

Recommended schedule

Day 1

Topics: *Differential pair circuits*

Questions: *1 through 15*

Lab Exercise: *Discrete differential amplifier (question 56)*

Explain suggested project ideas to students

Give project grading rubric to students, complete with deadlines

Day 2

Topics: *The basic operational amplifier*

Questions: *16 through 25*

Lab Exercise: *Discrete differential amplifier (question 56, continued)*

Day 3

Topics: *Using the operational amplifier as a comparator*

Questions: *26 through 35*

Lab Exercise: *Comparator circuit (question 57)*

MIT 6.002 video clip: Disk 4, Lecture 21; Open-loop opamp 27:30 to 29:32

Day 4

Topics: *Using the operational amplifier as a voltage buffer*

Questions: *36 through 45*

Lab Exercise: *Opamp voltage follower (question 58)*

MIT 6.002 video clip: Disk 4, Lecture 21; Open-loop opamp 41:30 to 43:10

Day 5

Topics: *Additional applications of feedback* (optional)

Questions: *46 through 55*

Lab Exercise: *Linear voltage regulator circuit (question 59)*

Socratic Electronics animation: Push-pull transistor amplifier with crossover distortion

Day 6

Exam 1: *includes Comparator circuit performance assessment*

Lab Exercise: *Select an opamp project to prototype and troubleshoot by the end of the next course section (ELTR130, Section 2)*

Troubleshooting practice problems

Questions: *62 through 71*

General concept practice and challenge problems

Questions: *72 through the end of the worksheet*

Impending deadlines

Troubleshooting assessment (project prototype) due at end of ELTR130, Section 2

Question 60: Troubleshooting log

Question 61: Sample troubleshooting assessment grading criteria

Project ideas

Audio signal generator amplifier: Uses an op-amp to amplify the output of a digital audio playback device (such as a CD-audio or MP3 player) for use as a sine wave signal generator. Sine waves at different frequencies are recorded on digital media as different tracks – the op-amp circuit providing voltage and current gain – allowing the use of any inexpensive consumer-grade audio playback device as an audio frequency signal generator.

Intercom system: Uses an op-amp to amplify the output of a speaker (used as a microphone) to power another speaker located some distance away. With a reversing switch, the roles of the two speakers may be reversed (send versus receive).

Seismograph: Uses an op-amp to amplify small voltages generated by a stationary "pickup" coil located near a pendulum-mounted permanent magnet. Vibrations in the earth create motion between the magnet and the coil, inducing voltage in the coil. The op-amp output then drives a meter, recording device, or an alarm.

Pulse-width modulation signal generator: There are many ways to make such a circuit, but almost all of them use a comparator to compare an adjustable DC reference voltage against a varying (oscillating) voltage produced by an oscillator circuit. The resulting comparator output will be a square wave with variable duty cycle, useful for driving power transistors for PWM power control of electric loads.

Series voltage regulator: Uses an op-amp to "buffer" the reference voltage of a zener diode, driving a transistor to maintain constant DC voltage to a load. The op-amp provides much greater precision and regulation over a wide range of load resistances than a simple zener-BJT regulator circuit could on its own.

Amplified audio detector: The "sensitive audio detector" circuit suggested in ELTR115 (AC 2) may be improved with the addition of an op-amp amplification stage. This can drastically raise input impedance and sensitivity.

Infra-red motion sensor: Passive infra-red detectors are available for purchase (or salvaged from old motion-sensitive light controller circuits) which output a small DC voltage corresponding to IR light intensity. By amplifying this voltage and passing it through an active differentiator circuit, an output voltage representing *rate of change* of IR light will be produced. This signal may then be sent to a comparator to trigger an alarm or take some other action when a warm object *moves* by the sensor.

High-impedance analog voltmeter: Uses a JFET or MOSFET input op-amp to drive an analog meter movement for precise measurement of DC voltage.

Skill standards addressed by this course section

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

E Technical Skills – Analog Circuits

- E.10** Understand principles and operations of operational amplifier circuits.
- E.11** Fabricate and demonstrate operational amplifier circuits.
- E.12** Troubleshoot and repair operational amplifier circuits.

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: *Differential pair circuits.*

Perhaps the most difficult concept to grasp regarding differential pair circuits is that they are basically a hybrid of common-collector, common-base, and common-emitter amplifiers. This is why a strong knowledge of the three basic amplifier types is essential for understanding how differential pairs work, and why I begin exploring differential pairs by reviewing C-C, C-E, and C-B amplifiers.

Difficult concept: *Determining comparator output polarity.*

The key to determining the polarity of a comparator's output is applying Kirchhoff's Voltage Law to the two signals at the input terminals to find the differential input voltage, then seeing whether the differential voltage's polarity matches the polarity markings of the comparator's input terminals. If so, the output will saturate in a positive direction. If not, the output will saturate in a negative direction.

Difficult concept: *Negative feedback.*

Few concepts are as fundamentally important in electronics as negative feedback, and so it is essential for the electronics student to learn well. However, it is not an easy concept for many to grasp. The notion that a portion of the output signal may be "fed back" into the input in a degenerative manner to stabilize gain is far from obvious. One of the most powerfully illustrative examples I know of is the use of negative feedback in a voltage regulator circuit to compensate for the base-emitter voltage drop of 0.7 volts (see question file #02286).

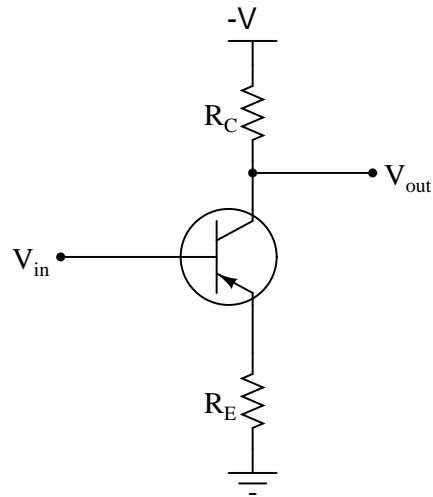
Common mistake: *Thinking that an opamp's output current is supplied through its input terminals.*

This is a misconception that seems to have an amazing resistance to correction. There seem to always be a few students who think that there is a direct path for current from the input terminals of an opamp to its output terminal. It is very important to realize that *for most practical purposes, an opamp draws negligible current through its input terminals!* What current does go through the output terminal is *always* supplied by the power terminals and from the power supply, never by the input signal(s). To put this into colloquial terms, the input terminals on an opamp tell the output what to do, but they do not give the output its "muscle" (current) to do it.

I think the reason for this misconception is the fact that power terminals are often omitted from opamp symbols for brevity, and after a while of seeing this it is easy to forget they are really still there performing a useful function!

Question 1

Identify the type of transistor amplifier this is (common-collector, common-emitter, or common-base), and identify whether it is *inverting* or *noninverting*.



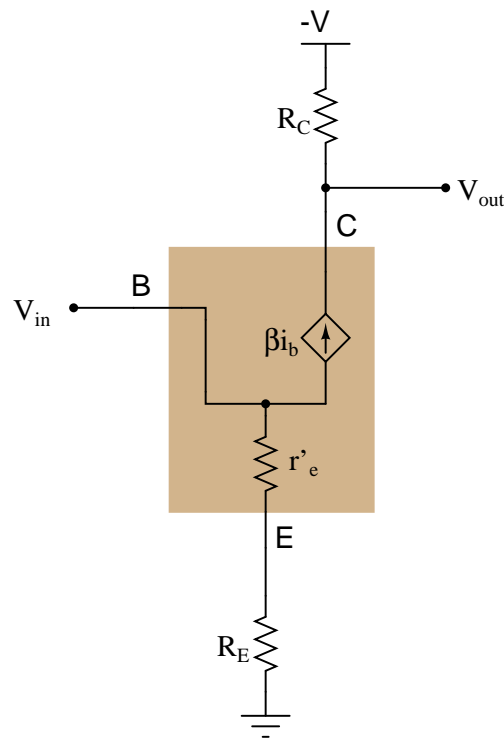
Also, explain how to derive the voltage gain equation for this amplifier:

$$A_V = \frac{R_C}{R_E + r'_e}$$

file 00882

Answer 1

This is a *common-emitter* amplifier circuit, and it is inverting. Here is a schematic hint for explaining why the voltage gain formula is as it is. Note that the transistor is modeled here as a resistance and a controlled current source:



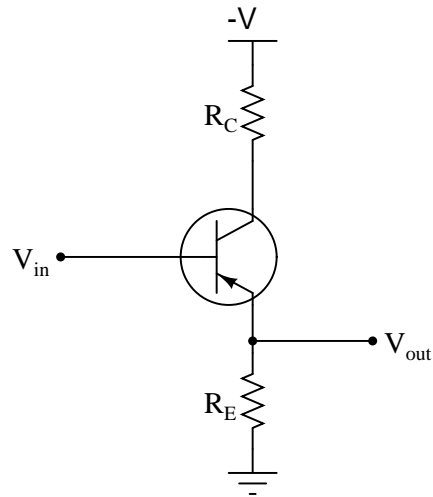
Follow-up question: the voltage gain equation for this type of transistor amplifier is usually shown in a simpler form than what I provided at the end of the question. Write this simpler form, and explain why it is approximately true.

Notes 1

In discussion with your students, analyze the response of this single-transistor amplifier circuit for a variety of input voltages. In other words, perform a *thought experiment* to re-familiarize them with the behavior of this transistor amplifier configuration. Plot the input and output voltages, if necessary, on a graph. Discuss what the term "inverting" means in this context.

Question 2

Identify the type of transistor amplifier this is (common-collector, common-emitter, or common-base), and identify whether it is *inverting* or *noninverting*.



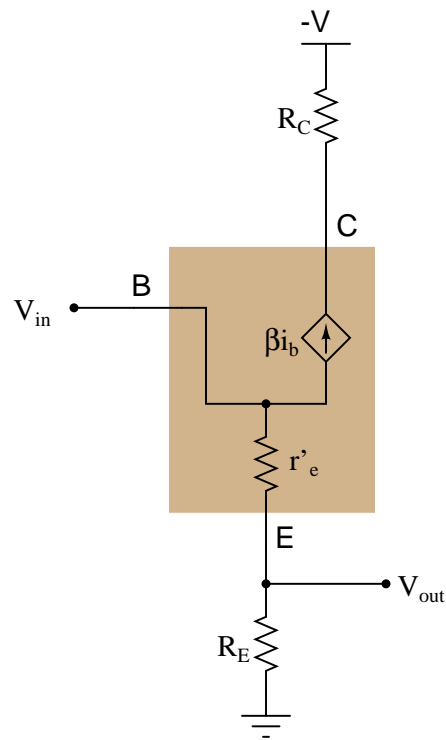
Also, explain how to derive the voltage gain equation for this amplifier:

$$A_V = \frac{R_E}{R_E + r'_e}$$

file 00883

Answer 2

This is a *common-collector* amplifier circuit, and it is noninverting. Here is a schematic hint for explaining why the voltage gain formula is as it is. Note that the transistor is modeled here as a resistance and a controlled current source:



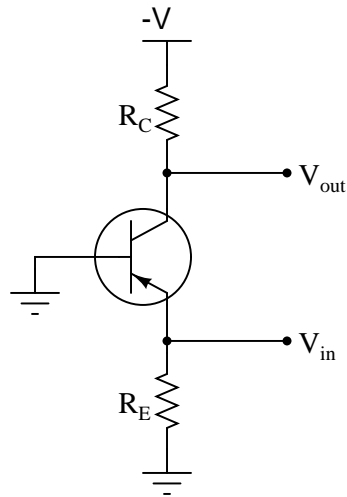
Follow-up question: the voltage gain equation for this type of transistor amplifier is usually shown in a simpler form than what I provided at the end of the question. Write this simpler form, and explain why it is approximately true.

Notes 2

In discussion with your students, analyze the response of this single-transistor amplifier circuit for a variety of input voltages. In other words, perform a *thought experiment* to re-familiarize them with the behavior of this transistor amplifier configuration. Plot the input and output voltages, if necessary, on a graph. Discuss what the term "noninverting" means in this context.

Question 3

Identify the type of transistor amplifier this is (common-collector, common-emitter, or common-base), and identify whether it is *inverting* or *noninverting*.



