component's function in this circuit, beyond memorizing a phrase!

Question 38

The first amplifier circuit shown here is *direct-coupled*, while the second is *capacitively coupled*.





Which of these two designs would be more suitable for use in a DC voltmeter circuit (amplifying a measured DC voltage)? What applications would the *other* amplifier design be suited for?

file 01119

Answer 38

The direct-coupled amplifier circuit's bandwidth extends down to 0 Hz, unlike the other amplifier. This makes it suitable for DC signal amplification. The capacitive-coupled amplifier circuit would be better suited for applications where AC signals are solely dealt with.

Follow-up question: in each of these amplifier circuits, identify the point at which the signal's phase becomes shifted by 180^o. In other words, show where the voltage signal becomes inverted, and then inverted again, so that the output is in phase with the input.

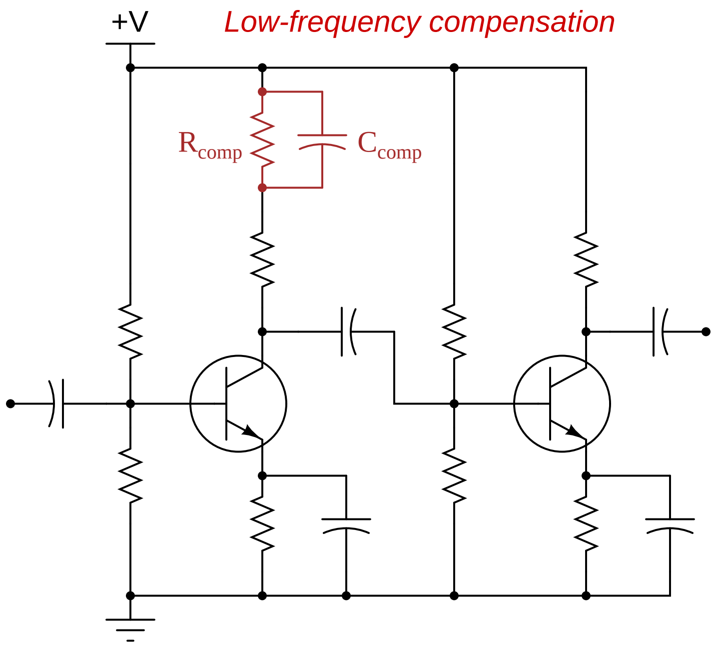
Notes 38

A good question to ask your students is, "What is *bandwidth*?" It is important that your students understand the basic concept of "bandwidth", and what factors influence it in a circuit.

Ask your students to suggest possible values (in microfarads) for the coupling capacitor in the second circuit, based on common resistor values (between 1 kΩ and 100 kΩ), and a modest audio frequency range (1 kHz to 20 kHz). No exact values are needed here, but it is important that they be able to make an approximate estimation of the necessary (minimum) capacitance, if for no other reason than to demonstrate their comprehension of the coupling capacitor's intended purpose.

Question 39

One of the problems with capacitively-coupled amplifier circuits is poor low-frequency response: as the input signal frequency decreases, all capacitive reactances increase, leading to a decreased voltage gain. One solution to this problem is the addition of a capacitor in the collector current path of the initial transistor stage:



Explain how the presence of this "compensating" capacitor helps to overcome the loss of gain normally experienced as a result of the other capacitors in the circuit.

file 01122

Answer 39

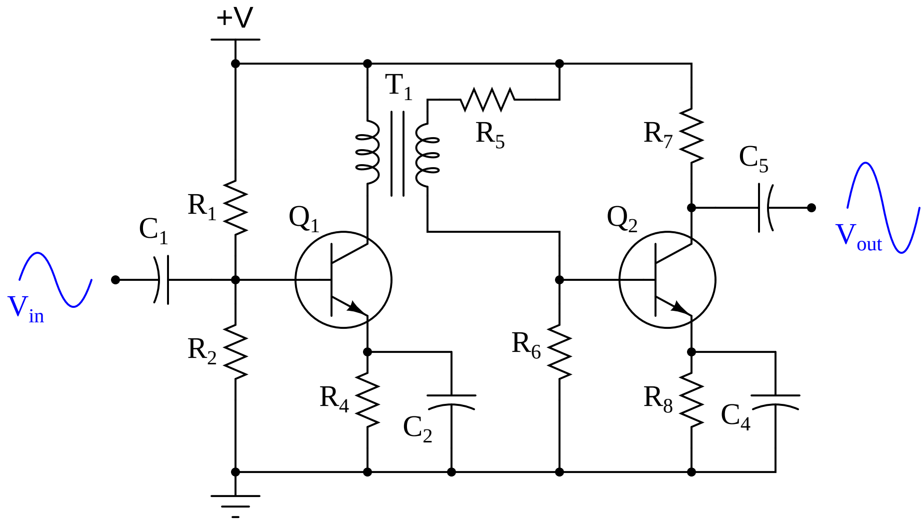
The additional capacitor's rising reactance at low frequencies boosts the gain of the first transistor stage by increasing the impedance from the first transistor's collector to the +V power supply rail.

Notes 39

This technique is commonly used in video amplifier circuits, although a complete video amplifier circuit would not be this crude (no peaking coils).

Question 40

This two-stage transistor amplifier circuit is *transformer-coupled*:



What advantage(s) does a transformer-coupled amplifier have over circuits using other methods of coupling? Are there any disadvantages to using a transformer for signal coupling between transistor stages? Explain in detail.

file 01121

Answer 40

Transformers allow for impedance transformation between stages, as well as phase inversion (if desired). However, their parasitic (leakage) inductance and inter-winding capacitance may cause the amplifier to have strange frequency response characteristics.

Follow-up question: label the transformer's polarity using "dot" notation in order to achieve no inversion of signal from input to output (as shown).

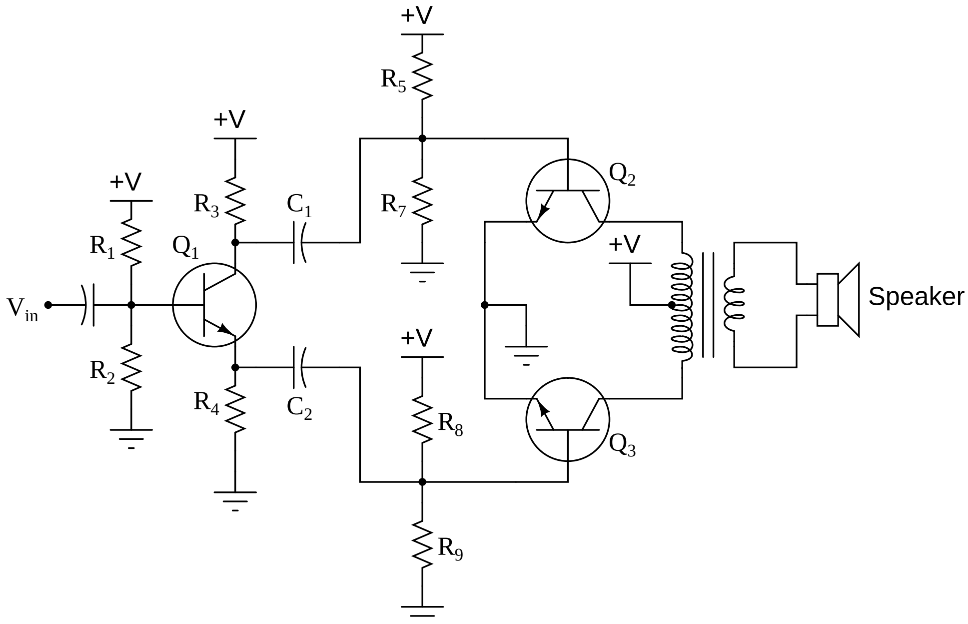
Notes 40

Ask your students to explain what *impedance transformation* is and why it is important, especially in amplifier circuits. This will be a good review of both transformer theory and the maximum power transfer theorem.

Regarding phase inversion, a fun challenge here is to have students specify the "dot convention" necessary for this particular transformer to obtain the non-inverting characteristic of this two-stage amplifier circuit. In other words, have them draw dots near the transformer windings (with the proper relative relationship) to produce the phasing shown by the sine-wave symbols in the diagram.

Question 41

One design of push-pull audio amplifier uses two identical transistors and a center-tapped transformer to couple power to the load (usually a speaker, in an audio-frequency system):



Unlike complementary-pair push-pull amplifier circuits, this circuit absolutely requires a preamplifier stage called a *phase splitter*, comprised here by transistor Q_1 and resistors R_3 and R_4.

Explain what the purpose of the "phase splitter" circuit is, and why it is necessary to properly drive the power transistors Q_2 and Q_3.

Hint: determine the phase relationships of the voltage signals at the base, collector, and emitter terminals of transistor Q_1, with respect to ground.

file 01123

Answer 41

A "phase splitter" circuit produces two complementary output voltages (180^o phase-shifted from each other), as necessary to drive the power transistors at opposite times in the audio waveform cycle.

Follow-up question: typically, the collector and emitter resistors of the phase splitter circuit (R_3 and R_4 in this example) are equally sized. Explain why.

Notes 41

Ask your students to qualitatively analyze the voltage signal waveforms at all parts of this circuit. When does Q_1 conduct current? When does Q_2 conduct current?

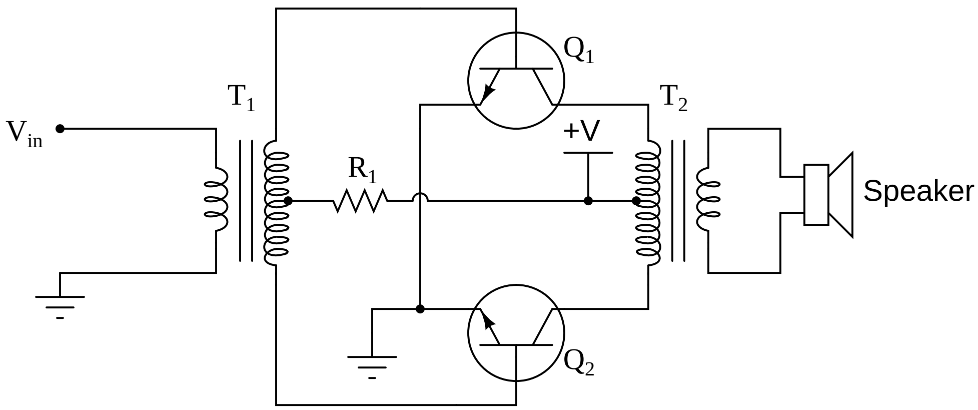
Also, discuss the operational class of this amplifier circuit. Is it Class B, or Class AB? What would need to be changed in order to shift the circuit's operational mode?

Explain to your students that this circuit topology was very common in the days of electron tube electronics, when there was no such thing as complementary active components (i.e., NPN versus PNP). Triode, tetrode, and pentode tubes are all positive-driven devices, conducting more current as the grid voltage becomes more positive. Thus, the only way to make a push-pull amplifier with electron tubes was to use a pair to drive the center-tapped winding of an audio power transformer, and use a phase splitter circuit to drive the two tubes.

Most modern (semiconductor) audio amplifier designs avoid the use of an audio output transformer. Ask your students why they think this may be the case.

Question 42

Examine this push-pull audio amplifier circuit:



Answer the following questions about this circuit based on your analysis of it:

- How is phase splitting accomplished in this circuit?
- What is the purpose of resistor R_1?
- What would happen if resistor R_1 failed open?
- What would happen if the wire connecting the base of transistor Q_2 to the input transformer (T_1) were to fail open?

file 01126

Answer 42

- The input transformer T_1 provides phase splitting.
- R_1 establishes the Q point of both transistors.
- If R_1 failed open, both transistors would go into cutoff mode.
- If the wire connecting the base of transistor Q_2 to the input transformer (T_1) were to fail open, one-half of the output waveform would become clipped.

Notes 42

Ask your students to give detailed reasons for their answers. The answers provided for this question are minimal – it is your job as the instructor to ensure students are *thinking* their way through this question, and not just repeating something they've read or heard from others.

Question 43

Radio-frequency amplifiers often use small inductors called *peaking coils* in the coupling circuitry between transistor stages. Describe the purpose of these inductors.

file 01127

Answer 43

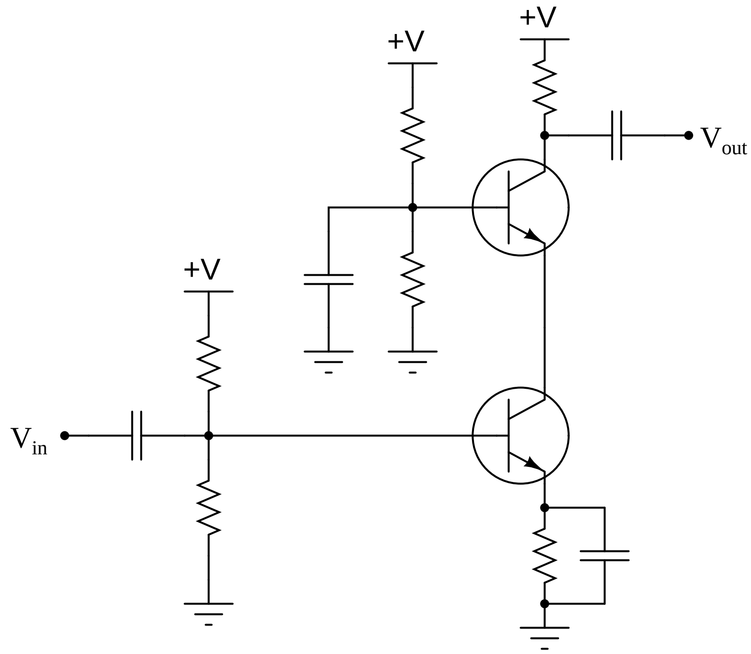
Peaking coils are added to amplifier circuits to help counteract capacitive reactance at high frequencies.

Notes 43

The answer I gave for this question is very minimal, and is just enough to give your students a hint. Ask your students to explain why capacitive reactance is an issue in high-frequency transistor amplifier circuits, and why an inductor would be used to counter X_C. Also, ask if there are any disadvantages to inserting peaking coils into amplifier circuits.