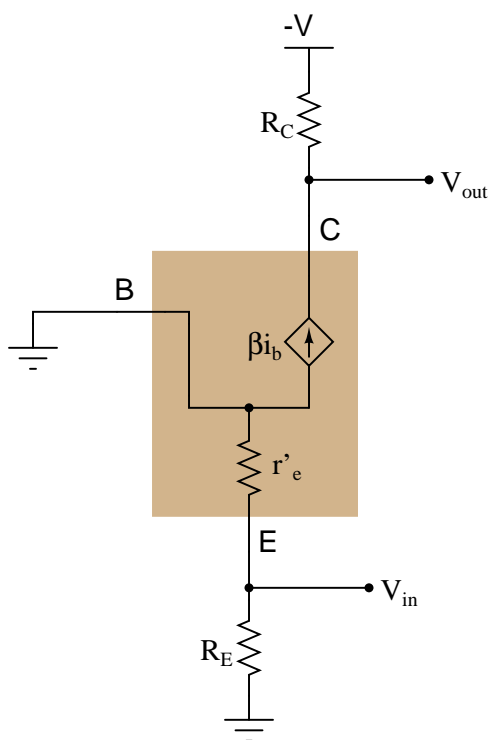
Also, explain how to derive the voltage gain equation for this amplifier:

$$A_V = \frac{R_C}{r'_e}$$

file 03920

Answer 3

This is a *common-base* amplifier circuit, and it is noninverting. Here is a schematic hint for explaining why the voltage gain formula is as it is. Note that the transistor is modeled here as a resistance and a controlled current source:

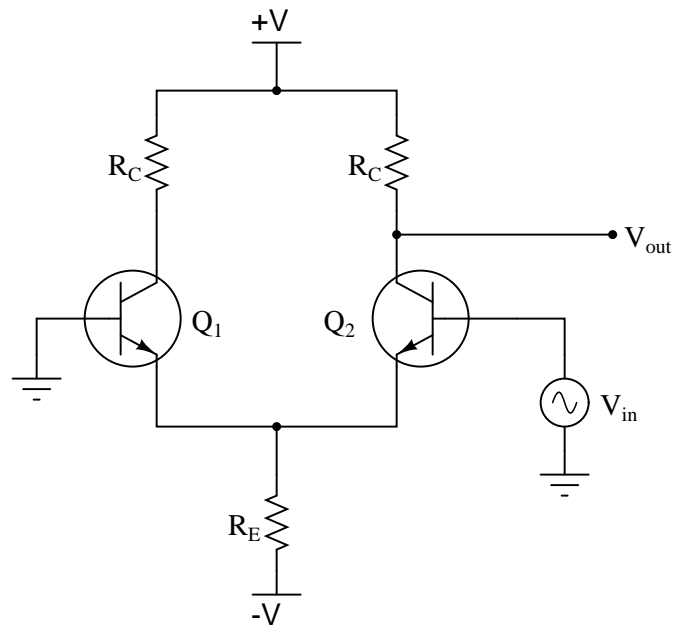


Notes 3

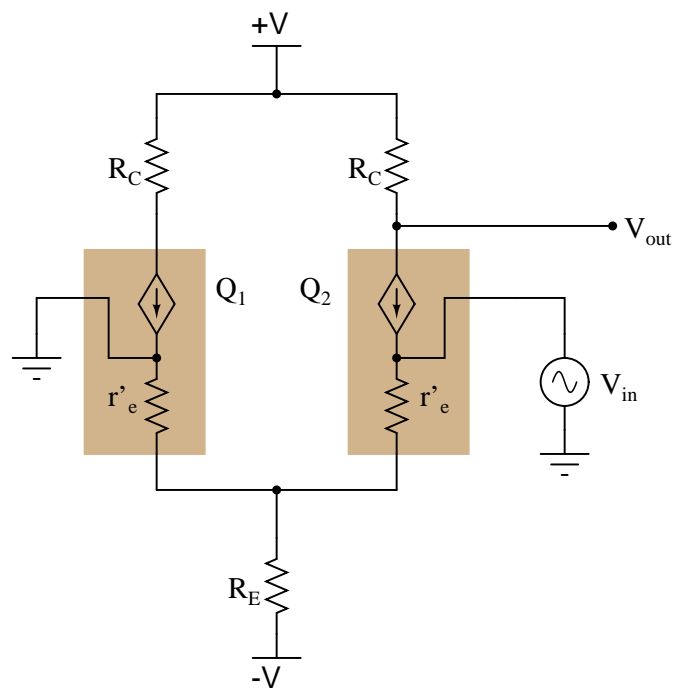
In discussion with your students, analyze the response of this single-transistor amplifier circuit for a variety of input voltages. In other words, perform a *thought experiment* to re-familiarize them with the behavior of this transistor amplifier configuration. Plot the input and output voltages, if necessary, on a graph. Discuss what the term "noninverting" means in this context.

Question 4

Here, a differential pair circuit is driven by an input voltage at the base of Q_2 , while the output is taken at the collector of Q_2 . Meanwhile, the other input (Q_1 base) is connected to ground:



Identify what types of amplifier circuits the two transistors are functioning as (common-collector, common-emitter, common-base) when the differential pair is used like this, and write an equation describing the circuit's voltage gain. Here is another schematic, showing the transistors modeled as controlled current sources, to help you with the equation:



Answer 4

Q_2 operates as a common-emitter amplifier, while Q_1 does not really act as an amplifier at all (given that no input or output connects to it). The gain equation is as such:

$$A_{V(invert)} = \frac{R_C}{r'_e + (r'_e || R_E)}$$

Follow-up question #1: explain why it is appropriate to simplify the gain equation to this:

$$A_{V(invert)} \approx \frac{R_C}{2r'_e}$$

Follow-up question #2: explain why the simplified gain equation is sometimes written with a negative sign in it:

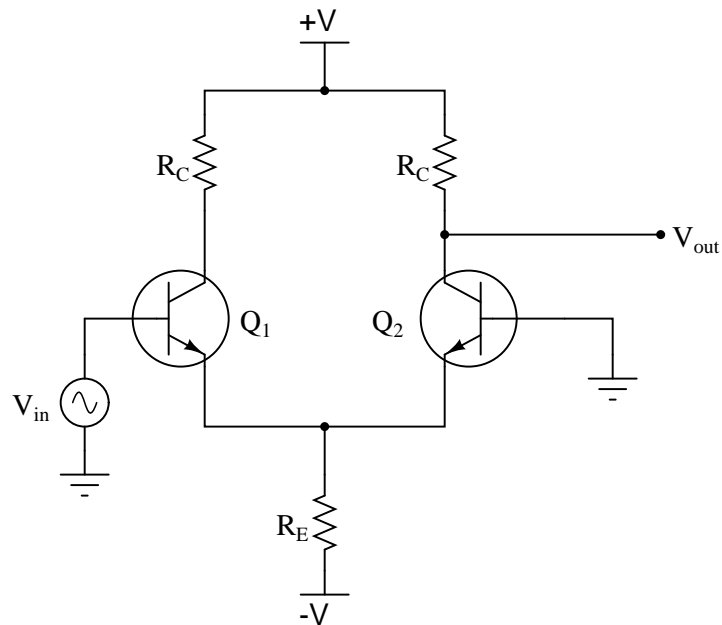
$$A_{V(invert)} \approx -\frac{R_C}{2r'_e}$$

Notes 4

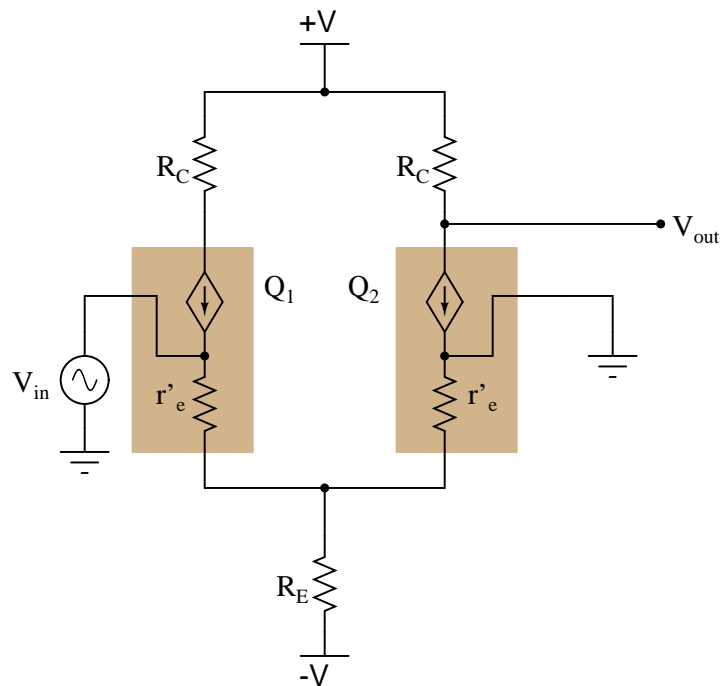
The purpose of this question is to have students analyze the resistances in the differential pair circuit to develop their own gain equation, based on their understanding of how simpler transistor amplifier circuit gains are derived. Ultimately, this question should lead into another one asking students to express the *differential* voltage gain of the circuit (a superposition of the gain equations for each input considered separately).

Question 5

Here, a differential pair circuit is driven by an input voltage at the base of Q_1 , while the output is taken at the collector of Q_2 . Meanwhile, the other input (Q_2 base) is connected to ground:



Identify what types of amplifier circuits the two transistors are functioning as (common-collector, common-emitter, common-base) when the differential pair is used like this, and write an equation describing the circuit's voltage gain. Here is another schematic, showing the transistors modeled as controlled current sources, to help you with the equation:



file 03922

Answer 5

Q_1 operates as a common-collector amplifier, while Q_2 acts as a common-base amplifier. The gain equation is as such:

$$A_{V(noninvert)} = \left[\frac{R_C}{r'_e + (r'_e || R_E)} \right] \left[\frac{r'_e || R_E}{r'_e} \right]$$

Follow-up question: explain why it is appropriate to simplify the gain equation to this:

$$A_{V(noninvert)} \approx \frac{R_C}{2r'_e}$$

Notes 5

The purpose of this question is to have students analyze the resistances in the differential pair circuit to develop their own gain equation, based on their understanding of how simpler transistor amplifier circuit gains are derived. Ultimately, this question should lead into another one asking students to express the *differential* voltage gain of the circuit (a superposition of the gain equations for each input considered separately).

Admittedly, the unsimplified equation shown in the answer is daunting, and students may wonder where I got it. You may help them understand that the basic gain equation for a BJT amplifier is founded on the assumption that $I_C \approx I_E$, that any current through the emitter terminal will be "repeated" at the collector terminal to flow through the collector resistance. Thus, voltage gain is nothing more than a ratio of resistances, given that emitter current and collector current are assumed to be the same:

$$V_{out(AC)} = I_C R_C \quad \text{and} \quad V_{in(AC)} = I_E R_{E(total)}$$

. . . so . . .

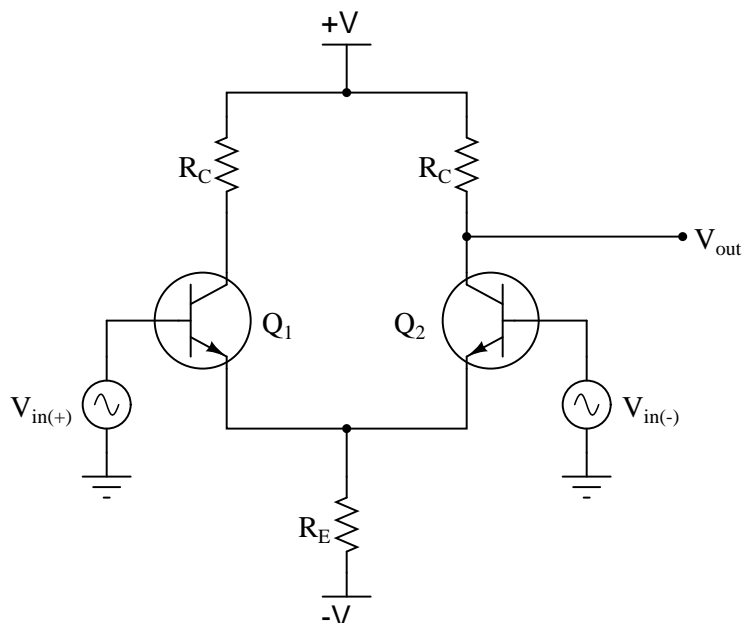
$$A_V = \frac{V_{out(AC)}}{V_{in(AC)}} = \frac{I_C R_C}{I_E R_{E(total)}} = \frac{I_C R_C}{I_C R_{E(total)}} = \frac{R_C}{R_{E(total)}}$$

Thus, deriving a gain equation for a BJT amplifier is usually as simple as figuring out what resistance the collector current goes through and dividing that by the amount of resistance the base-to-emitter current has to go through. In a grounded-base amplifier, this ratio is simply $\frac{R_C}{r'_e}$.