Question 44

A common wideband transistor amplifier circuit is the *cascode* design, using common-emitter and common-base transistor stages:



What advantage(s) does the cascode amplifier have over "normal" single- or multi-stage amplifier designs? What, specifically, makes it well suited for high-frequency applications, such as RF (Radio Frequency) signal amplifiers?

file 01125

Answer 44

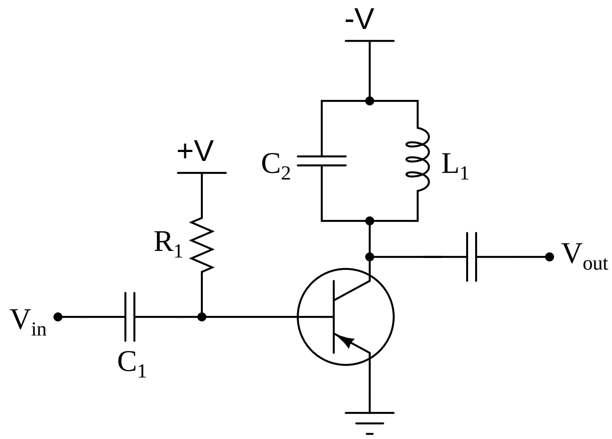
The combination of a common-collector first stage and a common-base second stage significantly reduces the debilitating effects of interjunction capacitance within the two transistors. Most cascode amplifiers require no *neutralization*, either: a testament to the effectiveness of the design.

Notes 44

This is one of the few popular applications for the common-base transistor amplifier configuration, and it is a solution that has been implemented with field-effect transistors as well as bipolar transistors (and even electron tubes, before that!). Ask your students to explain how the circuit works, especially noting the voltage gain of each stage, and the locations of interjunction (Miller-effect) capacitances in the circuit.

Question 45

Shown here is a schematic diagram for a class-C RF (radio frequency) amplifier circuit:



This circuit will look very strange if you are accustomed to analyzing audio-frequency and DC amplifier circuits. Note some of the distinct differences between this amplifier and an amplifier used to boost audio signals. Also, explain what "class-C" operation means, and how this amplifier is able to output a continuous sine wave despite the transistor's behavior in class-C mode.

Finally, write an equation that predicts this amplifier's operating frequency, based on certain component values which you identify.

file 02506

Answer 45

Operating in class-C mode, the transistor only turns on for a very brief moment in time during the waveform cycle. The "flywheel" action of the tank circuit maintains a sinusoidal output waveform during the time the transistor is off.

$$f = \frac{1}{2\pi\sqrt{L_1 C_2}}$$

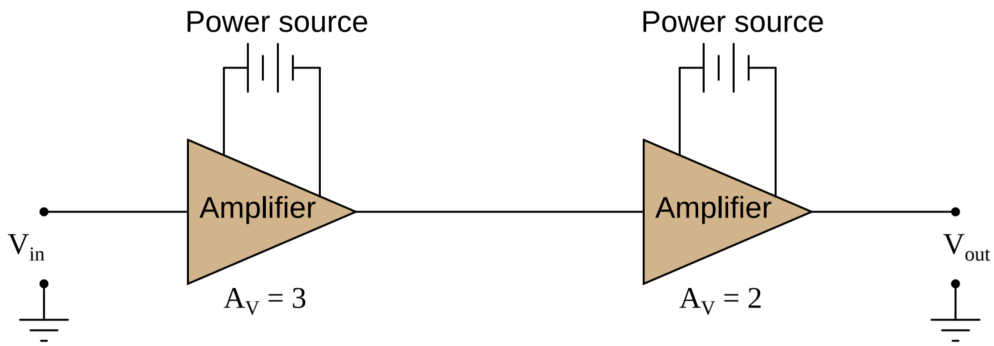
Follow-up question: why is this mode of amplifier operation – where the transistor is off most of the time and a tank circuit sustains sinusoidal oscillations – desirable for an amplifier circuit? Could this technique be applied to audio-frequency amplifier circuits? Why or why not?

Notes 45

Perhaps the most noteworthy detail of this circuit is the positive biasing voltage, despite the transistor being PNP and $V_C C$ being negative. Ask your students to explain why this is necessary to get the transistor operating in class-C mode.

Question 46

Calculate the overall voltage gain of this cascaded amplifier circuit, where the output of one voltage amplifier feeds into the input of another:



Also, convert the voltage gains of each amplifier into units of decibels, then convert the overall voltage gain ratio into units of decibels as well.

What do you notice about the overall gain of this circuit in relation to the individual amplifier gains, compared as ratios versus compared as decibel figures?

file 02534

Answer 46

Cascaded voltage gains expressed as ratios:

$$A_V = 3 \times 2 = 6$$

Cascaded voltage gains expressed a decibel figures:

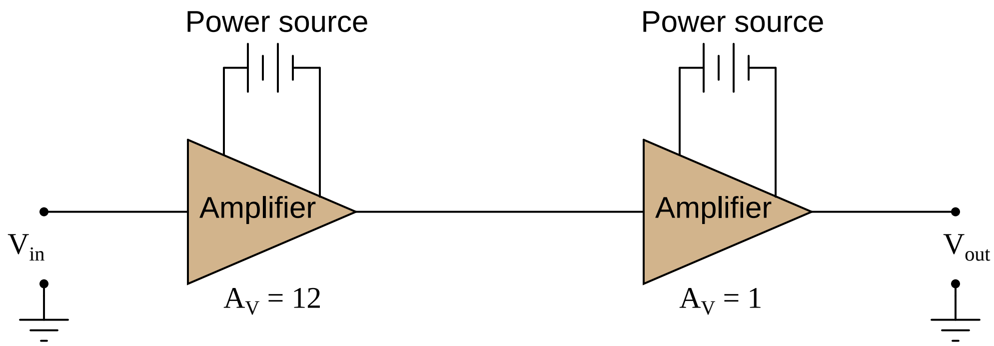
$$A_V = 9.54 \text{ dB} + 6.02 \text{ dB} = 15.56 \text{ dB}$$

Notes 46

Besides providing practice with ratio-to-decibel conversions, the purpose of this question is for students to realize that gains multiply as ratios but add as decibels.

Question 47

Calculate the overall voltage gain of this cascaded amplifier circuit, where the output of one voltage amplifier feeds into the input of another:



Also, convert the voltage gains of each amplifier into units of decibels, then convert the overall voltage gain ratio into units of decibels as well.

What do you notice about the overall gain of this circuit in relation to the individual amplifier gains, compared as ratios versus compared as decibel figures?

file 02535

Answer 47

Cascaded voltage gains expressed as ratios:

$$A_V = 12 \times 1 = 12$$

Cascaded voltage gains expressed a decibel figures:

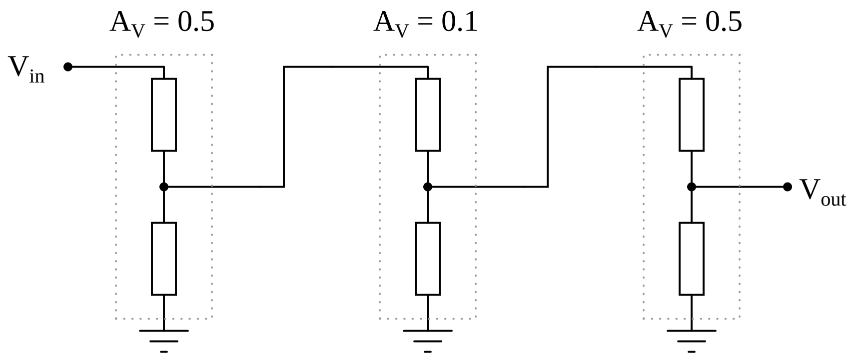
$$A_V = 21.58 \text{ dB} + 0 \text{ dB} = 21.58 \text{ dB}$$

Notes 47

Besides providing practice with ratio-to-decibel conversions, the purpose of this question is for students to realize that gains multiply as ratios but add as decibels.

Question 48

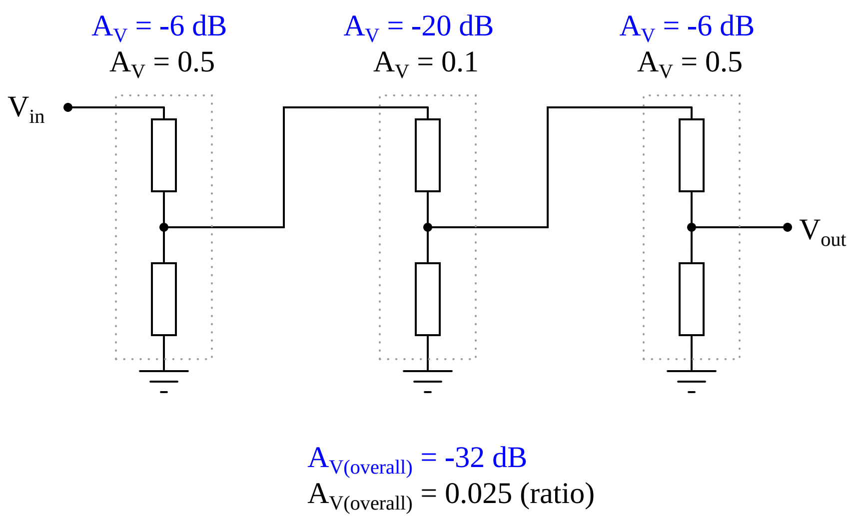
In this cascaded voltage divider circuit, determine the overall voltage gain ratio (from first input to last output), and also calculate the overall voltage gain in *decibels*, as well as the decibel figure for each divider's voltage gain:



What do you notice about the ratio figures versus the decibel figures, regarding how the individual stage gains compare with the overall gain?

file 00829

Answer 48

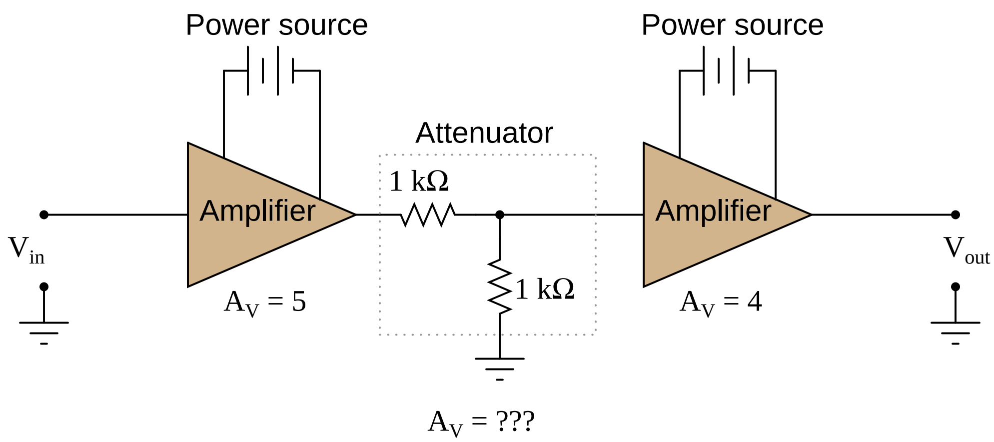


Notes 48

Discuss with your students the nature of cascaded gain figures in both ratio and decibel formats. Which format is easier to calculate manually (without using a calculator)? Why is this?

Question 49

In this circuit, one amplifier feeds into an *attenuator* circuit, which then feeds into a second amplifier stage. Calculate the "gain" of the attenuator, and then calculate the overall voltage gain of this three-stage circuit:



Also, convert the voltage gains of each stage into units of decibels, then convert the overall voltage gain ratio into units of decibels as well.

What do you notice about the overall gain of this circuit in relation to the individual amplifier gains, compared as ratios versus compared as decibel figures?

file 02536

Answer 49

Cascaded voltage gains expressed as ratios:

$$A_V = 5 \times \left(\frac{1}{2}\right) \times 4 = 10$$

Cascaded voltage gains expressed a decibel figures:

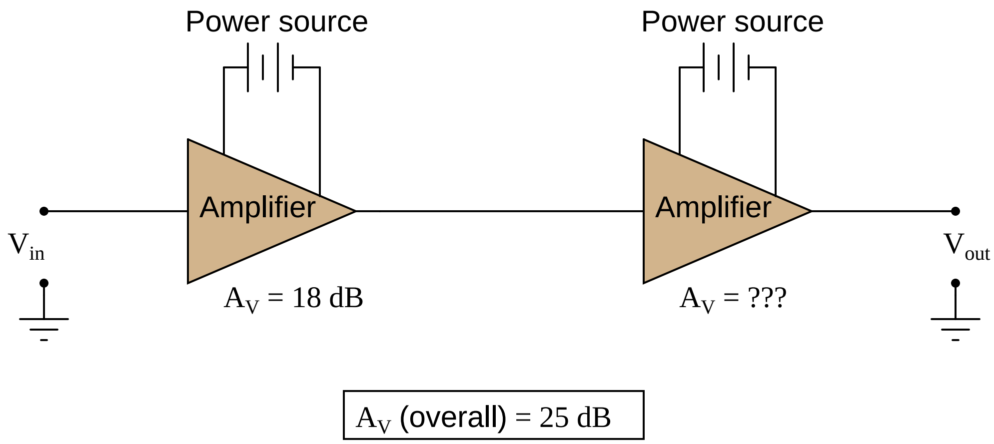
$$A_V = 13.98 \text{ dB} + (-6.02 \text{ dB}) + 12.04 = 20 \text{ dB}$$

Notes 49

Besides providing practice with ratio-to-decibel conversions, the purpose of this question is for students to realize that gains multiply as ratios but add as decibels.

Question 50

Calculate the necessary gain of the second-stage amplifier to give the whole circuit a voltage gain of 25 decibels, then translate all decibel figures into gain ratios:



file 02537

Answer 50

- Stage 1 gain = 18 dB = 7.94
- Stage 2 gain = 7 dB = 2.24
- Overall gain = 25 dB = 17.8

Notes 50

This question is nothing more than "drill" for students to practice decibel/ratio conversions.

Question 51

Here are a few good steps to take prior to applying any specific troubleshooting strategies to a malfunctioning amplifier circuit:

- Measure the output signal with an oscilloscope.
- Determine if the amplifier is receiving a good input signal.
- Check to see that the amplifier is receiving good-quality power.

Explain why taking these simple steps may save a lot of time in the troubleshooting process. For example, why bother checking the amplifier's output signal if you already know it isn't outputting what it's supposed to? What, exactly, constitutes "good-quality" power for an amplifier circuit?

file 01584

Answer 51

It is usually a good idea to verify the exact nature of the malfunction before proceeding with troubleshooting strategies, even if someone has already informed you of the problem. Seeing the malfunction with your own eyes may illuminate the problem better than if you simply acted on someone else's description, or worse yet your own assumptions.

The rationale for checking the input signal should be easy to understand. I'll let you answer this one!

"Good-quality" power consists of DC within the proper voltage range of the amplifier circuit, with negligible ripple voltage.

Follow-up question #1: suppose you discover that the "faulty" amplifier is in fact *not* receiving any input signal at all? Does this test exonerate the amplifier itself? How would might you simulate a proper input signal for the amplifier, for the purposes of testing it?