With this circuit, however, the input signal must fight its way through the r'_e of Q_1 before ever getting to Q_2 to be amplified, which is why the voltage gain equation is so much more complex. After going through the dynamic emitter resistance of Q_1 , it splits between the dynamic emitter resistance of Q_2 and the "tail" resistance R_E . The term $r'_e + (r'_e || R_E)$ is the amount of resistance the AC input signal travels through, and the fraction $\frac{r'_e || R_E}{r'_e}$ defines the splitting of current (most to the emitter of Q_2 , a small amount through R_E).

Question 6

Write an approximate equation describing the *differential* voltage gain for a differential pair circuit such as this, in terms of the component values:



file 03923

Answer 6

$$A_{V(diff)} = \frac{R_C}{2r'_e}$$

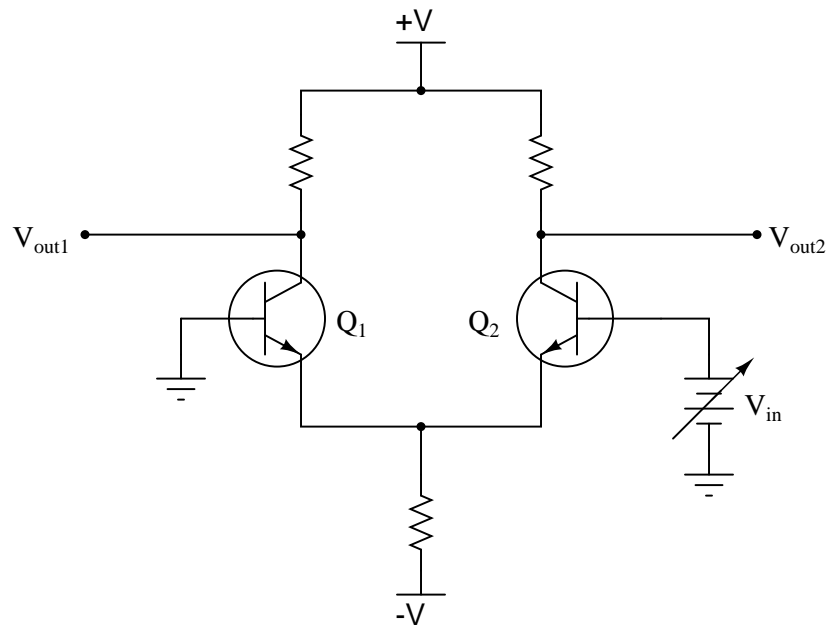
Follow-up question: what component value(s) should be altered to maximize differential voltage gain in a differential pair circuit, and why?

Notes 6

The purpose of this question is to have students apply the Superposition theorem to combine two voltage gain equations into a single *differential* voltage gain equation.

Question 7

Describe what happens to each of the output voltages (V_{out1} and V_{out2}) as the input voltage (V_{in}) *decreases*:



file 01242

Answer 7

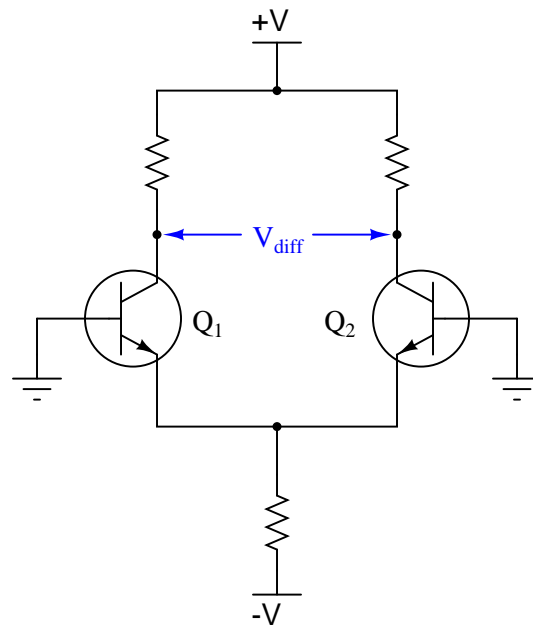
V_{out1} will decrease (become more negative), while V_{out2} will increase (become more positive).

Notes 7

With four terminals to connect to the outside world, this circuit is a *differential-input, differential-output* amplifier.

Question 8

Suppose this differential-pair circuit was perfectly balanced. In this condition, how much voltage would be expected between the two transistors' collector terminals?

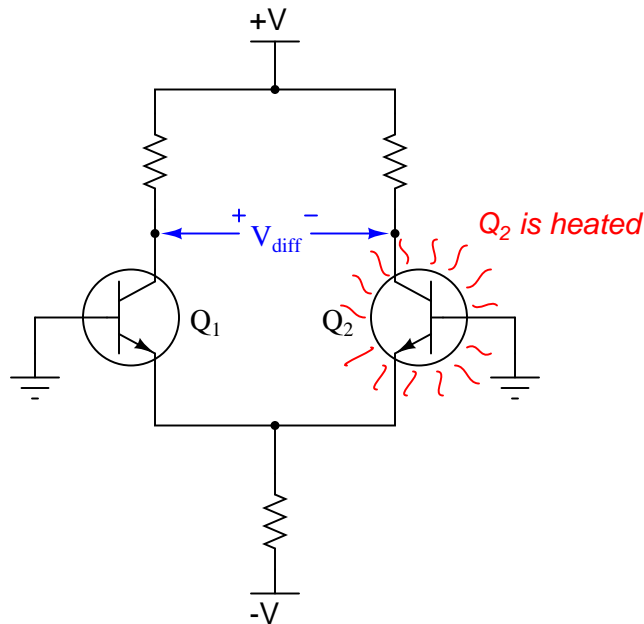


What would happen to this differential voltage (V_{diff}) if transistor Q_2 were to increase in temperature, while transistor Q_1 remained at the same temperature? Explain your answer.

file 00887

Answer 8

In a balanced condition, $V_{diff} = 0$ volts. If Q2 heats up and Q1 does not, a differential voltage will develop between the two collector terminals, with Q1's collector being the positive and Q2's collector being the negative:



Follow-up question: what does this phenomenon mean with regard to the stability of differential-pair transistor circuits under different operating conditions? What might be a good way to maximize circuit stability over a wide range of operating temperatures?

Notes 8

Fundamentally, the issue in this question is what happens to a transistor when it heats up, but the electrical supply (power and input signal) parameters do not change. Ask your students to relate this phenomenon to the behavior of other PN junction devices, such as diodes.

Question 9

What is *common-mode voltage*, and how should a differential amplifier (ideally) respond to it?
file 00939

Answer 9

"Common-mode voltage" is the amount of voltage common to both inputs of a differential amplifier. Ideally, a differential amplifier should *reject* this common-mode voltage, only amplifying the difference between the two input voltages.

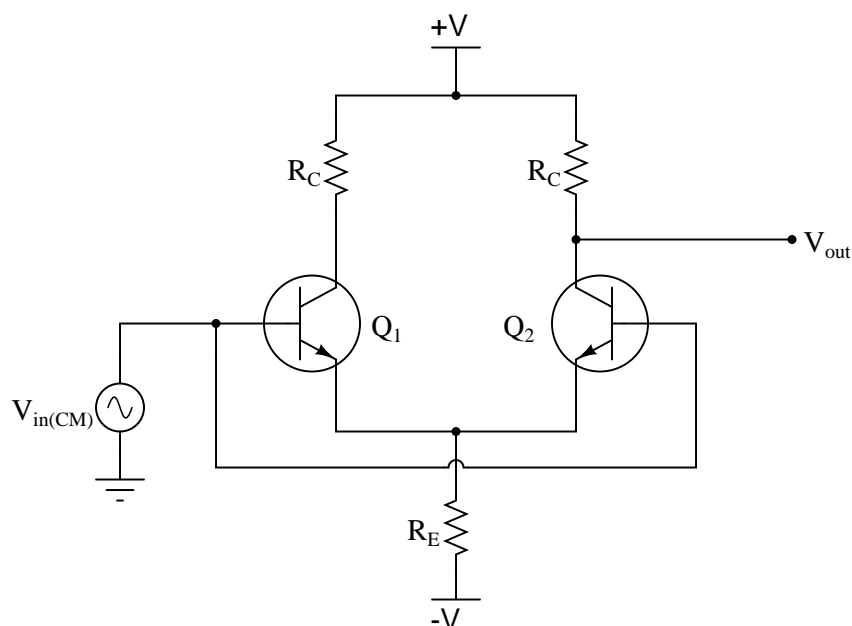
Follow-up question: what does the phrase *common-mode rejection ratio* (CMRR) mean for a differential amplifier?

Notes 9

Ask your students to provide examples of common-mode voltage to a differential amplifier. For example, x amount of voltage on one input and y amount of voltage on the other constitutes z amount of common-mode voltage . . .

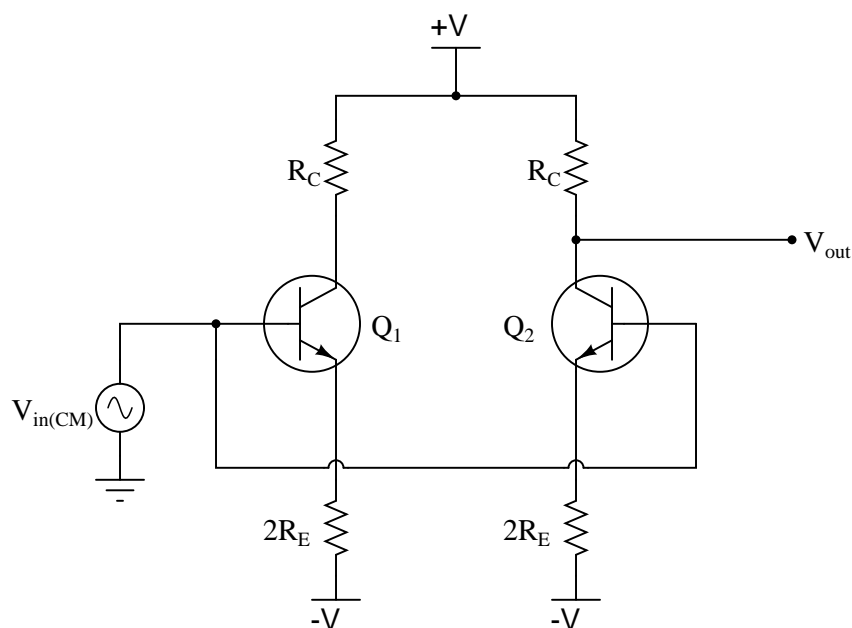
Question 10

If we connect the two transistor bases together in a differential pair circuit, it can only see common-mode input voltage (no differential input voltage):



An important performance parameter of any differential amplifier is its common-mode voltage gain. Ideally, a differential-input amplifier should ignore any and all common-mode voltage, but in reality there is always some amplification of common-mode voltage. We need to figure out how much of that there will be in any differential-pair circuit.

To help us analyze this circuit (with both inputs tied together so it *only* sees common-mode input voltage), I will re-draw it in such a way that reflects the symmetrical nature of the circuit:



First, explain why this re-drawing is justified, and then write the equation describing the common-mode voltage gain of this circuit, in terms of the component values.

file 03924

Answer 10

If the transistors are identical, and receive the same input signal at their base terminals, they will pass the same amount of current from collector to emitter. This means the "tail" resistor's current (I_{R_E}) is evenly split between the two transistors. With an even split of current, the one resistor will act the same as two resistors of twice that value, each one carrying only the current of one transistor.

Re-drawn like this, it should be plain to see that the differential pair acts as a swamped common-emitter amplifier, with the common-mode voltage gain described by the following equation:

$$A_{V(CM)} = \frac{R_C}{r'_e + 2R_E}$$

Follow-up question: what component value(s) should be altered to minimize common-mode voltage gain in a differential pair circuit, and why?

Notes 10

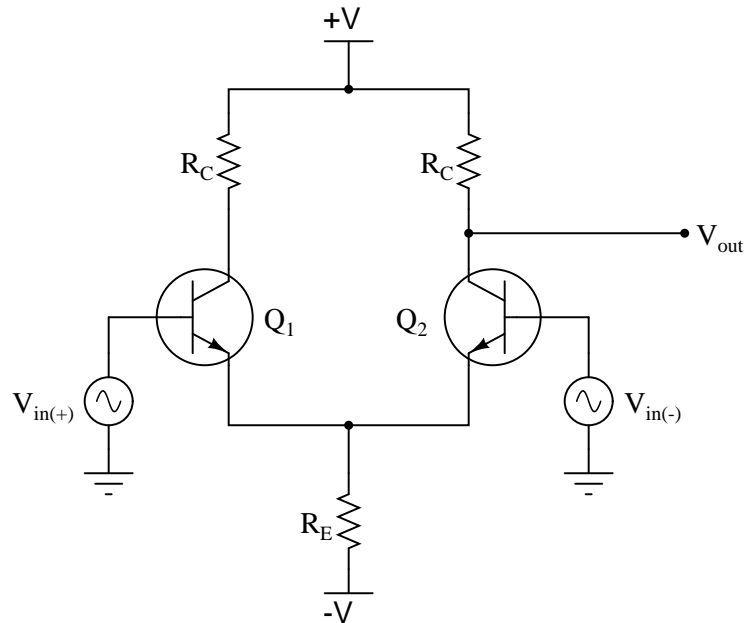
The purpose of this question is to have students recognize what factors in a differential pair circuit influence common-mode voltage gain, and then to realize that the value of the tail resistor has great influence over common-mode gain, while at the same time having negligible influence over differential gain.

Question 11

Common-mode rejection ratio is the ratio between a differential amplifier's differential voltage gain and its common-mode voltage gain:

$$\text{CMRR} = \frac{A_{V(\text{diff})}}{A_{V(\text{CM})}}$$

The greater this parameter's value, the better the differential amplifier will perform as a truly *differential* amplifier. Combine the equations for differential voltage gain and for common-mode voltage gain for the following differential amplifier circuit, into a single equation for CMRR:



[file 03925](#)

Answer 11

$$\text{CMRR} \approx \frac{R_E}{r'_e}$$

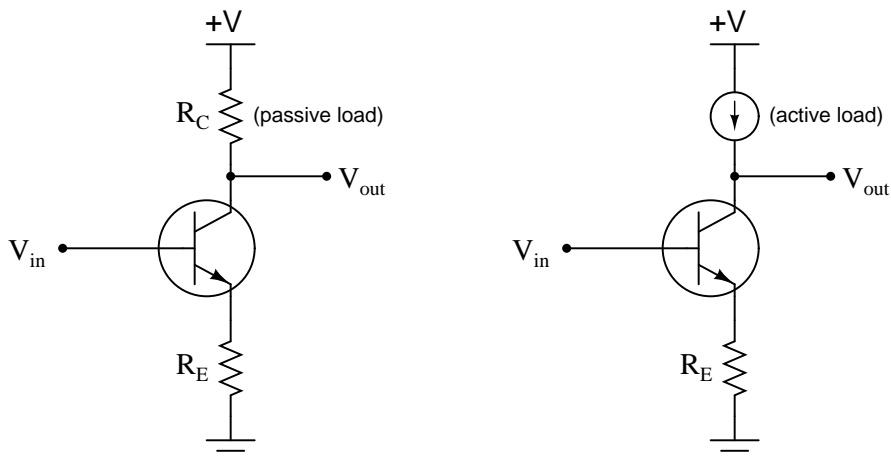
Follow-up question: what component value(s) should be altered to maximize CMRR in a differential pair circuit, and why?

Notes 11

You might want to add that CMRR is usually expressed in decibels, calculated the same way you would calculate decibels for any other ratio of voltages.

Question 12

An interesting technique to achieve extremely high voltage gain from a single-stage transistor amplifier is to substitute an *active load* for the customary load resistor (located at the collector terminal):



Usually, this "active load" takes the form of a current mirror circuit, behaving as a current *regulator* rather than as a true current *source*.

Explain why the presence of an active load results in significantly more voltage gain than a plain (passive) resistor. If the active load were a *perfect* current regulator, holding collector current absolutely constant despite any change in collector-base conductivity for the main amplifying transistor, what would the voltage gain be?

file 02657

Answer 12

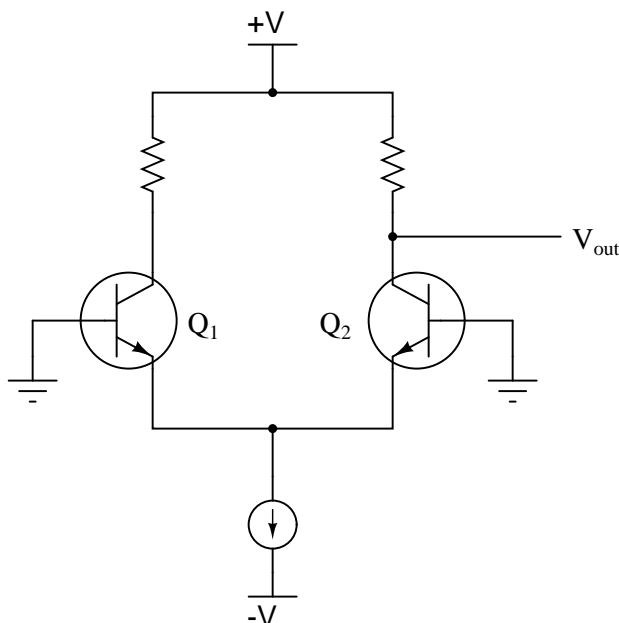
If the active load were a perfect current regulator, the voltage gain of this single-stage amplifier circuit would be infinite (∞), because the Thévenin equivalent resistance for a current source is infinite ohms.

Notes 12

There is more than one way to comprehend this effect, and why it works as it does. One of the more sophisticated ways is to consider what the internal resistance of a perfect current source is: infinite. Ask your students how they contemplated this effect, and what means they employed to grasp the concept.

Question 13

An improvement to the resistor-based differential amplifier design is the addition of a constant-current source where the two transistors' emitter currents mesh together:



What does the constant-current source "look like" to the rest of the amplifier, in terms of equivalent resistance? What advantage does this give to the amplifier's performance, over the (simpler) resistor design? Finally, how is this constant-current source actually constructed in a typical differential amplifier circuit?

[file 00936](#)

Answer 13

A constant-current source will "look like" a very large resistance to the rest of the circuit. This gives the amplifier a larger common-mode rejection ratio (CMRR). Usually, the current source is constructed using a *current mirror* circuit.

Notes 13

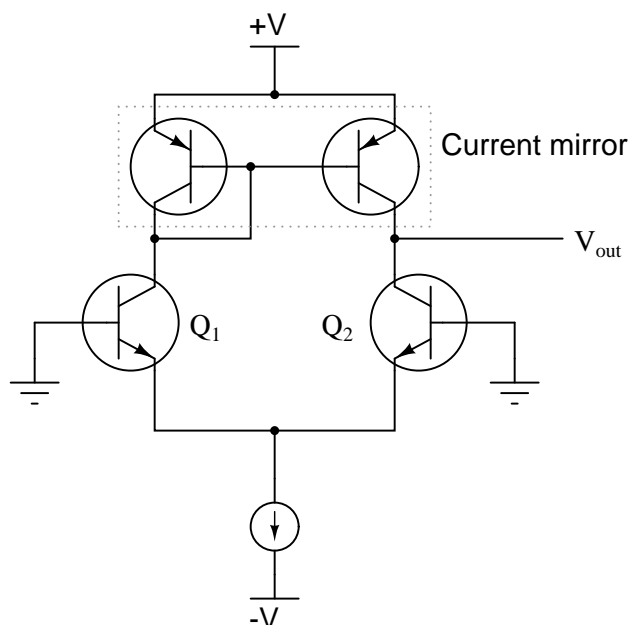
Ask your students to define CMRR and explain its importance in a differential amplifier circuit. Analyze the effects of common-mode input voltage on a simple resistor-based differential amplifier circuit, and then compare it to the circuit having a constant current source. How does the current source work to improve CMRR (reduce common-mode gain)?

Also, have your students draw a current mirror for this differential amplifier circuit and explain how it works.

I am expecting that your students have seen (or can research) the CMRR approximation for a differential pair circuit ($CMRR \approx \frac{R_E}{r'_e}$), and from this can deduce the importance of using a current source in the tail of the circuit instead of a passive resistor.

Question 14

Differential amplifiers often make use of *active loads*: a current mirror circuit to establish collector currents between the two transistors, rather than load resistors.



What does the current mirror "look like" to the common-emitter side of the differential amplifier circuit, when we apply the Superposition theorem? What aspect of the differential amplifier's performance is primarily enhanced with the addition of the current mirror to the circuit?

file 00937

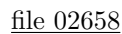
Answer 14

Adding a current mirror greatly increases the effective resistance on the collector terminal of the common-emitter side, and so greatly increases the amplifier's differential voltage gain.

Notes 14

Ask your students to explain why the differential voltage gain increases. One hint is the internal (Norton) resistance of an ideal current source: *infinite* ohms! Ask your students how this equivalent resistance compares to the (finite) values of the resistors replaced by the current mirror, and what impact that change has on voltage gain.

Identify as many active loads as you can in the following (simplified) schematic of an LM324 operational amplifier circuit:



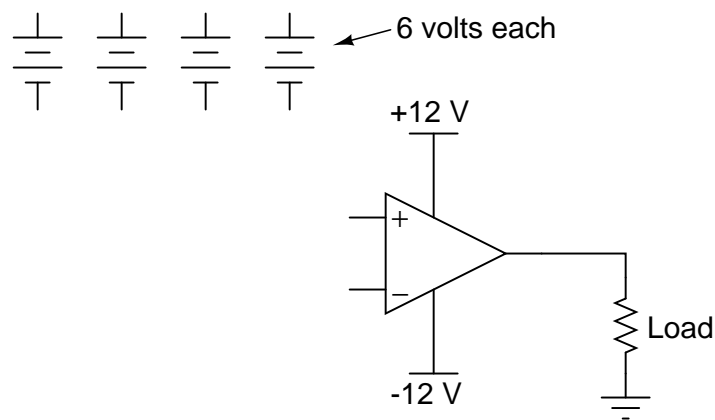
Of course, all the current sources are active loads, but there is one more at the lower-left corner of the schematic. I'll let you figure out where it is!

Even if students do not yet know what an "operational amplifier" circuit is, they should still be able to identify transistor stages, configurations, and active loads. In this case, most of the active loads are obvious (as revealed by the current source symbols).

26

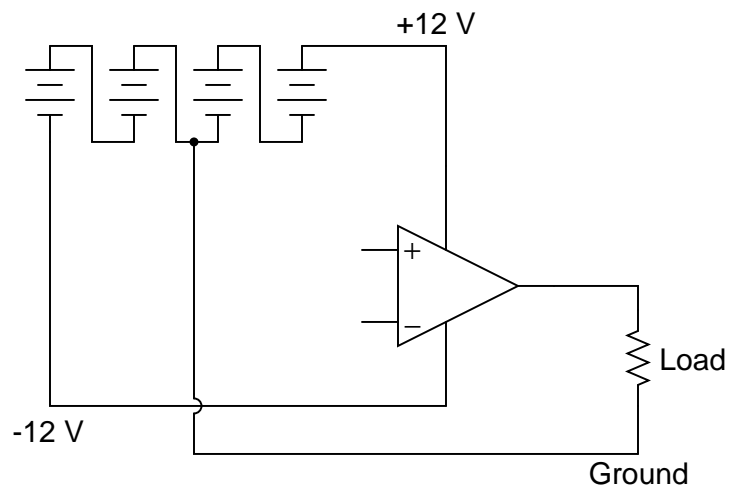
Question 16

Many op-amp circuits require a *dual* or *split* power supply, consisting of three power terminals: $+V$, $-V$, and Ground. Draw the necessary connections between the 6-volt batteries in this schematic diagram to provide $+12\text{ V}$, -12 V , and Ground to this op-amp:



[file 00880](#)

Answer 16

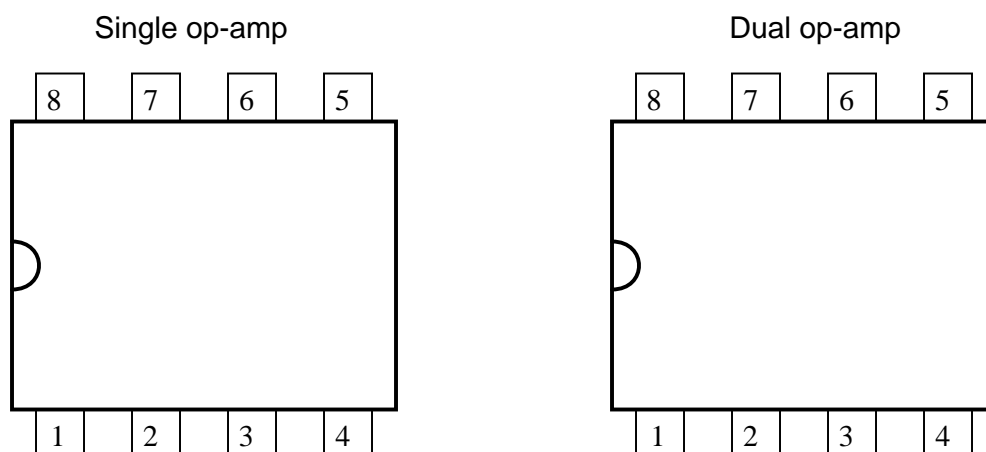


Notes 16

I encourage your students to learn how to power op-amp circuits with interconnected batteries, because it really helps to build their understanding of what a "split" power supply is, as well as allow them to build functioning op-amp circuits in the absence of a quality benchtop power supply.