Follow-up question #2: explain how to measure power supply ripple voltage, using only a digital multimeter. How would you measure ripple using an oscilloscope?

Notes 51

In my own experience I have found these steps to be valuable time-savers prior to beginning any formal troubleshooting process. In general terms, *check for output*, *check for input*, and *check for power*.

New technicians are often surprised at how often complex problems may be caused by something as simple as "dirty" power. Since it only takes a few moments to check, and can lead to a wide range of problems, it is not wasted effort.

Question 52

The likelihood that a given component will fail in the "open" mode is quite often not the same as the likelihood that it will fail "shorted." Based on the research you do and your own personal experience with troubleshooting electronic circuits, determine whether the following components are more likely to fail *open* or fail *shorted* (this includes partial, or high-resistance, shorts):

- Resistors:
- Capacitors:
- Inductors:
- Transformers:
- Bipolar transistors:

I encourage you to research information on these devices' failure modes, as well as glean from your own experiences building and troubleshooting electronic circuits.

file 01594

Answer 52

Remember that each of these answers merely represents the *most likely* of the two failure modes, either open or shorted, and that probabilities may shift with operating conditions (i.e. switches may be more prone to failing shorted due to welded contacts if they are routinely abused with excessive current upon closure).

- Resistors: **open**
- Capacitors: **shorted**
- Inductors: **open or short equally probable**
- Transformers: **open or short equally probable**
- Bipolar transistors: **shorted**

Follow-up question: When bipolar transistors fail shorted, the short is usually apparent between the collector and emitter terminals (although sometimes all three terminals may register shorted, as though the transistor were nothing more than a junction between three wires). Why do you suppose this is? What is it about the base terminal that makes it less likely to "fuse" with the other terminals?

Notes 52

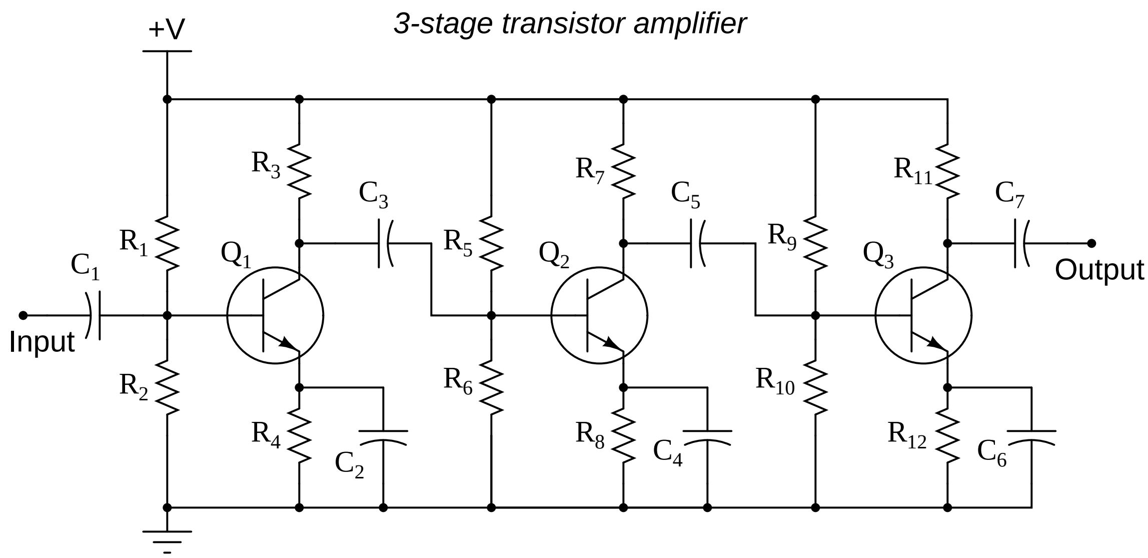
Emphasize to your students how a good understanding of common failure modes is important to efficient troubleshooting technique. Knowing which way a particular component is more likely to fail under normal operating conditions enables the troubleshooter to make better judgments when assessing the most probable cause of a system failure.

Of course, proper troubleshooting technique should always reveal the source of trouble, whether or not the troubleshooter has any experience with the failure modes of particular devices. However, possessing a detailed knowledge of failure probabilities allows one to check the most likely sources of trouble first, which generally leads to faster repairs.

An organization known as the *Reliability Analysis Center*, or *RAC*, publishes detailed analyses of failure modes for a wide variety of components, electronic as well as non-electronic. They may be contacted at 201 Mill Street, Rome, New York, 13440-6916. Data for this question was gleaned from the RAC's publication, *Part Failure Mode Distributions*.

Question 53

The three-stage amplifier shown here has a problem. Despite being supplied with good, "clean" DC power and an adequate input signal to amplify, there is no output signal whatsoever:

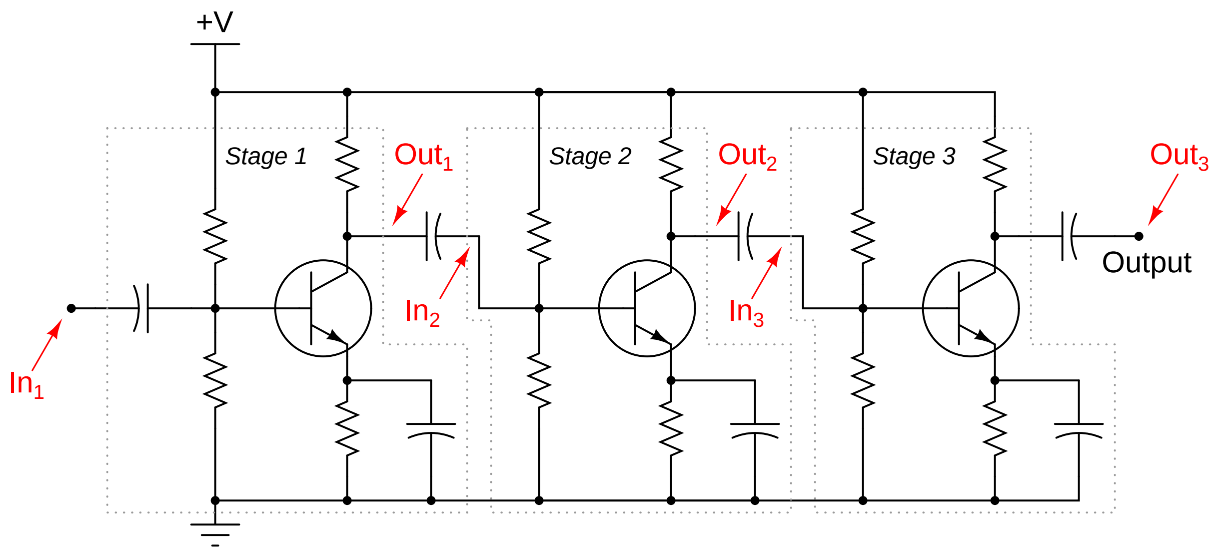


Explain how you would use the "divide and conquer" or "divide by two" strategy of troubleshooting to locate the amplification stage where the fault is. (This is where you divide the signal path into different sections, then test for good signal at points along that path so as to narrow the problem down to one-half of the circuit, then to one-quarter of the circuit, etc.)

Show the lines of demarcation where you would divide the circuit into distinct sections, and identify input and output test points for each of those sections.

file 01586

Answer 53



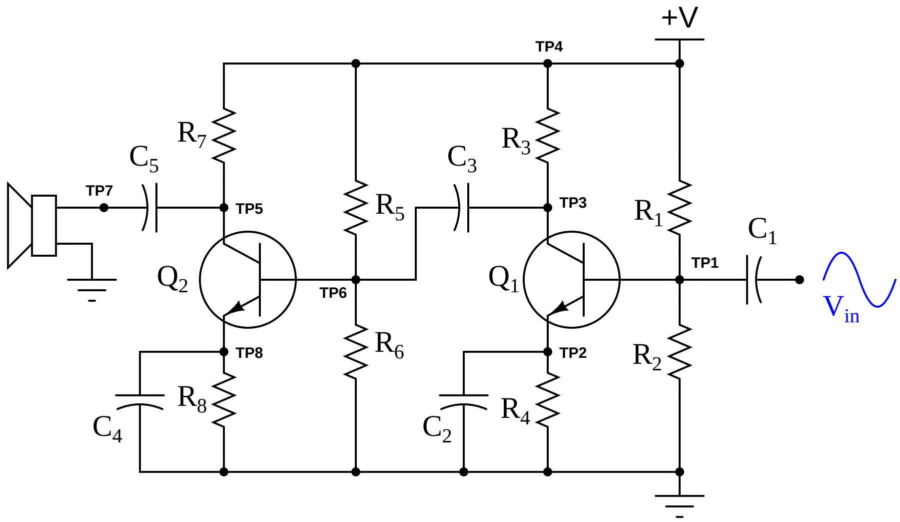
Challenge question: how well do you suppose this same troubleshooting strategy would work to locate the fault *within* a particular amplification stage?

Notes 53

Multi-stage amplifier circuits lend themselves well to the "divide and conquer" strategy of troubleshooting, especially when the stages are as symmetrical as these.

Question 54

The following amplifier circuit has a problem. Despite the presence of a strong input signal (as verified by an oscilloscope measurement at TP1), there is no sound coming from the speaker:



Explain a logical, step-by-step approach to identifying the source of the problem, by taking voltage signal measurements. Remember, the more efficient your troubleshooting technique is (the fewer measurements taken), the better!

file 01124

Answer 54

I'll let you have fun determining your own strategies here!

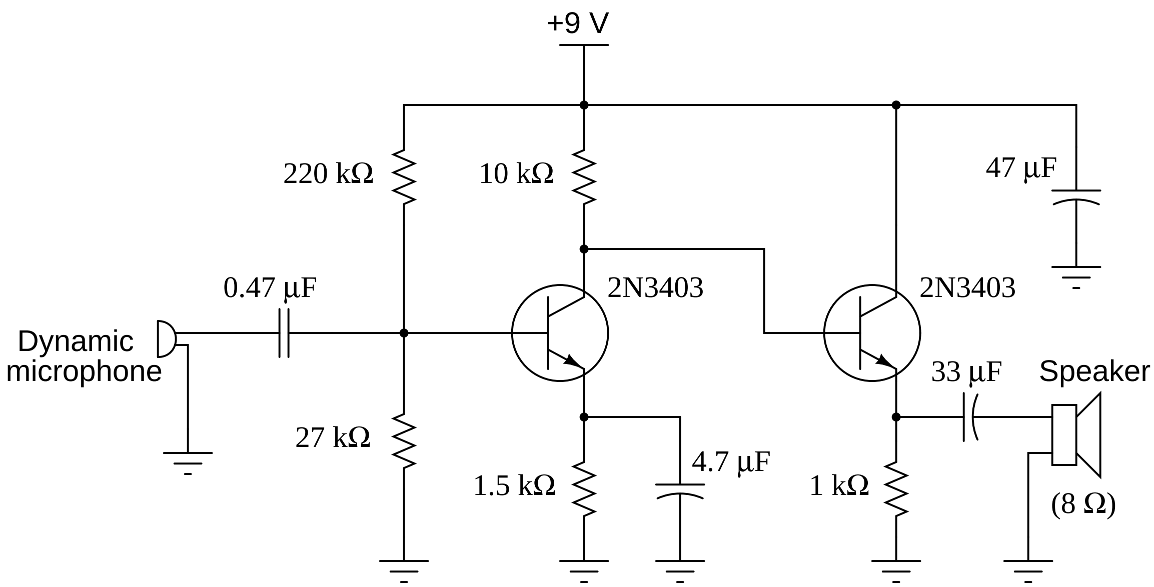
Notes 54

This question can easily occupy a large portion of your discussion time, so be sure to make room for it in your schedule!

A great way to help students grasp the concepts involved in this circuit as well as improve their troubleshooting technique, is to make a large-scale demonstration board of this circuit, which you can fault on the back side by disconnecting wires, opening or closing switches, etc. Then, have the students take an oscilloscope and practice finding problems in the circuit by voltage measurement only. I have built similar demonstration boards for my own classroom, and have found them to be extremely useful in building and assessing troubleshooting skills.

Question 55

In order to successfully troubleshoot any electronic circuit to the component level, one must have a good understanding of each component's function within the context of that circuit. Transistor amplifiers are no exception to this rule. The following schematic shows a simple, two-stage audio amplifier circuit:



Identify the role of the following components in this audio amplifier circuit:

- The 0.47 μF capacitor connected to the microphone
- The 220 kΩ and 27 kΩ resistor pair
- The 4.7 μF electrolytic capacitor connected across the 1.5 kΩ resistor
- The 33 μF electrolytic capacitor connected to the speaker
- The 47 μF electrolytic capacitor connected to the power supply rail

Additionally, answer the following questions concerning the circuit's design:

- What configuration is each stage (common-base, common-collector, common-emitter)?
- Why not just use one transistor stage to drive the speaker? Why is an additional stage necessary?
- What might happen if the 47 μF "decoupling" capacitor were not in the circuit?
- Why does the second stage of the amplifier not need its own voltage divider to set bias voltage as the first stage does?

file 01587

Answer 55

- The 0.47 μF capacitor connected to the microphone: *passes (AC) audio signal, blocks DC bias voltage from reaching microphone*
- The 220 kΩ and 27 kΩ resistor pair: *sets DC bias voltage for first transistor stage*
- The 4.7μF electrolytic capacitor connected across the 1.5 kΩ resistor: *bypasses (AC) audio signal around emitter resistor, for maximum AC voltage gain*
- The 33 μF electrolytic capacitor connected to the speaker: *couples (AC) audio signal to speaker while blocking DC bias voltage from speaker*
- The 47 μF electrolytic capacitor connected to the power supply rail: *"decouples" any AC signal from the power supply, by providing a low-impedance (short) path to ground*

The question regarding the necessity of the 47 μF decoupling capacitor is tricky to answer, so I'll elaborate a bit here. Power supply decoupling is a good design practice, because it can ward off a wide range of problems. AC "ripple" voltage should never be present on the power supply "rail" conductors, as transistor circuits function best with pure DC power. The purpose of a decoupling capacitor is to subdue any ripple, whatever its source, by acting as a low-impedance "short" to ground for AC while not presenting any loading to the DC power.

Although it may not seem possible at first inspection, the lack of a decoupling capacitor in this audio amplifier circuit can actually lead to self-oscillation (where the amplifier becomes a tone generator) under certain power supply and load conditions! If the power supply is poorly regulated and/or poorly filtered, the presence of a decoupling capacitor will greatly diminish line-frequency "hum" noise heard in the speaker.

For the rest of the questions, I'll let you figure out answers on your own!

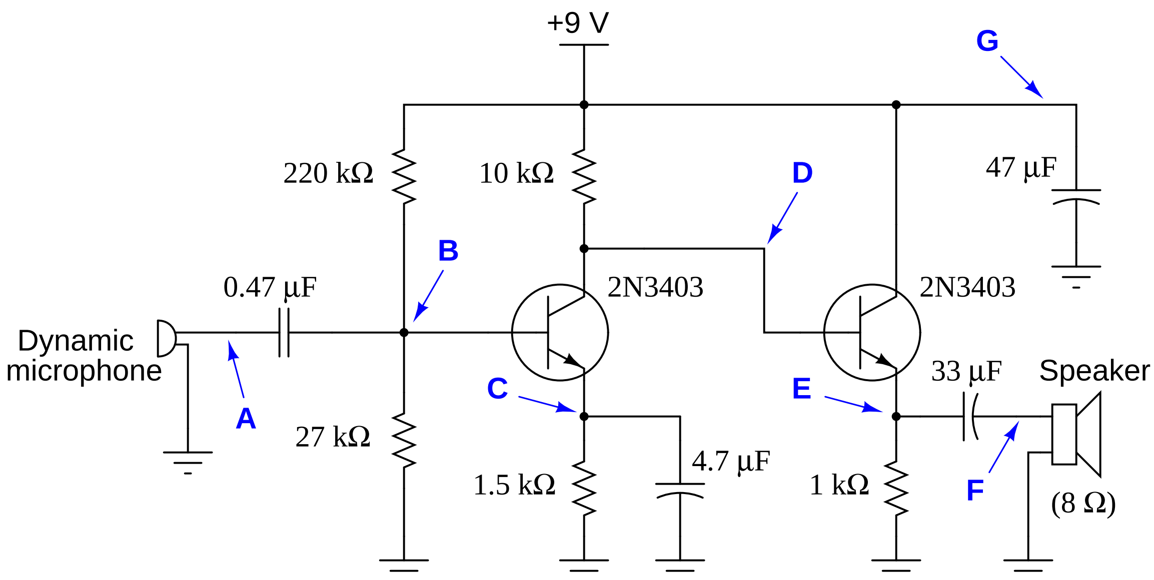
Notes 55

Incidentally, this circuit makes a good "intercom" amplifier for a student project. Using a small dynamic speaker for the microphone, and another speaker (or audio headset) on the receiving end of a long cable connected to the amplifier output, students can easily talk between two rooms in a building, or even between buildings.

Question 56

Often times, component failures in transistor circuits will cause significant shifting of DC (quiescent) parameters. This is a benefit for the troubleshooter, as it means many faults may be located simply by measuring DC voltages (with no signal input) and comparing those voltages against what is expected. The most difficult part, though, is determining what DC voltage levels to expect at various points in an amplifier circuit.

Examine this two-stage audio amplifier circuit, and estimate the DC voltages at all the points marked by bold letters and arrows (**A** through **G**), with reference to ground. Assume that conducting PN junctions will drop 0.7 volts, that loading effects on the voltage divider are negligible, and that the transistor's collector and emitter currents are virtually the same magnitude:



$V_A \approx$
$V_B \approx$
$V_C \approx$
$V_D \approx$
$V_E \approx$
$V_F \approx$
$V_G \approx$

file 01588

Answer 56

$V_A = 0$ volts (precisely)
$V_B \approx 0.98$ volts
$V_C \approx 0.28$ volts
$V_D \approx 7.1$ volts
$V_E \approx 6.4$ volts
$V_F = 0$ volts (precisely)
$V_G = 9$ volts (precisely)

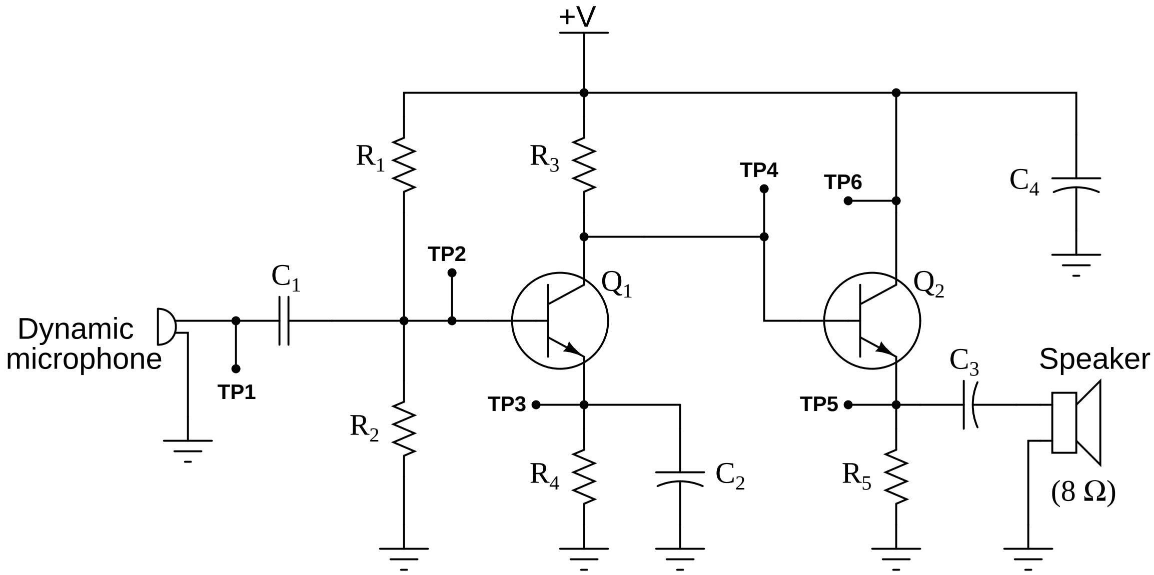
Follow-up question: explain why voltages V_A, V_F, and V_G can be precisely known, while all the other DC voltages in this circuit are approximate. Why is this helpful to know when troubleshooting a faulted amplifier circuit?

Notes 56

The calculations used to estimate these values are quite simple, and should prove no trouble for students to derive who have a basic knowledge of DC circuit calculations (voltage dividers, series voltage drops, etc.).

Question 57

Study this audio amplifier circuit closely:



Then, determine whether the DC voltage at each test point (V_{TP1} through V_{TP6}) with respect to ground will increase, decrease, or remain the same for each of the given fault conditions:

Fault	V_{TP1}	V_{TP2}	V_{TP3}	V_{TP4}	V_{TP5}	V_{TP6}
R1 failed open	Same					Same
R2 failed open	Same					Same
R3 failed open	Same					Same
R4 failed open	Same					Same
R5 failed open	Same					Same
Short between TP2 and ground	Same					Same
C2 failed shorted	Same					Same
Q1 collector failed open	Same					Same

When analyzing component faults, consider only one fault at a time. That is, for each row in the table, you should analyze the circuit as though the only fault in it is the one listed in the far left column of that row.

file 01593

Answer 57

If the voltage changes to zero, I show 0 in the table. If the increase or decrease is relatively small, I use thin arrows ($\uparrow$ or $\downarrow$). If the change is great, I use thick arrows ($\Uparrow$ or $\Downarrow$).

Fault	V_{TP1}	V_{TP2}	V_{TP3}	V_{TP4}	V_{TP5}	V_{TP6}
R1 failed open	Same	0	0	$\Uparrow$	$\Uparrow$	Same
R2 failed open	Same	$\uparrow$	$\uparrow$	$\Downarrow$	$\Downarrow$	Same
R3 failed open	Same	$\downarrow$	$\Downarrow$	$\Downarrow$	$\Downarrow$	Same
R4 failed open	Same	Same	$\uparrow$	$\Uparrow$	$\Uparrow$	Same
R5 failed open	Same	$\approx$ Same	$\approx$ Same	$\uparrow$	$\uparrow$	Same
Short between TP2 and ground	Same	0	0	$\Uparrow$	$\Uparrow$	Same
C2 failed shorted	Same	$\downarrow$	0	$\Downarrow$	$\Downarrow$	Same
Q1 collector failed open	Same	$\downarrow$	$\Downarrow$	$\Uparrow$	$\Uparrow$	Same

Follow-up question: why don't test point voltages V_{TP1} or V_{TP6} ever change?

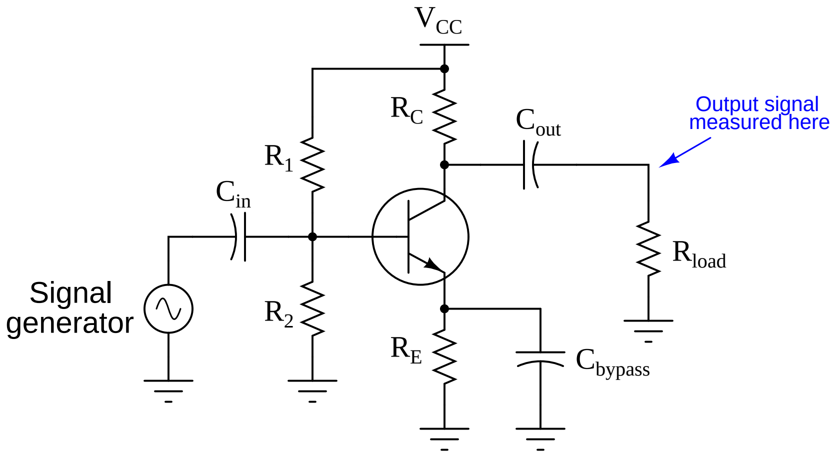
Notes 57

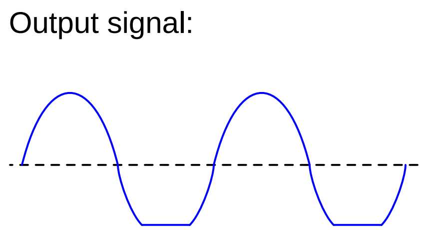
I was able to verify specific voltages by building this circuit and faulting each component as described. Although I was not always able to predict the magnitude of the change, I could always predict the direction. This is really all that should be expected of beginning students.

The really important aspect of this question is for students to understand *why* the test point voltages change as they do. Discuss each fault with your students, and how one can predict the effects just by looking at the circuit.

Question 58

Suppose you were troubleshooting the following amplifier circuit, and found the output signal to be "clipped" on the negative peaks:





If you knew that this amplifier was a new design, and might not have all its components properly sized, what type of problem would you suspect in the circuit? Please be as specific as possible.

file 01581

Answer 58

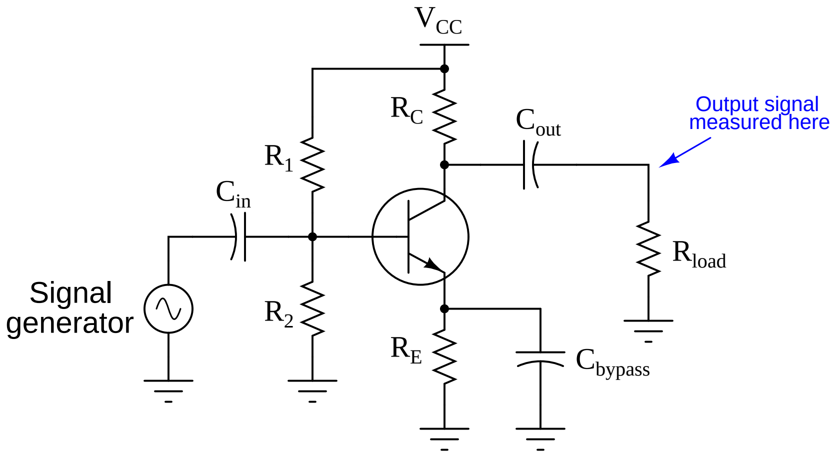
This amplifier most likely suffers from improper biasing, which may be remedied by changing the value of R_1 or R_2. (I'll let you determine which way the chosen resistor value must be altered, increase or decrease!)

Notes 58

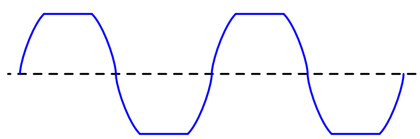
Discuss with your students how to determine whether the bias voltage is too great or too small, based on the observed output waveform. It isn't difficult to do so long as students understand *why* biasing exists and how it works.

Question 59

Suppose you were troubleshooting the following amplifier circuit, and found the output signal to be symmetrically "clipped" on both the positive and negative peaks:



Output signal:



If you knew that this amplifier was a new design, and might not have all its components properly sized, what type of problem would you suspect in the circuit? Please be as specific as possible.

file 01582

Answer 59

This amplifier suffers from excessive gain, which may be remedied by changing the value of R_C or R_E. (I'll let you determine which way the chosen resistor value must be altered, increase or decrease!)

Of course, changing either of these resistor values will alter the bias ("Q") point of the amplifier, which may necessitate subsequent changes in the value of either R_1 or R_2!

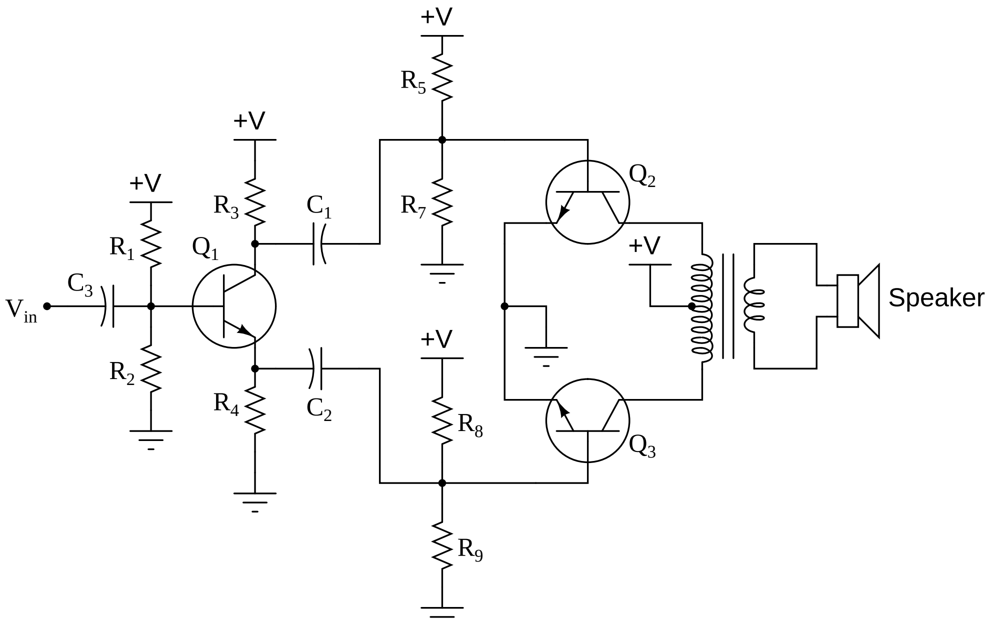
Notes 59

Discuss with your students how to determine the necessary changes in resistor values, based on the determination that the gain is excessive. This is actually very easy to do just by examining the gain formula for a common-emitter amplifier.