Question 17

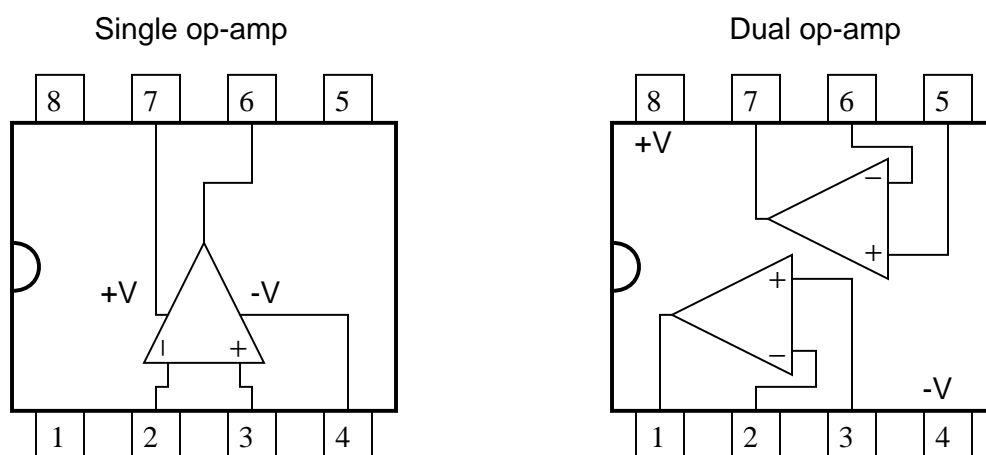
The 8-pin Dual-Inline-Package (DIP) is a common format in which single and dual operational amplifiers are housed. Shown here are the case outlines for two 8-pin DIPs. Draw the internal op-amp connections for a single op-amp unit, and for a dual op-amp unit:



You will need to research some op-amp datasheets to find this information. Examples of single op-amp chips include the LM741, CA3130, and TL081. Examples of dual op-amp chips include the LM1458 and TL082.

[file 00874](#)

Answer 17

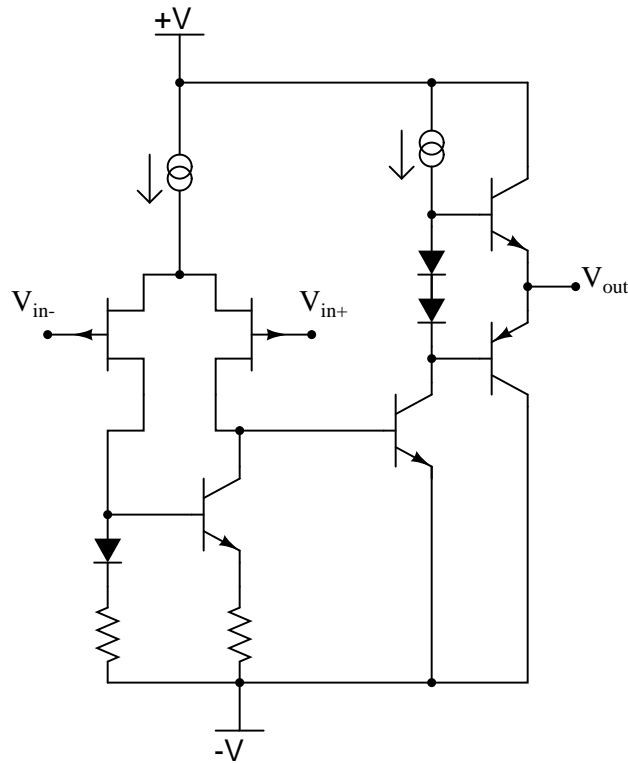


Notes 17

Ask your students to reveal their information sources, and what specific models of op-amp they researched.

Question 18

Shown here is a simplified schematic diagram of one of the operational amplifiers inside a TL08x (TL081, TL082, or TL084) op-amp integrated circuit:

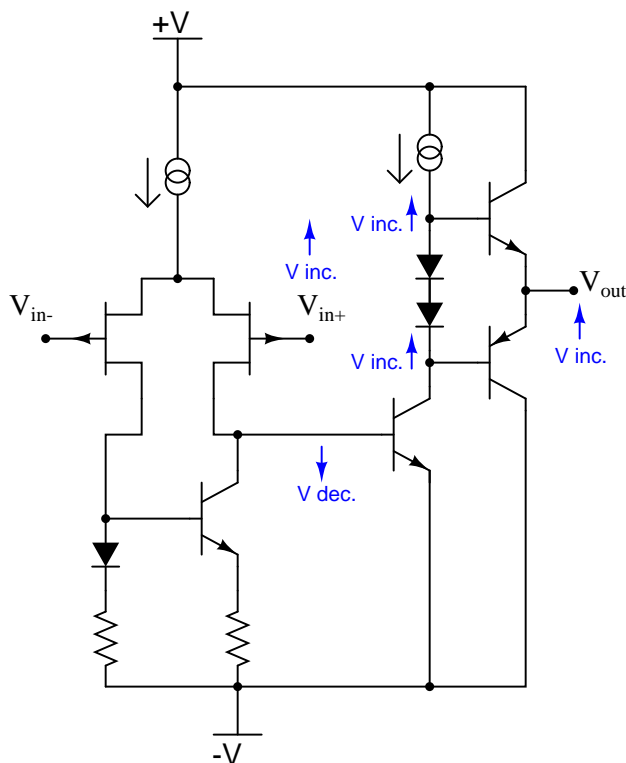


Qualitatively determine what will happen to the output voltage (V_{out}) if the voltage on the noninverting input (V_{in+}) increases, and the voltage on the inverting input (V_{in-}) remains the same (all voltages are positive quantities, referenced to $-V$). Explain what happens at every stage of the op-amp circuit (voltages increasing or decreasing, currents increasing or decreasing) with this change in input voltage.

file 00800

Answer 18

Here, I've labeled a few of the important voltage changes in the circuit, resulting from the increase in noninverting input voltage (V_{in+}):



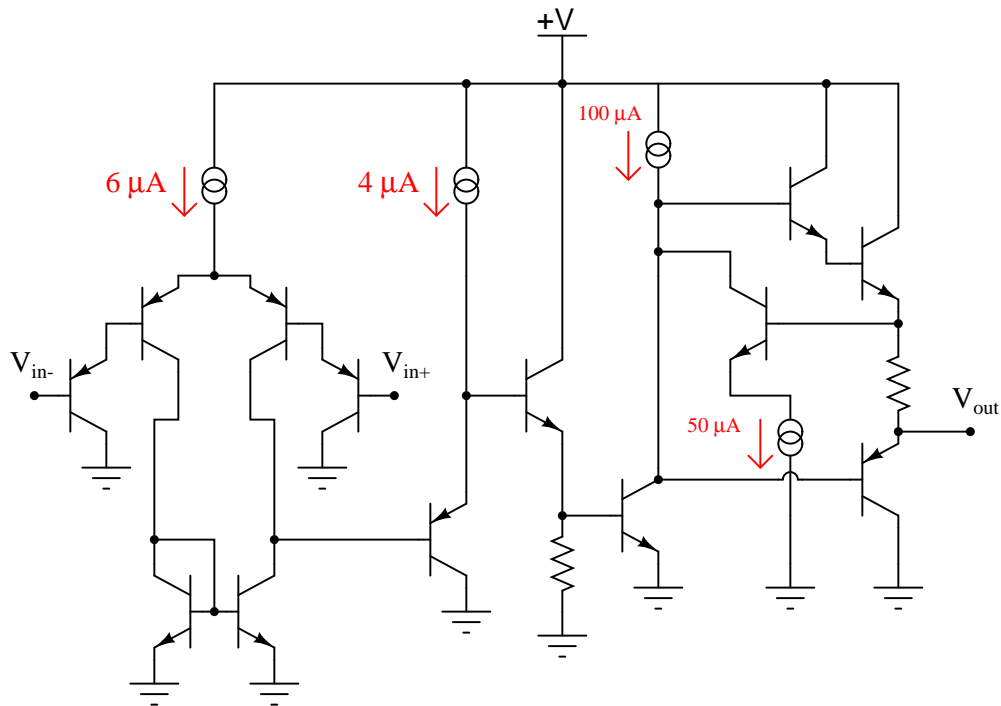
Notes 18

The answer provided here is minimal. Challenge your students to follow the whole circuit through until the end, qualitatively assessing voltage and current changes.

Incidentally, the strange-looking double-circle symbol is a *current source*. Ask your students if they were able to find a reference anywhere describing what this symbol means.

Question 19

Shown here is a simplified schematic diagram of one of the operational amplifiers inside an LM324 quad op-amp integrated circuit:

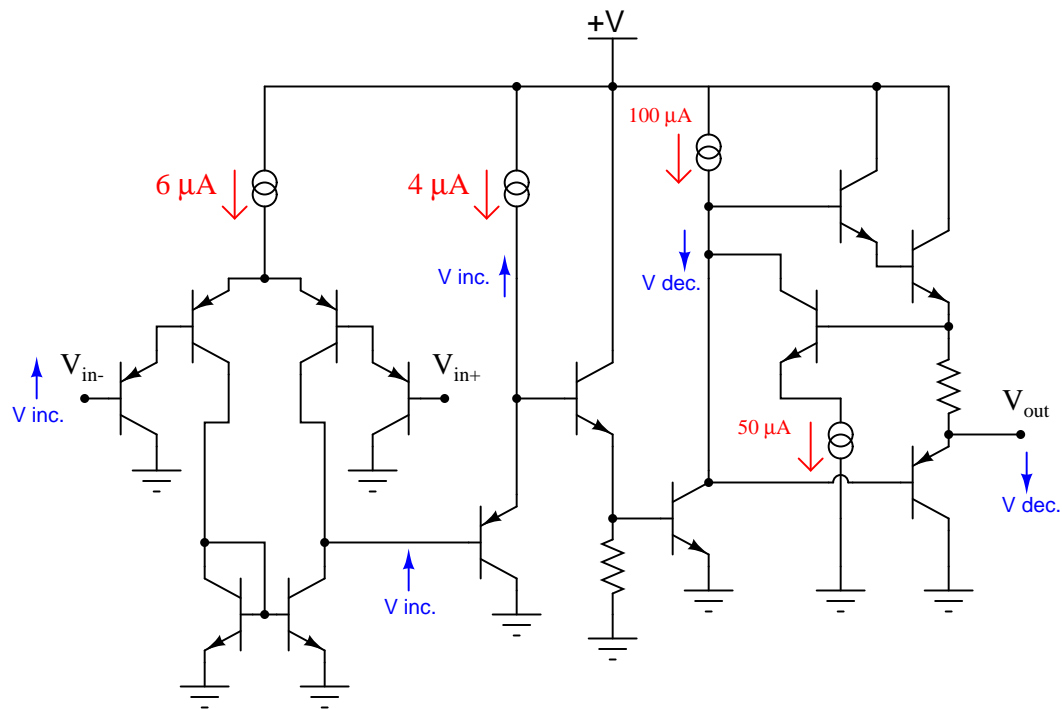


Qualitatively determine what will happen to the output voltage (V_{out}) if the voltage on the inverting input (V_{in-}) increases, and the voltage on the noninverting input (V_{in+}) remains the same (all voltages are positive quantities, referenced to ground). Explain what happens at every stage of the op-amp circuit (voltages increasing or decreasing, currents increasing or decreasing) with this change in input voltage.

file 00799

Answer 19

Here, I've labeled a few of the important voltage changes in the circuit, resulting from the increase in inverting input voltage (V_{in-}):



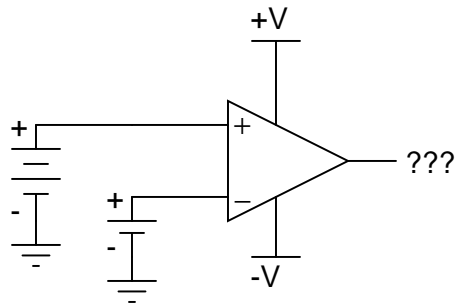
Notes 19

The answer provided here is minimal. Challenge your students to follow the whole circuit through until the end, qualitatively assessing voltage and current changes.