Another option to consider here is the addition of a negative feedback signal path to tame the amplifier's gain. This modification would have the added benefit of improving circuit linearity.

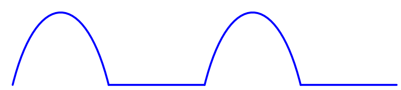
Question 60

This class-B audio power amplifier circuit has a problem: its output is very distorted, resembling half of a sine wave when tested with an input signal from a function generator:



Output signal:

(measured by oscilloscope at speaker terminals)



List some of the possible faults in this system, based on the output signal shown by the oscilloscope. Also, determine which components, if any, are known to be good based on the same data:

Possible faults in the system:

- Fault #1:
- Fault #2:
- Fault #3:

Components known to be okay in the system:

- Component #1:
- Component #2:
- Component #3:

file 01590

Answer 60

First, realize that we cannot know which half of the push-pull circuit is failed, due to the isolation of the transformer and the resulting uncertainty of polarity. *Please note that the lists shown here are not exhaustive.*

Possible faults in the system:

- Fault #1: Transistor Q_2 or Q_3 failed open
- Fault #2: Resistor R_5 or R_8 failed open
- Fault #3: Half of transformer primary winding failed open

Components known to be okay in the system:

- Component #1: Secondary winding of transformer
- Component #2: Resistor R_4
- Component #3: Input coupling capacitor C_3

Follow-up question #1: suppose that after testing this amplifier on your workbench with a "dummy" load (8 Ω resistor connected to the speaker terminals), you happened to notice that transistor Q_2 was slightly warm to the touch, while transistor Q_3 was still at room temperature. What would this extra information indicate about the amplifier's problem?

Follow-up question #2: describe the potential safety hazards involved with touching a power transistor in an operating circuit. If you wished to compare the operating temperature of these two transistors, how could you safely do it?

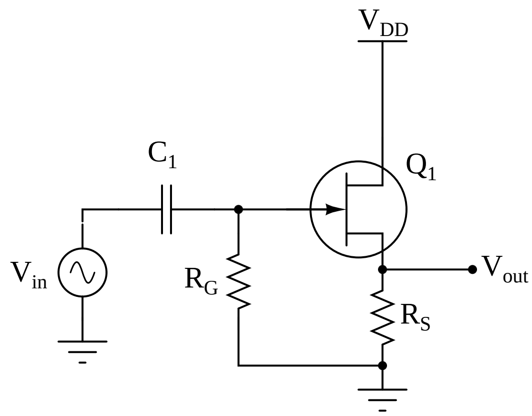
Notes 60

The symmetry inherent in push-pull amplifiers makes troubleshooting easier in some respects. As always, though, component-level troubleshooting requires a detailed understanding of component function within the context of the specific circuit being diagnosed. No matter how "simple" the circuit may be, a student will be helpless to troubleshoot it down to the component level unless they understand how and why each component functions.

Giving the clue regarding transistor temperature is important for two reasons. First, it provides more data for students to use in confirming fault possibilities. Second, it underscores the importance of non-electrical data. Efficient troubleshooters make (safe) use of all available data when investigating a problem, and that often requires creative thinking.

Competency: **Common-drain class-A amplifier** Version:

Schematic



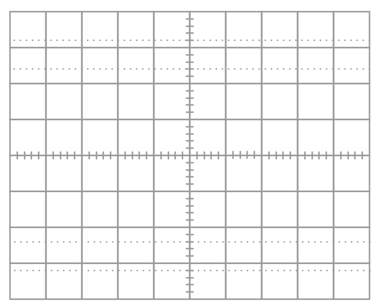
Given conditions

V_{in} = V_{DD} = R_G = R_S = C_1 =

Parameters

	Predicted	Measured
V_G (DC)		
V_{out} (AC)		
A_V		

Input and output waveforms (measured)



Inverting . . . ☐

or noninverting? ☐

file 01992

Answer 61

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 61

Use a variable-voltage, regulated power supply to supply any amount of DC voltage below 30 volts. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.). Use a sine-wave function generator to supply an audio-frequency input signal, and make sure its amplitude isn't set so high that the amplifier clips.

I have had good success using the following values:

- $V_{DD} = 9$ volts
- $V_{in} = 1$ volt (peak), $f = 2$ kHz
- $R_G = 100$ kΩ
- $R_S = 10$ kΩ
- $C_1 = 0.47$ μF

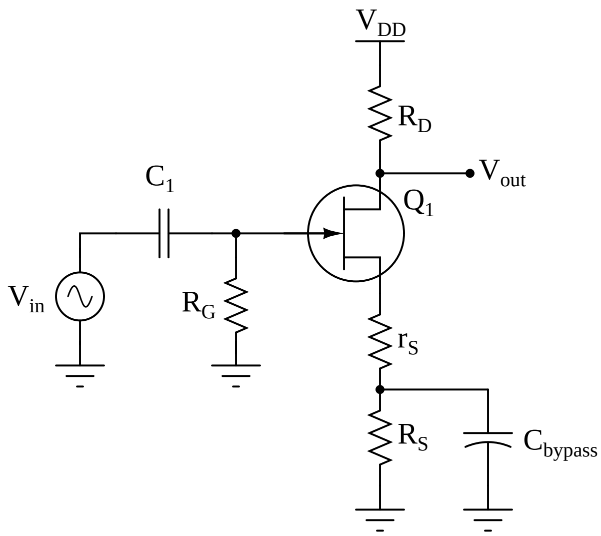
Please note that the quiescent output voltage is impossible to precisely predict, as it depends on the particular characteristics of the JFET used (I_D versus V_{GS}). The fact that this circuit uses self-biasing instead of voltage divider biasing makes the situation worse. Predicting quiescent gate voltage, however should be extremely easy (0 volts) if one understands how JFETs function.

An interesting parameter to explore in this circuit is the effect of the source resistor value on voltage gain. The theoretical voltage gain of a simple common-drain amplifier circuit is unity (1), but this may be approximated only with relatively large load resistor (R_S) values. Try substituting a 1 kΩ or less resistor for R_S, and notice what happens to the gain. Then, have your students explain why this happens!

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Common-source class-A amplifier** Version:

Schematic



Given conditions

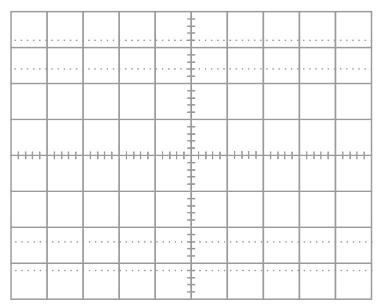
V_{in} = V_{DD} = R_G = R_D = C_1 =

r_S = R_S = C_{bypass} =

Parameters

	Predicted	Measured
V_G (DC)		
V_{out} (AC)		
A_V		

Input and output waveforms (measured)



Inverting . . . ☐

or noninverting? ☐

file 01993

Answer 62

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 62

Use a variable-voltage, regulated power supply to supply any amount of DC voltage below 30 volts. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.). Use a sine-wave function generator to supply an audio-frequency input signal, and make sure its amplitude isn't set so high that the amplifier clips.

I have had good success using the following values:

- V_{DD} = 12 volts
- V_{in} = 0.5 volt (peak-to-peak), f = 2 kHz
- R_G = 100 kΩ
- r_S = 2.2 kΩ
- R_S = 10 kΩ
- R_D = 10 kΩ
- C_1 = 0.47 μF
- C_{bypass} = 10 μF

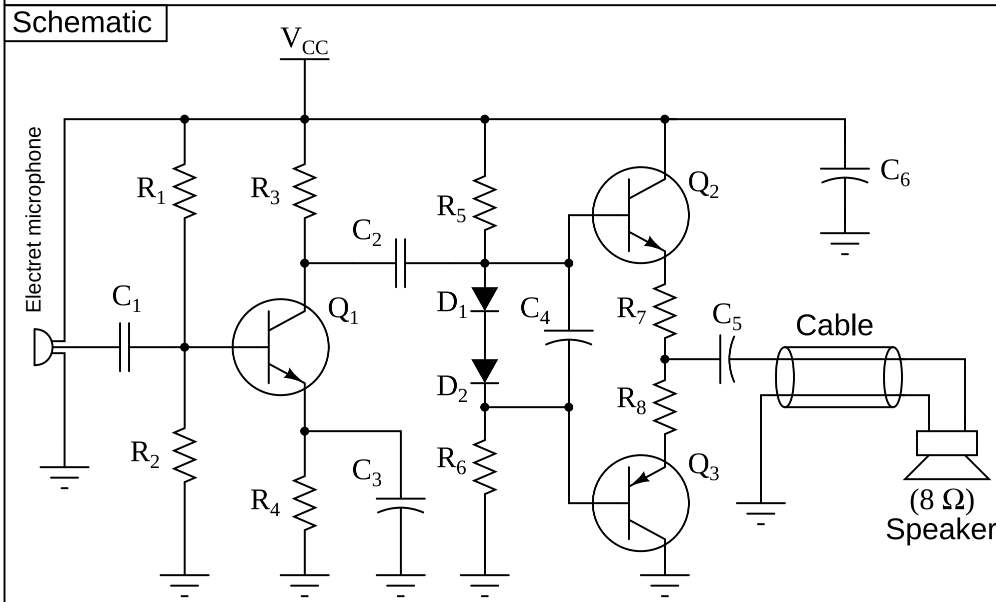
Please note that the quiescent output voltage is impossible to precisely predict, as it depends on the particular characteristics of the JFET used (I_D versus V_{GS}). The fact that this circuit uses self-biasing instead of voltage divider biasing makes the situation worse. Predicting quiescent gate voltage, however should be extremely easy (0 volts) if one understands how JFETs function.

All quiescent circuit values depend on V_{DD}, so if things aren't biased the way you would like, simply adjust the power supply voltage to suit.

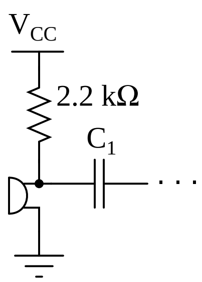
An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Audio intercom circuit, push-pull output** Version:

Schematic



Two-wire electret microphone schematic



Given component values

$C_1 = C_2 =$

$C_3 = C_4 =$

$C_5 =$

$C_6 =$

$V_{CC} =$

$R_1 =$

$R_2 =$

$R_3 =$

$R_4 =$

$R_5 = R_6 =$

$R_7 = R_8 =$

Fault analysis

Suppose component ☐ fails ☐ open ☐ shorted ☐ other ______________

What will happen in the circuit?

file 01995

Answer 63

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 63

Use a variable-voltage, regulated power supply to supply a DC voltage safely below the maximum rating of the electret microphone (typically 10 volts). Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.). Use a sine-wave function generator to supply an audio-frequency input signal, and make sure its amplitude isn't set so high that the amplifier clips.

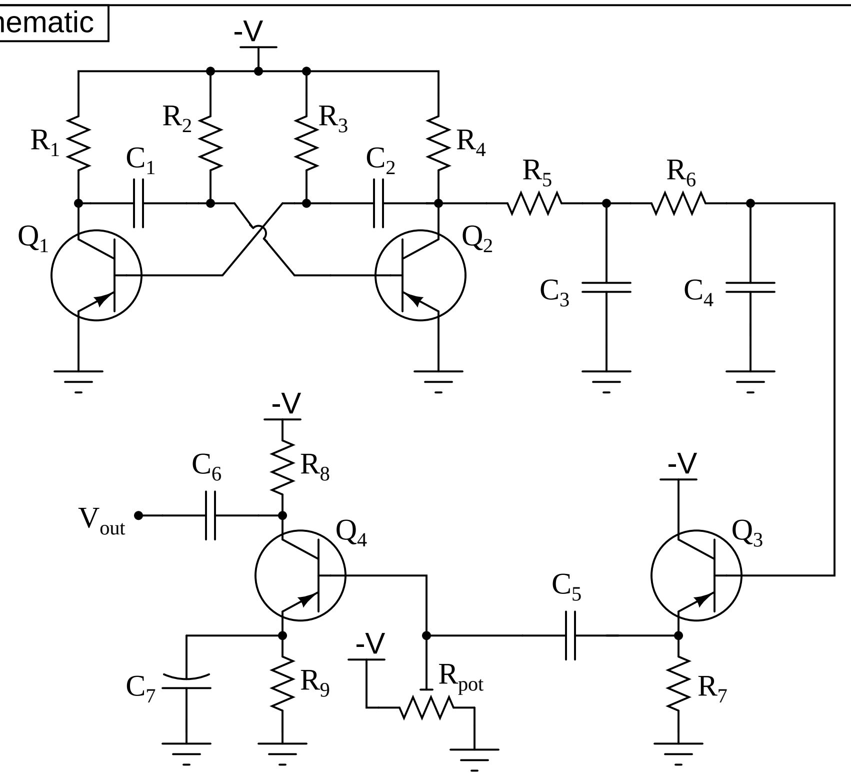
I have had good success using the following values:

- V_{CC} = 6 volts
- R_1 = 68 kΩ
- R_2 = 33 kΩ
- R_3 = 4.7 kΩ
- R_4 = 1.5 kΩ
- $R_5 = R_6$ = 10 kΩ
- $R_7 = R_8$ = 10 Ω
- $C_1 = C_2$ = 0.47 μF
- $C_3 = C_4$ = 47 μF
- C_5 = 1000 μF
- C_6 = 100 μF
- $D_1 = D_2$ = part number 1N4001
- Q_1 = part number 2N2222
- Q_2 = part number 2N2222
- Q_3 = part number 2N2907

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Oscillator/waveshaper/amplifier circuit** Version:

Schematic



Given conditions

-V =	R_1 =	R_6 =	C_1 =	C_5 =
	R_2 =	R_7 =	C_2 =	C_6 =
	R_3 =	R_8 =	C_3 =	C_7 =
	R_4 =	R_9 =	C_4 =	
	R_5 =	R_{pot} =		

Parameters

	Predicted waveshape	Measured waveshape		Predicted waveshape	Measured waveshape
$V_{C(Q2)}$			V_{C4}		
$V_{B(Q2)}$			V_{R7}		
V_{C3}			V_{out}		

file 02507

Answer 64

Use circuit simulation software to verify your predicted and measured parameter values.

Use a variable-voltage, regulated power supply to supply any amount of DC voltage below 30 volts. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

This circuit demonstrates the use of passive integrators to convert a square wave into a pseudo-sine wave output. The multivibrator portion produces nice, sharp-edged square wave signals at the transistor collector terminals when resistors R_1 and R_4 are substantially smaller than resistors R_2 and R_3. Component values I've used with success are 1 kΩ for R_1 and R_4, 100 kΩ for R_2 and R_3, and 0.001 μF for C_1 and C_2.

Resistors R_5 and R_6, along with capacitors C_3 and C_4, form a dual passive integrator network to re-shape the square-wave output of the multivibrator into a pseudo-sine wave. These components' values must be chosen according to the multivibrator frequency, so that the integration is realistic without the attenuation being excessive. Integrator component values that have worked well for the multivibrator components previously specified are 10 kΩ for R_5 and R_6, and 0.1 μF for C_3 and C_4.

Transistor Q_3 is just an emitter follower, placed there to give the amplifier section a high input impedance. Q_3's emitter resistor value is not critical. I have used a 1 kΩ resistor for R_7 with good success.

The last transistor (Q_4) is for voltage amplification. A "trimmer" style potentiometer (10 kΩ recommended for R_{pot}) provides easy adjustment of biasing for different supply voltages. Using the potentiometer, I have operated this circuit on supply voltages ranging from -6 volts to -27 volts. Use a bypass capacitor (C_7) large enough that its reactance at the operating frequency is negligible (less than 1 ohm is good), such as 33 μF. Resistor values I've used with success are 10 kΩ for R_8 and 4.7 kΩ for R_9. Coupling capacitor values are not terribly important, so long as they present minimal reactance at the operating frequency. I have used 0.47 μF for both C_5 and C_6 with good success.

You may find that the relatively high operating frequency of this circuit complicates matters with regard to parasitic capacitances. The fast rise and fall times of the strong square wave tend to couple easily to the sine-wave portions of the circuit, especially when the sine wave signal is so severely attenuated by the double integrators. One solution to this dilemma is to lower the operating frequency of the circuit, allowing a lower cutoff frequency for the double integrator (two-pole lowpass filter) section which in turn will improve the signal-to-noise ratio throughout. If you wish to try this, you may use these suggested component values:

- R_1 = 1 kΩ
- R_2 = 100 kΩ
- R_3 = 100 kΩ
- R_4 = 1 kΩ
- R_5 = 100 kΩ
- R_6 = 100 kΩ
- R_7 = 1 kΩ
- R_8 = 10 kΩ
- R_9 = 4.7 kΩ
- R_{pot} = 10 kΩ
- C_1 = 0.047 μF
- C_2 = 0.047 μF
- C_3 = 0.1 μF
- C_4 = 0.047 μF
- C_5 = 1 μF
- C_6 = 1 μF
- C_7 = 33 μF

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Troubleshooting log

Actions / Measurements / Observations (i.e. *What I did and/or noticed . . .*)	**Conclusions** (i.e. *What this tells me . . .*)

file 03933

Answer 65

I do not provide a grading rubric here, but elsewhere.

Notes 65

The idea of a troubleshooting log is three-fold. First, it gets students in the habit of documenting their troubleshooting procedure and thought process. This is a valuable habit to get into, as it translates to more efficient (and easier-followed) troubleshooting on the job. Second, it provides a way to document student steps for the assessment process, making your job as an instructor easier. Third, it reinforces the notion that each and every measurement or action should be followed by reflection (conclusion), making the troubleshooting process more efficient.

Question 66

NAME: ________________ **Troubleshooting Grading Criteria**

You will receive the highest score for which *all* criteria are met.

100 % *(Must meet or exceed all criteria listed)*

A. Absolutely flawless procedure
B. No unnecessary actions or measurements taken

90 % *(Must meet or exceed these criteria in addition to all criteria for 85% and below)*

A. No reversals in procedure (i.e. changing mind without sufficient evidence)
B. Every single action, measurement, and relevant observation properly documented

80 % *(Must meet or exceed these criteria in addition to all criteria for 75% and below)*

A. No more than one unnecessary action or measurement
B. No false conclusions or conceptual errors
C. No missing conclusions (i.e. at least one documented conclusion for action / measurement / observation)

70 % *(Must meet or exceed these criteria in addition to all criteria for 65%)*

A. No more than one false conclusion or conceptual error
B. No more than one conclusion missing (i.e. an action, measurement, or relevant observation without a corresponding conclusion)

65 % *(Must meet or exceed these criteria in addition to all criteria for 60%)*

A. No more than two false conclusions or conceptual errors
B. No more than two unnecessary actions or measurements
C. No more than one undocumented action, measurement, or relevant observation
D. Proper use of all test equipment

60 % *(Must meet or exceed these criteria)*

A. Fault accurately identified
B. Safe procedures used at all times

50 % *(Only applicable where students performed significant development/design work – i.e. not a proven circuit provided with all component values)*

A. Working prototype circuit built and demonstrated

0 % *(If any of the following conditions are true)*

A. Unsafe procedure(s) used at any point

file 03932

Answer 66

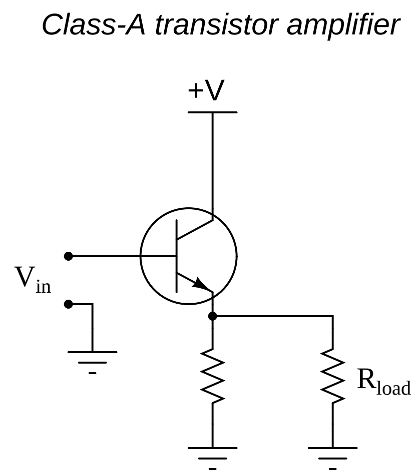
Be sure to document all steps taken and conclusions made in your troubleshooting!

Notes 66

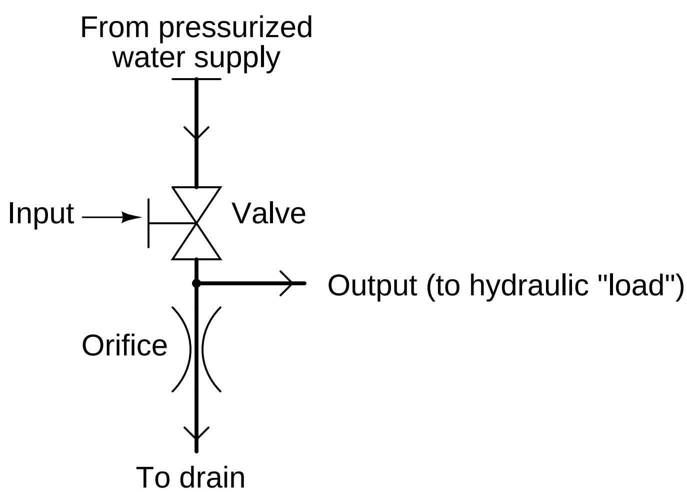
The purpose of this assessment rubric is to act as a sort of "contract" between you (the instructor) and your student. This way, the expectations are all clearly known in advance, which goes a long way toward disarming problems later when it is time to grade.

Question 67

A *Class-A* transistor amplifier uses a single transistor to generate an output signal to a load. The amplifier shown here happens to be of the "common collector" topology, one of three configurations common to single-transistor circuits:



An analogue for this electronic circuit is this water-pressure control, consisting of a variable valve passing water through an orifice (a restriction), then on to a drain:



The "input" to this amplifier is the positioning of the valve control handle. The "output" of this amplifier is water pressure measured at the end of the horizontal "output" pipe.

Explain how either of these "circuits" meets the criteria of being an amplifier. In other words, explain how *power* is boosted from input to output in both these systems. Also, describe how efficient each of these amplifiers is, "efficiency" being a measure of how much current (or water) goes to the load device, as compared to how much just goes straight through the controlling element and back to ground (the drain).

file 00867

Answer 67

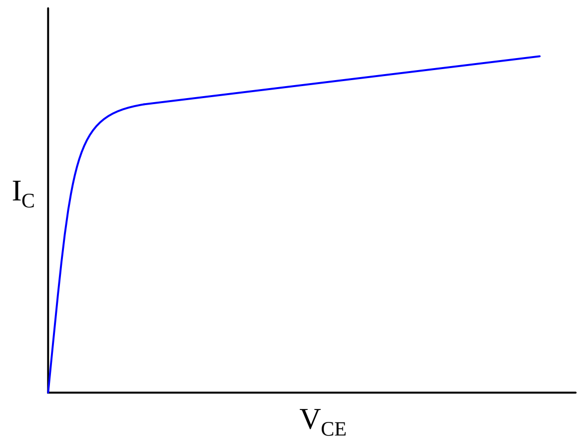
In both systems, a small amount of energy (current through the "base" terminal of the transistor, mechanical motion of the valve handle) exerts control over a larger amount of energy (current to the load, water to the load). The systems shown here are rather wasteful, especially at high output voltage (pressure).

Notes 67

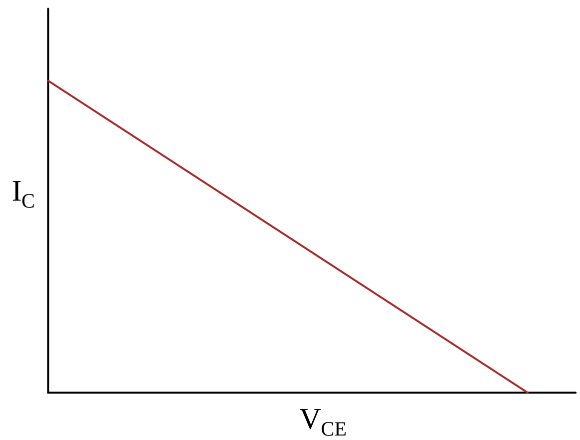
Wasteful they may be, but "Class-A" transistor circuits find very common use in modern electronics. Explain to your students that its inefficiency restricts its practical use to low-power applications.

Question 68

We know that graphs are nothing more than collections of individual points representing correlated data in a system. Here is a plot of a transistor's characteristic curve (for a single value of base current):



And here is a plot of the "load line" for a transistor amplifier circuit:



For each of these graphs, pick a single point along the curve (or line) and describe what that single point represents, in real-life terms. What does any single point of data along either of these graphs *mean* in a transistor circuit?

If a transistor's characteristic curve is superimposed with a load line on the same graph, what is the significance of those two plots' intersection?

file 00945

Answer 68

For a transistor's characteristic curve, one point of data represents the amount of current that will go through the collector terminal for a given amount of base current, and a given amount of collector-emitter voltage drop.

For a load line, one point of data represents the amount of collector-emitter voltage available to the transistor for a given amount of collector current.

The intersection of a characteristic curve and a load line represents the one collector current (and corresponding V_{CE} voltage drop) that will "satisfy" all components' conditions.

Notes 68

Discuss this question thoroughly with your students. So many students of electronics learn to plot load lines for amplifier circuits without ever really understanding *why* they must do so. Load line plots are very useful tools in amplifier circuit analysis, but the meaning of each curve/line must be well understood before it becomes useful as an instrument of understanding.

Ask your students which of the two types of graphs (characteristic curves, or load lines) represents a component's natural, or "free", behavior, and which one represents the bounded conditions within a particular circuit.

Question 69

A common term used in semiconductor circuit engineering is *small signal analysis*. What, exactly, is "small signal" analysis, and how does it contrast with *large signal analysis*?

file 01680

Answer 69

Small signal analysis is where the signals are presumed to be small enough in magnitude that the active device(s) should respond in a nearly linear manner. *Large signal analysis* is where the signals are presumed to be large enough that component nonlinearities become significant.

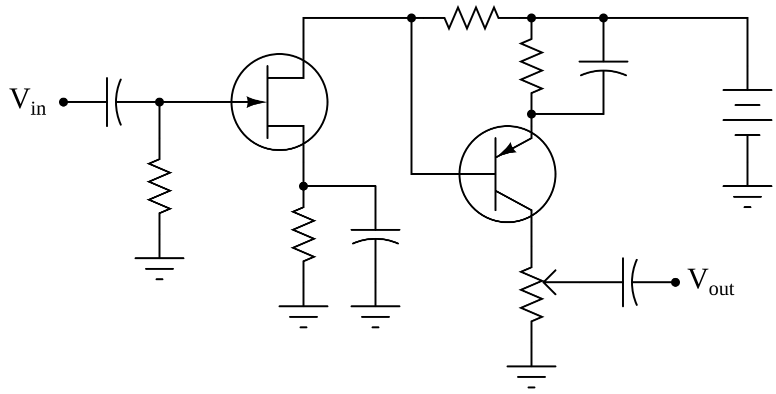
Follow-up question: why would engineers bother with two modes of analysis instead of just one (large signal), where the components' true (nonlinear) behavior is taken into account? Explain this in terms of network theorems and other mathematical "tools" available to engineers for circuit analysis.

Notes 69

When researching engineering textbooks and other resources, these terms are quite often used without introduction, leaving many beginning students confused.

Question 70

Determine whether this amplifier circuit is inverting or noninverting (i.e. the phase shift between input and output waveforms):



Be sure to explain, step by step, *how* you were able to determine the phase relationship between input and output in this circuit. Also identify the type of amplifier each transistor represents (common-???).

file 01183

Answer 70

Noninverting. The JFET is connected as a common-source, while the BJT is connected as a common-emitter.

Notes 70

There are several other questions you could ask about this amplifier circuit. For example:

- How is the Q-point bias established for the JFET?
- How is the Q-point bias established for the BJT?
- What purpose does the potentiometer serve?
- Is there another possible location for the potentiometer that would perform the same function?

Note: the schematic diagram for this circuit was derived from one found on page 36 of John Markus' Guidebook of Electronic Circuits, first edition. Apparently, the design originated from a Motorola publication on using field effect transistors ("Tips on using FET's," HMA-33, 1971).

Question 71

It is a well-known fact that temperature affects the operating parameters of bipolar junction transistors. This is why grounded-emitter circuits (with no emitter feedback resistor) are not practical as stand-alone amplifier circuits.

Does temperature affect junction field-effect transistors in the same way, or to the same extent? Design an experiment to determine the answer to this question.

file 01182

Answer 71

Did you really think I would tell you the answer to this question? Build the circuit(s) and discover the answer for yourselves!

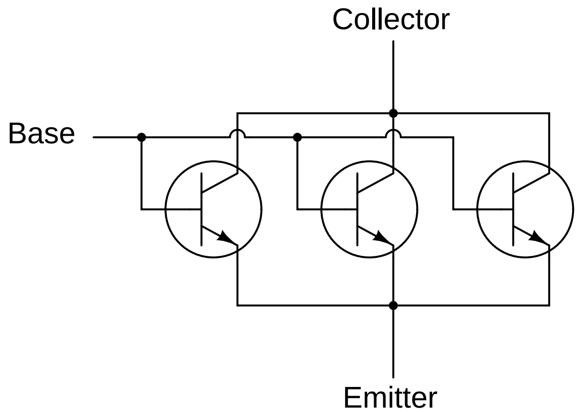
Notes 71

The purpose of this question is to get students thinking in an experimental mode. It is very important that students learn to set up and run their own experiments, so they will be able to verify (or perhaps discover!) electronic principles after they have graduated from school. There will be times when the answers they seek are not to be found in a book, and they will have to "let the electrons teach them" what they need to know.