Incidentally, the strange-looking double-circle symbol is a *current source*. Ask your students if they were able to find a reference anywhere describing what this symbol means.

Question 20

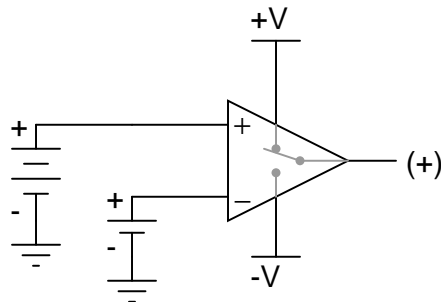
Ideally, what should the output voltage of an op-amp do if the noninverting voltage is greater (more positive) than the inverting voltage?



[file 00802](#)

Answer 20

In this condition, the output of the op-amp should saturate positive (+V), as if a direct connection were made inside the op-amp between the output terminal and the +V power supply terminal:

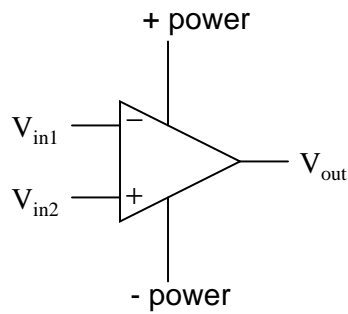


Notes 20

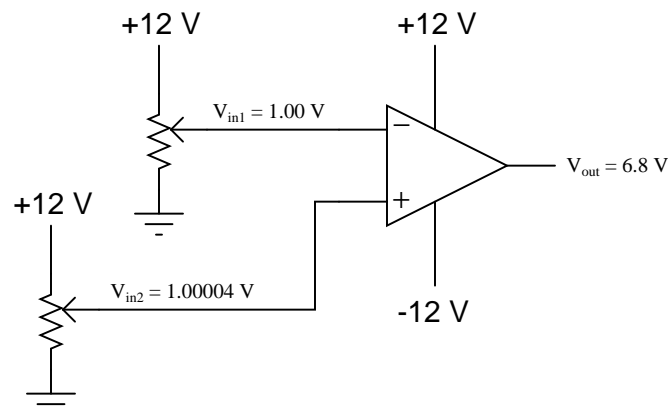
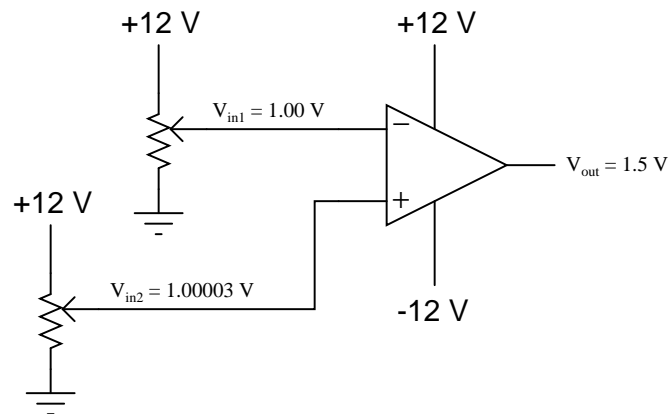
Determining which "way" the output of an op-amp drives under different input voltage conditions is confusing to many students. Discuss this with them, and ask them to present any principles or analogies they use to remember "which way is which."

Question 21

An *operational amplifier* is a particular type of *differential amplifier*. Most op-amps receive two input voltage signals and output one voltage signal:



Here is a single op-amp, shown under two different conditions (different input voltages). Determine the voltage gain of this op-amp, given the conditions shown:



Also, write a mathematical formula solving for differential voltage gain (A_V) in terms of an op-amp's input and output voltages.

file 00848

Answer 21

$$A_V = 530,000$$

$$A_V = \frac{\Delta V_{out}}{\Delta(V_{in2} - V_{in1})}$$

Follow-up question: convert this voltage gain figure (as a ratio) into a voltage gain figure in decibels.

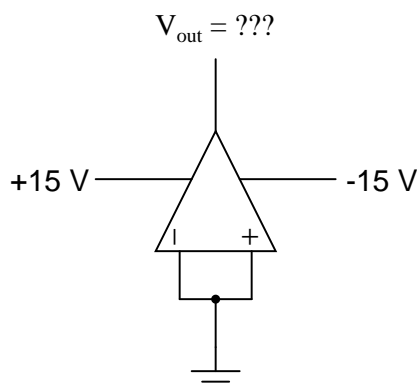
Notes 21

The calculations for voltage gain here are not that different from the voltage gain calculations for any other amplifier, except that here we're dealing with a *differential* amplifier instead of a single-ended amplifier.

A differential voltage gain of 530,000 is not unreasonable for a modern operational amplifier! A gain so extreme may come as a surprise to many students, but they will discover later the utility of such a high gain.

Question 22

Ideally, when the two input terminals of an op-amp are shorted together (creating a condition of *zero differential voltage*), and those two inputs are connected directly to ground (creating a condition of *zero common-mode voltage*), what should this op-amp's output voltage be?



In reality, the output voltage of an op-amp under these conditions is not the same as what would be ideally predicted. Identify the fundamental problem in real op-amps, and also identify the best solution.

[file 00847](#)

Answer 22

Ideally, $V_{out} = 0$ volts. However, the output voltage of a real op-amp under these conditions will invariably be "saturated" at full positive or full negative voltage due to differences in the two branches of its (internal) differential pair input circuitry. To counter this, the op-amp needs to be "trimmed" by external circuitry.

Follow-up question: the amount of differential voltage required to make the output of a real opamp settle at 0 volts is typically referred to as the *input offset voltage*. Research some typical input offset voltages for real operational amplifiers.

Challenge question: identify a model of op-amp that provides extra terminals for this "trimming" feature, and explain how it works.

Notes 22

In many ways, real op-amps fall short of their ideal expectations. However, modern op-amps are far, far better than the first models manufactured. And with such a wide variety of models to choose from, it is possible to obtain an almost perfect match for whatever design application you have, for a modest price.

If possible, discuss how "trimming" works in a real op-amp. If your students took the "challenge" and found some op-amp datasheets describing how to implement trimming, have them relate the connection of external components to the op-amp's internal circuitry.

Question 23

What does it mean if an operational amplifier has the ability to "swing its output rail to rail"? Why is this an important feature to us?

file 00844

Answer 23

Being able to "swing" the output voltage "rail to rail" means that the full range of an op-amp's output voltage extends to within millivolts of either power supply "rail" (+V and -V).

Challenge question: identify at least one op-amp model that has this ability, and at least one that does not. Bring the datasheets for these op-amp models with you for reference during discussion time.

Notes 23

Discuss what this feature means to us as circuit builders in a practical sense. Ask those students who tackled the challenge question to look up the output voltage ranges of their op-amp models. Exactly how close to +V and -V can the output voltage of an op-amp lacking "rail-to-rail" output capability "swing"?

Question 24

A very important parameter of operational amplifier performance is *slew rate*. Describe what "slew rate" is, and why it is important for us to consider in choosing an op-amp for a particular application.

[file 00846](#)

Answer 24

"Slew rate" is the maximum rate of voltage change over time ($\frac{dv}{dt}$) that an op-amp can output.

Notes 24

Ask your students why $\frac{dv}{dt}$ might be an important parameter in a circuit? In what application(s) might we need the op-amp to "swing" its output voltage rapidly? In what application(s) might we not care about the op-amp's slew rate?

Question 25

Some precision operational amplifiers are *programmable*. What does this feature mean? In what way can you "program" an op-amp?

file 00845

Answer 25

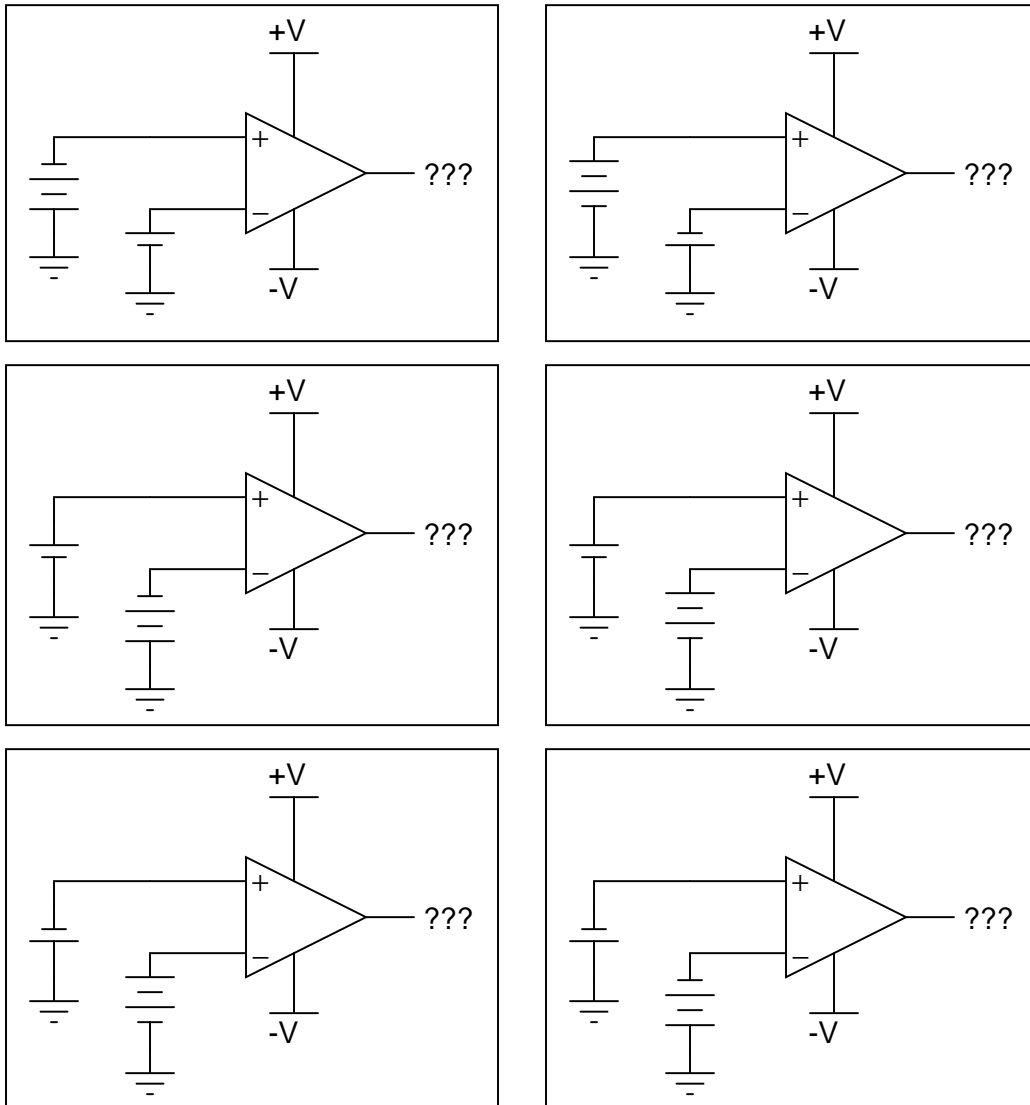
A "programmable" op-amp is one with extra connections to its internal circuitry allowing you to set the current source values using external components.