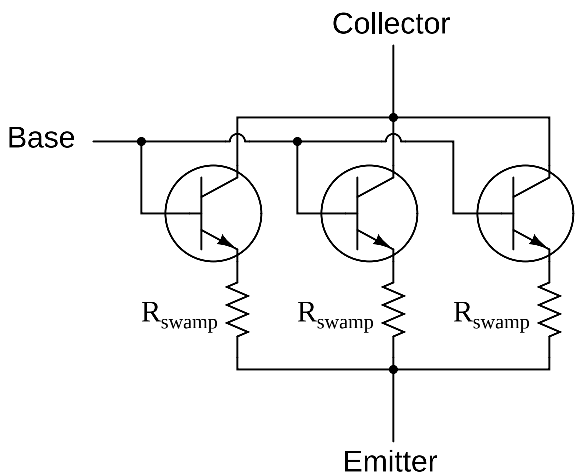
Remind your students that proper scientific experiments include both *experimental* and *control* subjects, so that results are based upon a comparison of measurements.

Question 72

In some applications where transistors must amplify very high currents, bipolar transistors are paralleled together so that their current ratings add:



However, if transistors are directly paralleled as shown, reliability problems may develop. A better way of "ganging" multiple transistors together is to connect a low-value *swamping resistor* to each emitter terminal:



Explain what purpose these resistors serve in a paralleled transistor network. And what exactly does "swamping" mean, anyway?

file 01485

Answer 72

Swamping is a design term, meaning to introduce a quantity or quantities into a circuit such that any intrinsic differences between components become insignificant in comparison. In this circuit, the swamping resistors help ensure that the total controlled current is more evenly split between the three transistors.

Follow-up question: can you think of any disadvantages to using swamping resistors in high-power circuitry?

Notes 72

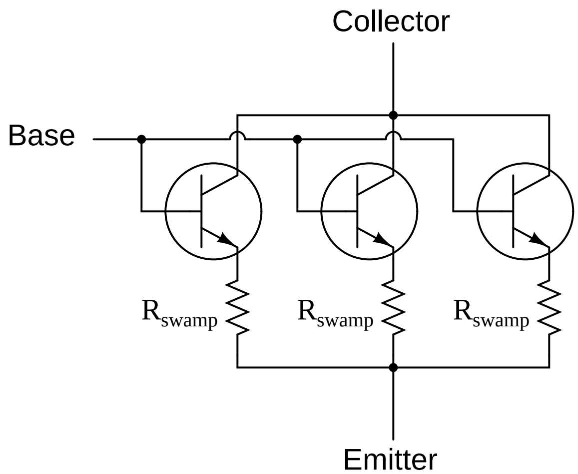
I once had the misfortune of performing component-level repair on a large power inverter (208 volt, three-phase) that used large "banks" of directly paralleled bipolar transistors for the final switching elements. These inverters had a bad habit of destroying transistors, and I noticed that invariably there would be only one or two transistors out of about a dozen on each heat sink rail that were blown – and I mean *blown*, holes blasted through the metal TO-3 cases! – while the rest were perfectly fine. These transistor banks did not employ swamping resistors, and so the current distribution between them was quite unbalanced.

In case students ask, you should let them know that swamping resistors are not just used in transistor banks. Large rectifier diode banks (where multiple diodes are paralleled) also benefit from swamping resistors.

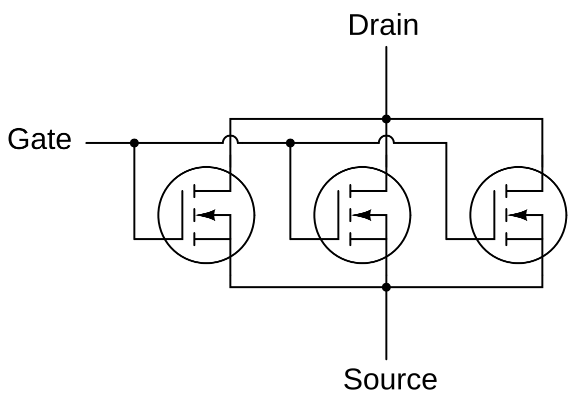
As for applications where swamping resistors are impractical, it is possible to gain better reliability by using more transistors (or diodes) than necessary with an even current split. In other words, over-build the circuit.

Question 73

In some applications where transistors must amplify very high currents, bipolar transistors are paralleled together so that their current ratings add. When this is done, it is a good idea to use *swamping resistors* at the transistor emitter connections to help ensure even balancing of currents:



However, if we use MOSFETs instead of BJTs, we do not have to use swamping resistors:



Explain why MOSFETs do not require swamping resistors to help evenly distribute current, while BJTs do.

file 03900

Answer 73

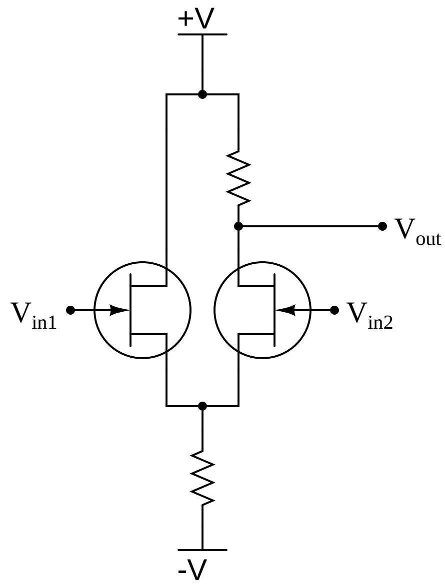
The amount of controlling voltage varies with temperature for the BJT, but not for the MOSFET.

Notes 73

The answer given here is purposefully vague. Let your students do the necessary research! Tell them that manufacturers' application notes are valuable sources of information for questions such as this.

Question 74

Identify what type of amplifier circuit this is, and also what would happen to the output voltage if V_{in2} were to become more positive:



file 01176

Answer 74

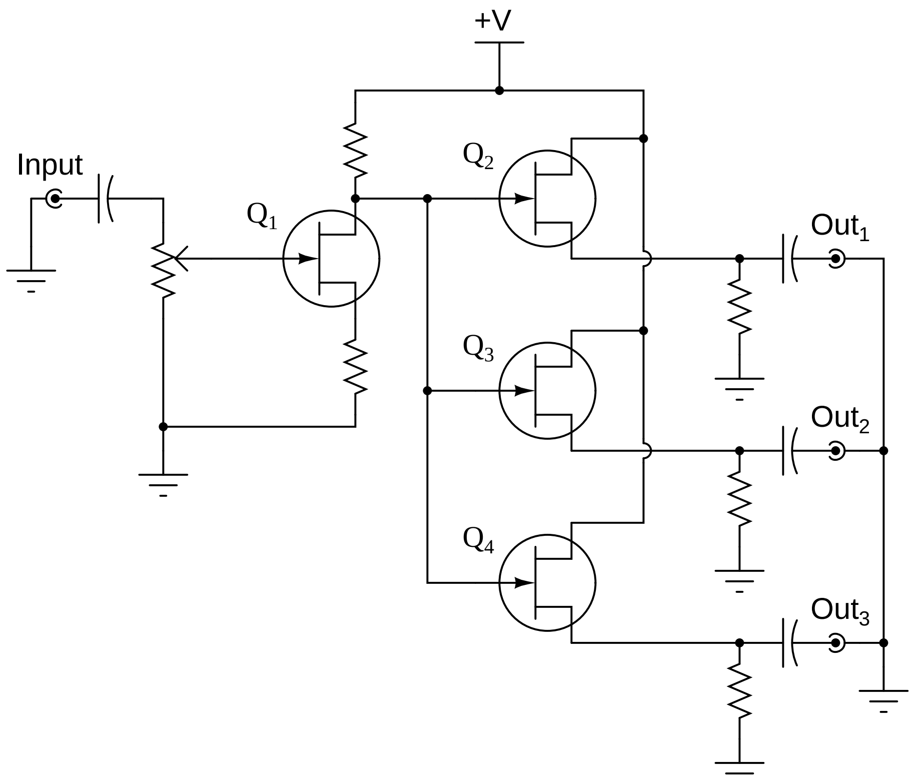
This is a *differential amplifier* circuit. If V_{in2} were to become more positive, V_{out} would become more negative.

Notes 74

Students should be able to relate this circuit to its bipolar transistor counterpart. Ask them to explain what advantages or disadvantages this circuit holds over a bipolar differential amplifier circuit.

Question 75

The following circuit is a "multicoupler" for audio signals: one audio signal source (such as a microphone) is distributed to three different outputs:



Suppose an audio signal is getting through from the input to outputs 2 and 3, but not through to output 1. Identify possible failures in the circuit that could cause this. Be as specific as you can, and identify how you would confirm each type of failure using a multimeter.

file 01185

Answer 75

Given the existence of multiple answers for this question, I will defer the answer(s) to your instructor, to review during class discussion.

Notes 75

Always be sure to spend plenty of time discussing troubleshooting scenarios with your students, because diagnostic skills are the highest level (and the most valuable) to develop.

Some of your students may be unfamiliar with the symbols used for the input and output jacks. Elaborate on this symbolism, if necessary.

Ask your students to identify the configuration (common-source, common-drain, or common-gate) of each JFET in this circuit, and how these respective configurations relate to the voltage gain (A_V) of each amplification stage.

Question 76

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

What, exactly, is "rolloff?" What is an "octave," in the context of the units of measurement used to specify rolloff? If we were to plot the response of a typical amplifier in the form of a Bode plot, what type of filter circuit characteristic (band-pass, band-stop, etc.) would it best resemble?

file 01247

Answer 76

Most amplifiers' frequency responses resemble that of low-pass filters. "Rolloff" is the term used to denote the steepness of the amplifier's Bode plot as it attenuates the amplified signal at ever-increasing frequencies.

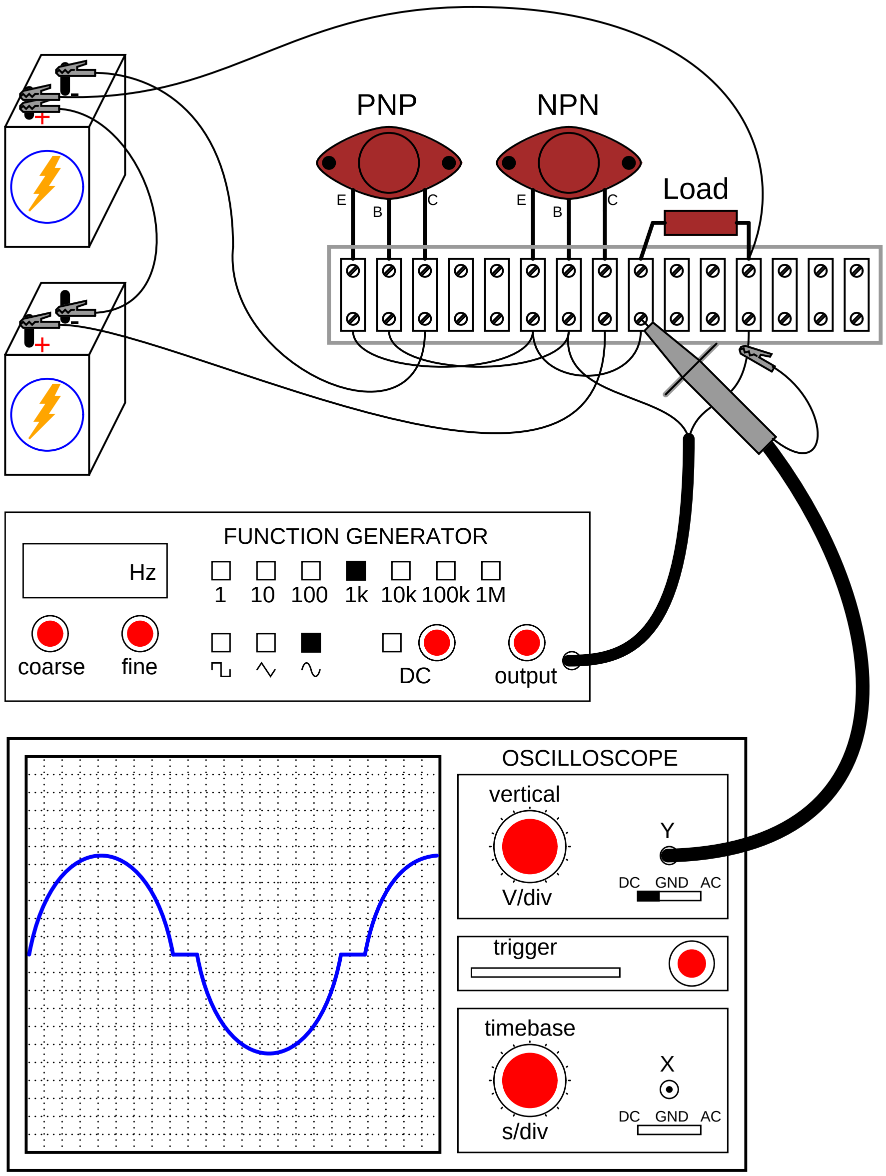
An "octave" denotes a doubling of signal frequency. This unit applies well to logarithmic-scale Bode plots.

Notes 76

Have one of your students draw a picture of a Bode plot for a (realistic) low-pass filter: that is, a non-ideal low-pass filter response. Review with your students what a log-scale plot looks like, and ask them to relate the ratio-units of "decibel" and "octave" to such a scale.