Notes 25

What possible benefits are there to "programming" the current source values in an operational amplifier? Discuss this with your students, asking them to share what they've found through their research.

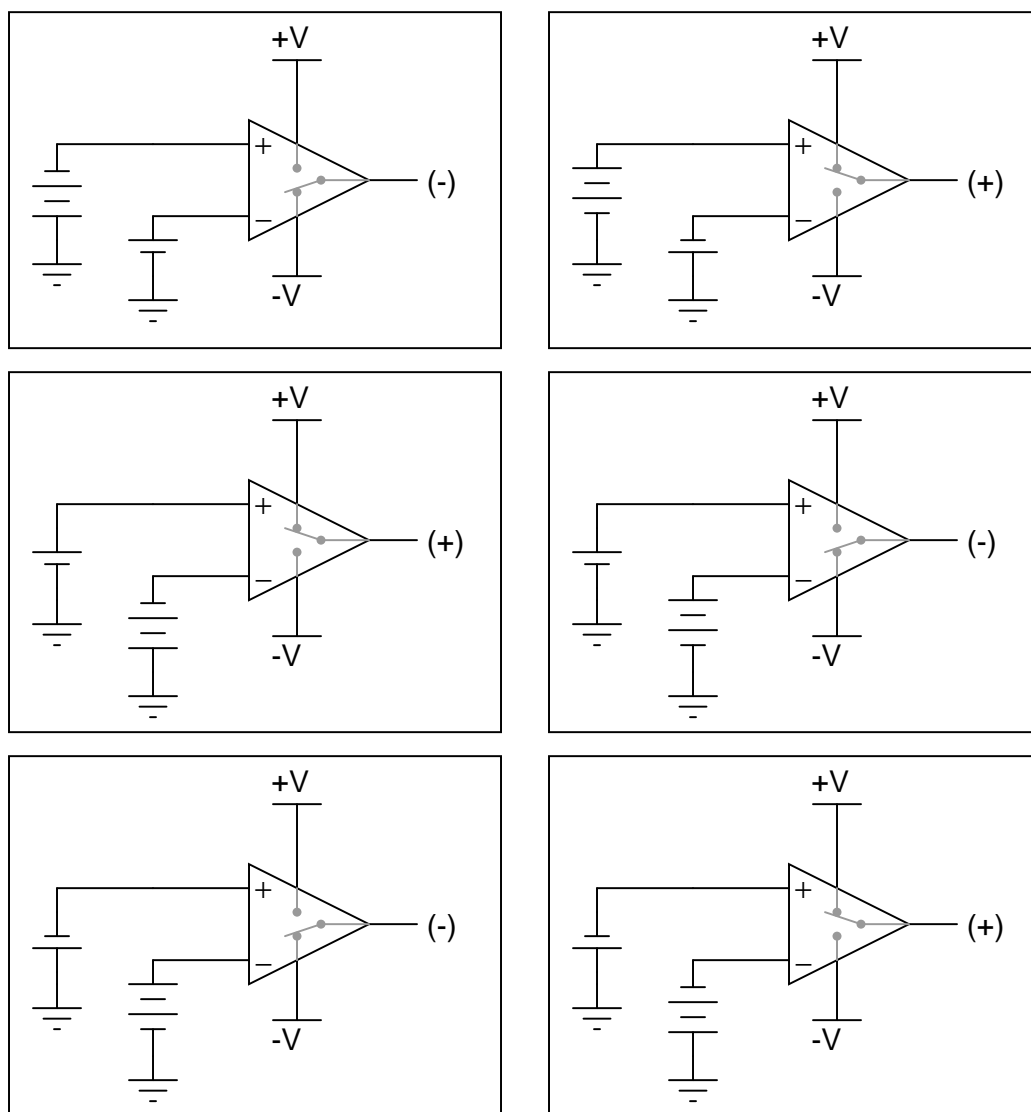
Question 26

Determine the output voltage polarity of this op-amp (with reference to ground), given the following input conditions:



file 00803

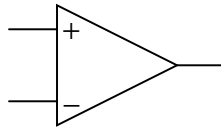
In these illustrations, I have likened the op-amp's action to that of a single-pole, double-throw switch, showing the "connection" made between power supply terminals and the output terminal.



Determining which "way" the output of an op-amp drives under different input voltage conditions is confusing to many students. Discuss this with them, and ask them to present any principles or analogies they use to remember "which way is which."

Question 27

Although the following symbol is generally interpreted as an operational amplifier ("op-amp"), it may also be used to represent a *comparator*:



What is the difference between a comparator such as the model LM319, and a true operational amplifier such as the model LM324? Are the two devices interchangeable, or is there any significant difference despite the exact same schematic symbols? Explain your answer.

file 00875

Answer 27

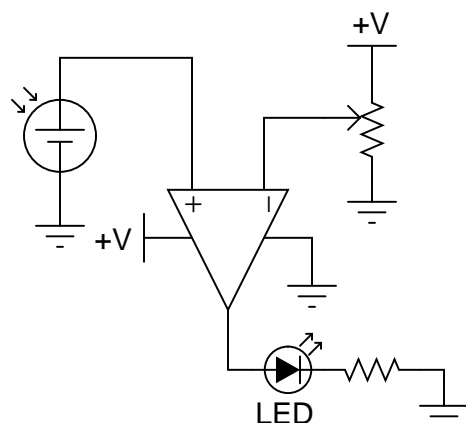
Comparators are designed for *open-loop* operation only (no feedback), while operational amplifiers are designed to perform well with feedback. For many simple applications, though, a true op-amp does a reasonable job as a comparator.

Notes 27

The answer to this question invokes a couple of terms your students may not be familiar with yet: "open-loop" and "feedback". Discuss these terms with your students, asking them first if they were able to arrive at definitions for them.

Question 28

In this circuit, a solar cell converts light into voltage for the opamp to "read" on its noninverting input. The opamp's inverting input connects to the wiper of a potentiometer. Under what conditions does the LED energize?



file 00872

Answer 28

The LED energizes under bright-light conditions, de-energizing when the light decreases below the threshold set by the potentiometer.

Follow-up question: determine what would have to be changed in this circuit to make the LED turn on when the solar cell becomes *dark*.

Notes 28

There is more than one way to accomplish the task posed by the follow-up question. Be sure to ask your students for their ideas on how to reverse the LED's operation!

Question 29

What does the phrase *open-loop voltage gain* mean with reference to an operational amplifier? For a typical opamp, this gain figure is extremely high. Why is it important that the open-loop voltage gain be high when using an opamp as a comparator?

file 00873

Answer 29

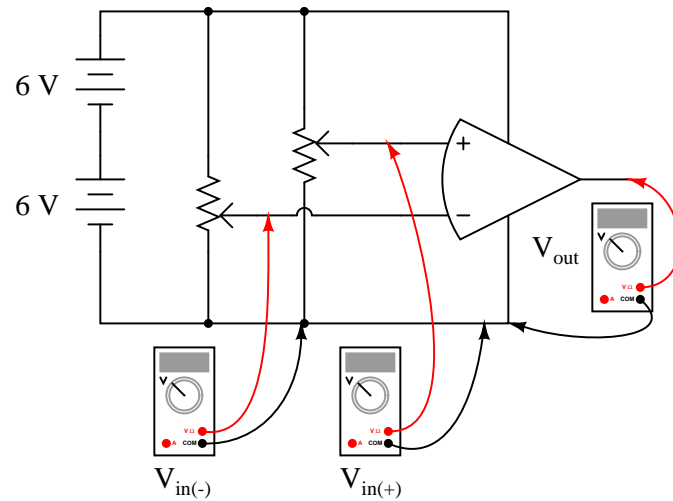
"Open-loop voltage gain" simply refers to the differential voltage gain of the amplifier, without any connections "feeding back" the amplifier's output signal to one or more of its inputs. A high gain figure means that a very small differential voltage is able to drive the amplifier into saturation.

Notes 29

The word "saturation" is used often in electronics, especially in reference to amplifiers. Discuss the meaning and significance of this term with your students, especially in reference to comparator circuits, where the opamp is being used simply to compare to voltages and tell which one is greater.

Question 30

A student is operating a simple comparator circuit and documenting the results in a table:



$V_{in(+)}$	$V_{in(-)}$	V_{out}
3.00 V	1.45 V	10.5 V
3.00 V	2.85 V	10.4 V
3.00 V	3.10 V	1.19 V
3.00 V	6.75 V	1.20 V
$V_{in(+)}$	$V_{in(-)}$	V_{out}
2.36 V	6.50 V	1.20 V
4.97 V	6.50 V	1.21 V
7.05 V	6.50 V	10.5 V
9.28 V	6.50 V	10.4 V
$V_{in(+)}$	$V_{in(-)}$	V_{out}
10.4 V	9.87 V	10.6 V
1.75 V	1.03 V	10.5 V
0.31 V	1.03 V	10.5 V
5.50	5.65 V	1.19 V

One of these output voltage readings is anomalous. In other words, it does not appear to be "correct". This is very strange, because these figures are real measurements and not predictions! Perplexed, the student approaches the instructor and asks for help. The instructor sees the anomalous voltage reading and says two words: *latch-up*. With that, the student goes back to research what this phrase means, and what it has to do with the weird output voltage reading.

Identify which of these output voltage measurements is anomalous, and explain what "latch-up" has to do with it.

file 00876

Answer 30

Latch-up occurs when one of the input voltage signals approaches too close to one of the power supply rail voltages. The result is the op-amp output saturating "high" even if it isn't supposed to.

Challenge question: suppose we expected both input voltages to range between 0 and 10 volts during normal operation of this comparator circuit. What could we change in the circuit to allow this range of operation and avoid latch-up?

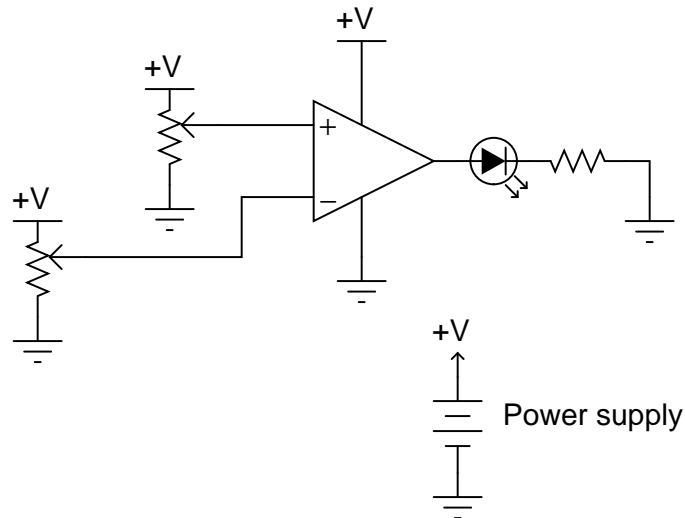
Notes 30

Ask your students what they found in their research on "latch-up," and if this is an idiosyncrasy of all op-amp models, or just some.

Incidentally, the curved op-amp symbol has no special meaning. This symbol was quite popular for representing op-amps during their early years, but has since fallen out of favor. I show it here just to inform your students, in case they ever happen to encounter one of these symbols in an old electronic schematic.