Question 77

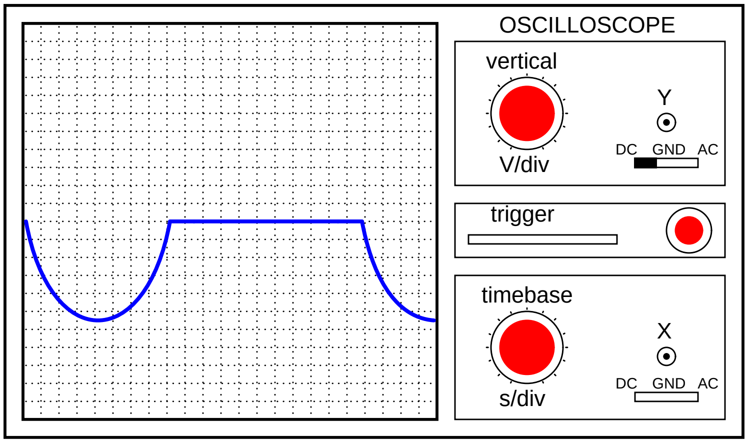
What would happen to the output voltage waveform of this amplifier if the NPN transistor failed open between collector and emitter?



file 00971

Answer 77

The positive half of the waveform would be "missing":

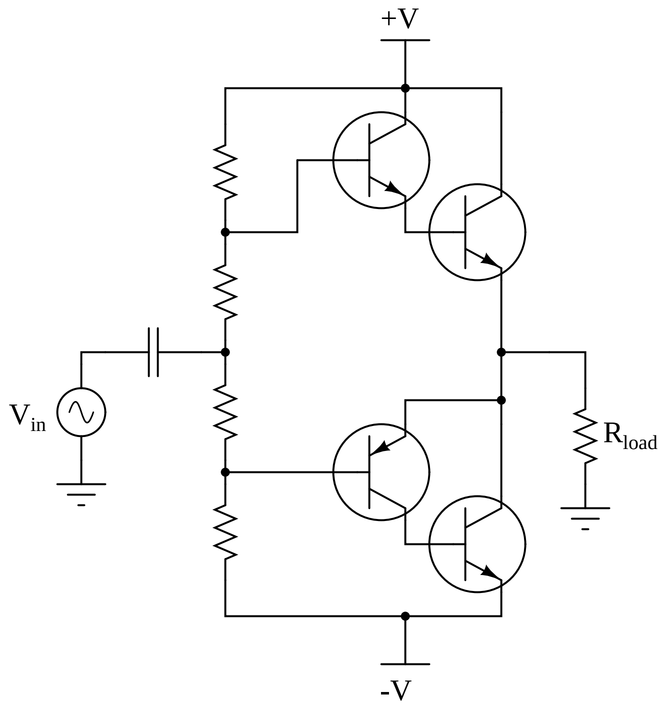


Notes 77

Ask your students to identify which transistor "sources" current to the load, and which transistor "sinks" current from the load, and the answer should be easy to understand.

Question 78

High-power PNP transistors tend to be scarcer and more expensive than high-power NPN transistors, a fact which complicates the construction of a high-power complementary push-pull amplifier circuits. An ingenious solution to this problem is to modify the basic Darlington push-pull circuit, replacing the final PNP transistor with an NPN transistor, like this:

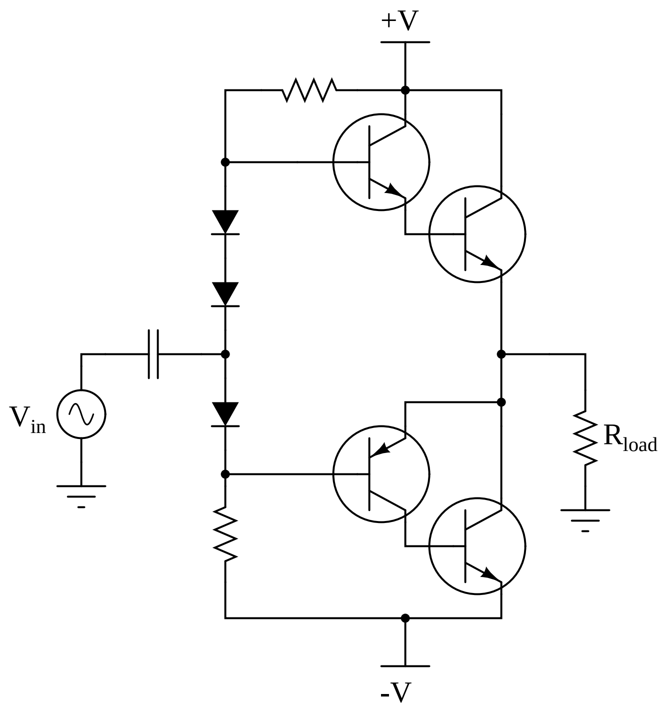


The cascaded combination of an NPN and PNP transistor is called a *Sziklai pair*, or *complementary Darlington pair*. In this case, the small PNP transistor controls the larger NPN power transistor in the Sziklai pair, performing the same basic function as a PNP Darlington pair.

Modify the circuit shown here to use diodes in the biasing network instead of just resistors. The solution is not quite the same for this circuit as it is for a conventional Darlington push-pull circuit!

file 00976

Answer 78

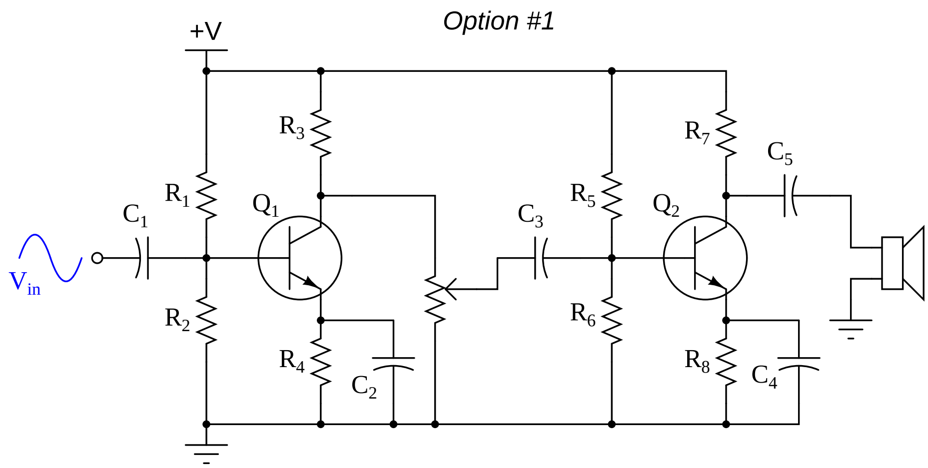


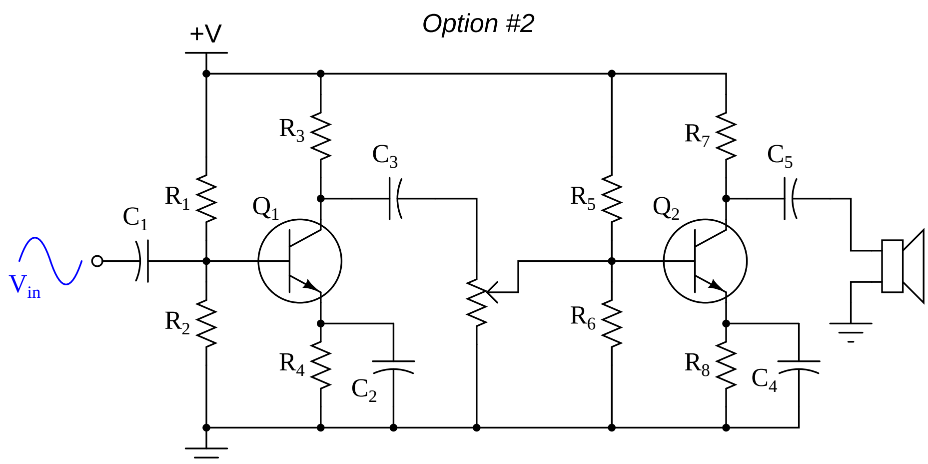
Notes 78

Discuss the difference between the two halves of this amplifier circuit (the upper Darlington half, and the lower Sziklai half), paying special attention to the number of PN junctions between base and (final) emitter terminals.

Question 79

Suppose two engineers were debating where to place a potentiometer in this audio amplifier circuit, to be used as a volume control:





Which option would be better, and why? What ill effects could result from locating the potentiometer in the wrong place in this circuit?

file 01118

Answer 79

Option #1 is definitely the better choice, because the potentiometer's setting will not affect the biasing of Q_2 as it would in option #2.

Notes 79

The purpose of this question is to make students realize that the biasing of each transistor stage is important in a multi-stage amplifier. One of the major challenges of designing a multi-stage amplifier is to ensure adequate signal coupling between stages without creating bias problems.

Question 80

What is the overall voltage gain of two cascaded amplifiers (the output of the first amplifier going into the input of the second), each with an individual voltage gain of 3 dB? Express the overall voltage gain in decibels, and also as a ratio.

file 00870

Answer 80

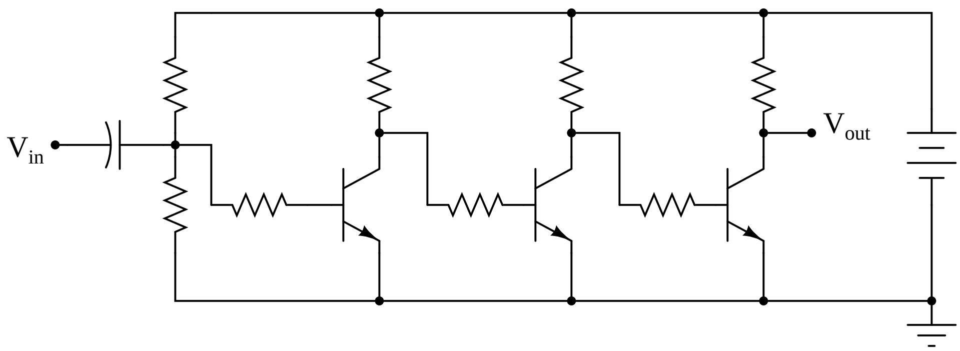
$A_{V(final)} = 6$ dB, or a ratio of 2.825:1

Notes 80

Ask your students to convert the figure of 3 dB (voltage gain) into a ratio. How does this ratio compare with the overall ratio for the two cascaded amplifiers? What do the figures indicate about cascaded gains in general, expressed in decibel form as well as ratio form? Ask your students if they think it is mathematically easier to compute cascaded gains in ratio form or decibel, and why.

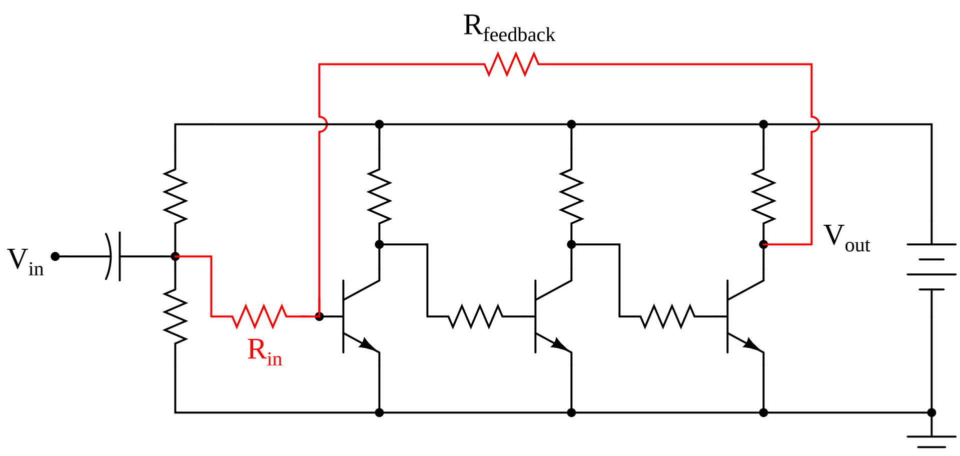
Question 81

Suppose the following three-stage transistor amplifier were constructed:



With no emitter swamping resistors anywhere in this circuit, the voltage gain of each stage is guaranteed to be large, but unstable as well. With three stages arranged like this, one feeding into the next, the final voltage gain will be very large, and very unstable.

However, if we add another resistor to the circuit ($R_{feedback}$), something very interesting takes place. Suddenly, the amplifier circuit's overall voltage gain is decreased, but the stability of this gain becomes much improved:



Interestingly, the voltage gain of such a circuit will be nearly equal to the quotient of the two highlighted resistors, $R_{feedback}$ and R_{in}:

$$A_V \approx \frac{R_{feedback}}{R_{in}}$$

This approximation holds true for large variations in individual transistor gain (β) as well as temperature and other factors which would normally wreak havoc in the circuit with no feedback resistor in place.

Describe what role the feedback resistor plays in this circuit, and explain how the addition of negative feedback is an overall benefit to this circuit's performance. Also, explain how you can tell this feedback is *negative* in nature ("degenerative").

file 02252

Answer 81

The feedback resistor provides a signal path for negative feedback, which "tames" the unruly gain and instability otherwise inherent to such a crude three-stage transistor amplifier circuit.

We can tell that the feedback is negative in nature because it comes from an odd number of inverting amplifier stages (there is still an inverse relationship between output and input).

Follow-up question: how much effect do you suppose the replacement of a transistor with a slightly different β or r'_e parameter would affect each circuit?

Notes 81

Although the circuit shown is a little too crude to be practical, it does illustrate the power of negative feedback as a stabilizing influence.

The question regarding the *de*-generative nature of the feedback is an important one. Discuss with your students how one could not simply pick up the feedback signal from anywhere in the circuit!

Question 82

Radio-frequency amplifiers often use small inductors called *peaking coils* in the coupling circuitry between transistor stages. Describe the purpose of these inductors.

file 01127

Answer 82

Peaking coils are added to amplifier circuits to help counteract capacitive reactance at high frequencies.

Notes 82

The answer I gave for this question is very minimal, and is just enough to give your students a hint. Ask your students to explain why capacitive reactance is an issue in high-frequency transistor amplifier circuits, and why an inductor would be used to counter X_C. Also, ask if there are any disadvantages to inserting peaking coils into amplifier circuits.

Question 83

A common class of operation used in radio-frequency (RF) amplifier circuits is *class-C*. Explain what this means, contrasting it against the class-A and class-B operations common in audio-frequency amplifier circuits.

file 02504

Answer 83

Class-C amplification is where the active device (transistor, usually) is conducting substantially less than 50% of the waveform period.

Notes 83

A natural question that arises when students first hear of class-C operation is, "How does a class-C amplifier circuit reproduce the entire waveform, if the transistor is completely off most of the time?" The answer to this lies in *resonance*, usually supplied in the form of a tank circuit, to maintain oscillations while the transistor is cut off.

Question 84

Contrast *class-A*, *class-B*, and *class-C* amplifier operations, explaining what defines each class. Then, rank these three classes in order of least power efficiency to greatest power efficiency.

file 02505

Answer 84

I'll let you research what the definition of each "class" of amplifier operation is! These definitions are fairly easy to find, so you should not experience much difficulty.

Class-A is least efficient, followed by class-B, and then class-C which is most power efficient.

Notes 84

Students are liable to wonder why class-C operation is not the most popular in electronic circuits, since it is the most power-efficient of the three classes. Discuss the limitations of class-C operation, specifically in terms of waveform distortion.