Question 31

In this circuit, an op-amp turns on an LED if the proper input voltage conditions are met:

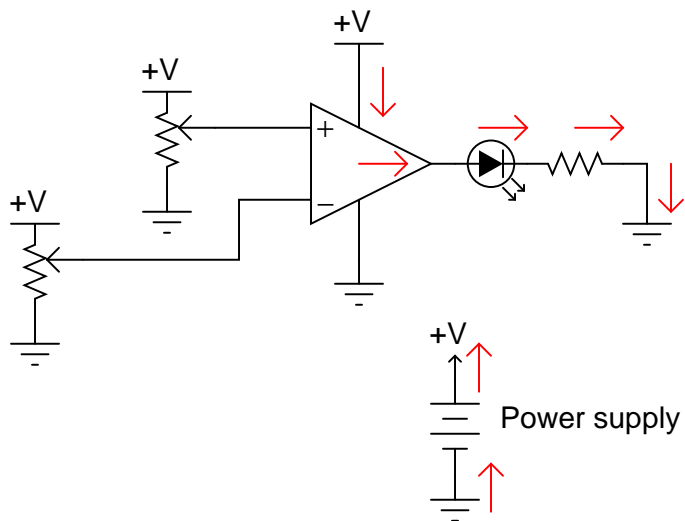


Trace the complete path of current powering the LED. Where, exactly, does the LED get its power from?

file 00801

Answer 31

The arrows shown in this diagram trace "conventional" current flow, not electron flow:

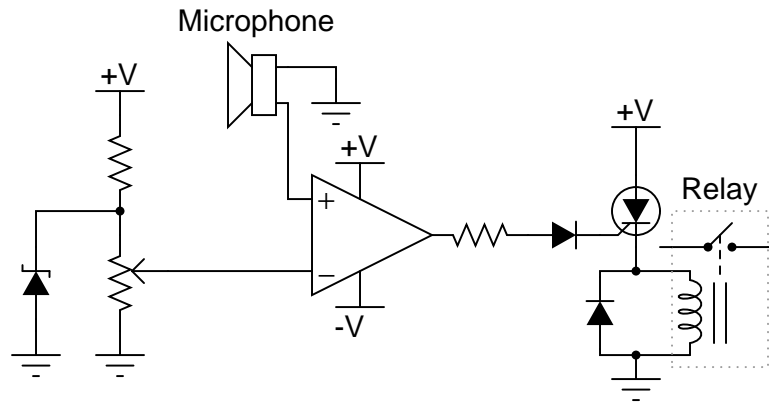


Notes 31

The important thing to note here is that the load current does not pass through either of the op-amp's input terminals. All load current is sourced by the op-amp's power supply! Discuss the importance of this fact with your students.

Question 32

Explain the operation of this sound-activated relay circuit:



[file 00879](#)

Answer 32

The relay will energize if a loud enough sound is detected by the microphone. The threshold volume is set by the potentiometer.

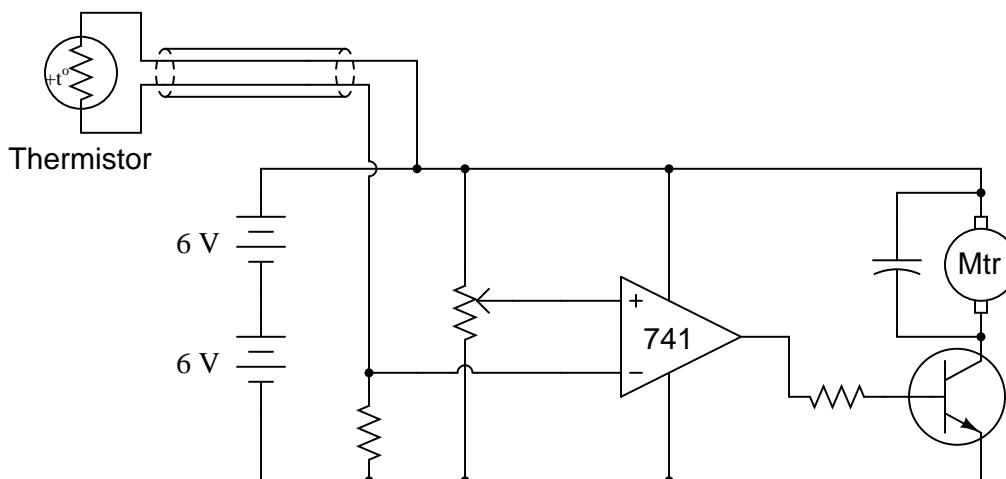
Follow-up question: how could we equip this circuit with the ability to turn the relay off once it has been turned on?

Notes 32

There is a lot going on in this circuit that is not addressed in the answer I give. The basic purpose of the circuit should be fairly clear to understand, but the function of several components deserve further explanation. Ask your students to explain the functions of the diode on the comparator's output, the diode in parallel with the relay coil, the zener diode in parallel with the potentiometer, and the SCR.

Question 33

In this automatic cooling fan circuit, a comparator is used to turn a DC motor on and off when the sensed temperature reaches the "setpoint" established by the potentiometer:



The circuit works just as it is supposed to in turning the motor on and off, but it has a strange problem: the transistor gets warm when the motor is *off*! Oddly enough, the transistor actually cools down when the motor turns on.

Describe what you would measure first in troubleshooting this problem. Based on the particular model of op-amp used (a model LM741C), what do you suspect is the problem here?

[file 00877](#)

Answer 33

The problem here is that the model 741 op-amp cannot "swing" its output rail-to-rail. An op-amp with rail-to-rail output voltage capability would not make the transistor heat up in the "off" mode.

Challenge question: what purpose does the capacitor serve in this circuit? Hint: the capacitor is not required in a "perfect world," but it helps eliminate spurious problems in the real world!

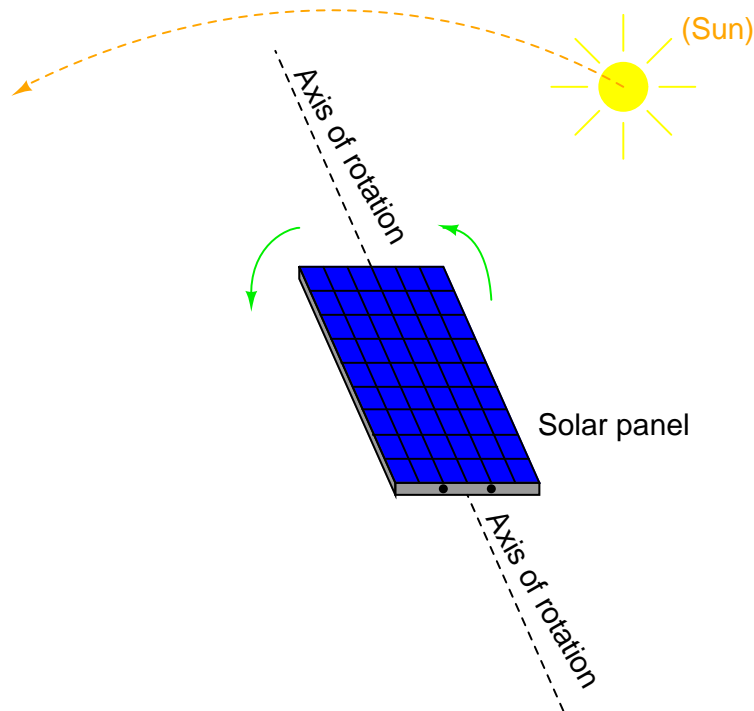
Notes 33

I've actually encountered this transistor heating problem in designing and building a very similar DC motor control circuit using the 741. There is a way to overcome this problem without switching to a different model of op-amp!

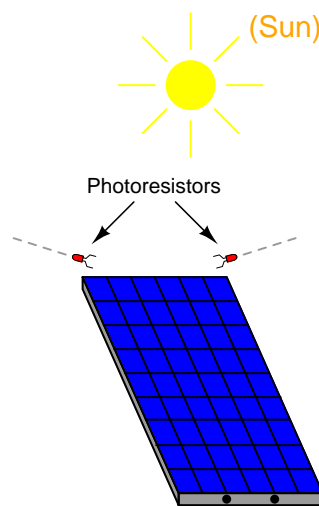
After discussing the nature of the problem with your students, you should talk about the virtues of getting a "low performance" op-amp such as the model 741 to work in a scenario like this rather than changing to an op-amp model capable of rail-to-rail operation. In my estimation, switching to a more modern op-amp in a circuit as simple as this is "cheating". There is nothing about this circuit that fundamentally taxes the capabilities of a 741 op-amp. All it takes is a little creativity to make it work properly.

Question 34

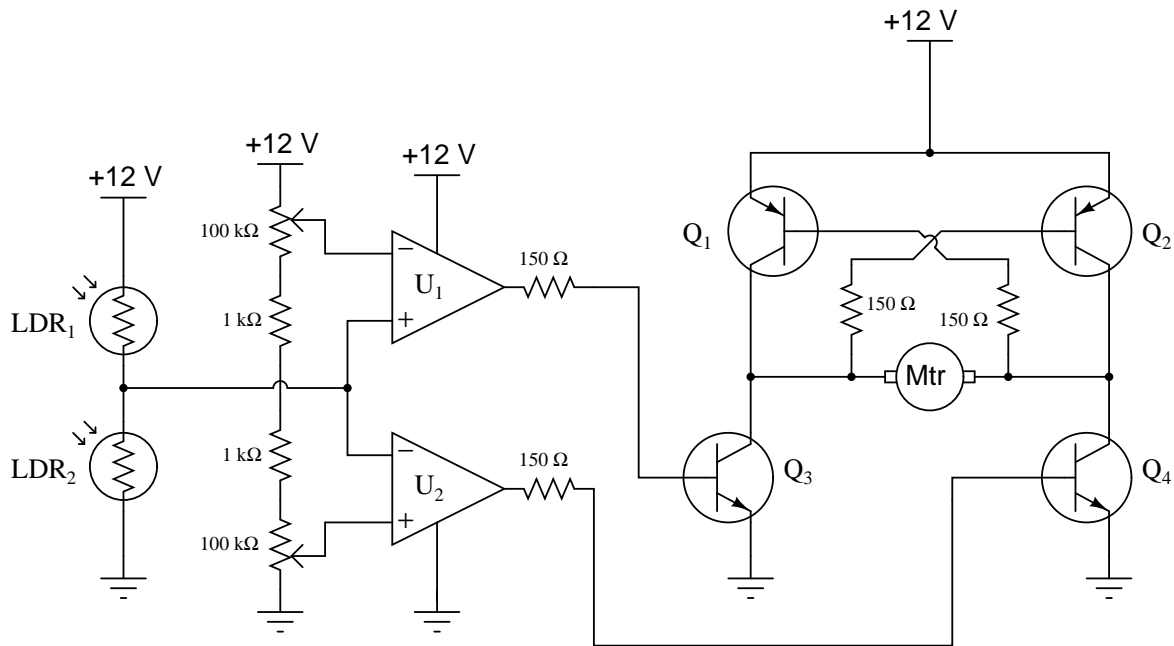
Photovoltaic solar panels produce the most output power when facing directly into sunlight. To maintain proper positioning, "tracker" systems may be used to orient the panels' direction as the sun "moves" from east to west across the sky:



One way to detect the sun's position relative to the panel is to attach a pair of Light-Dependent Resistors (LDR's) to the solar panel in such a way that each LDR will receive an equal amount of light only if the panel is pointed directly at the sun:



Two comparators are used to sense the differential resistance produced by these two LDR's, and activate a tracking motor to tilt the solar panel on its axis when the differential resistance becomes too great. An "H-drive" transistor switching circuit takes the comparators' output signals and amplifies them to drive a permanent-magnet DC motor one way or the other:



In this circuit, what guarantees that the two comparators never output a "high" (+V) voltage simultaneously, thus attempting to move the tracking motor clockwise and counter-clockwise at the same time?

[file 00881](#)

Answer 34

With the potentiometers connected in series like this, the upper comparator's reference voltage will always be greater than the lower comparator's reference voltage. In order for both comparators to saturate their outputs "high," the voltage from the photoresistor divider would have to be greater than the upper potentiometer's voltage *and* less than the lower potentiometer's voltage at the same time, which is an impossibility. This comparator configuration is commonly known as a *window comparator* circuit.

Notes 34

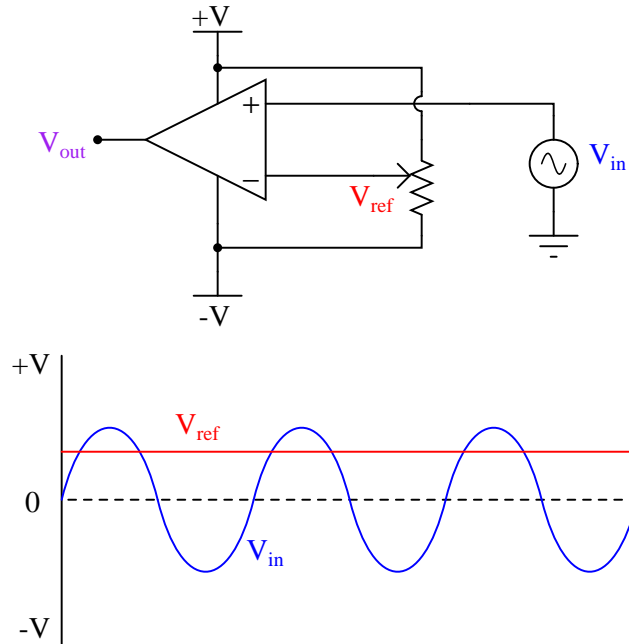
There is a lot going on in this comparator circuit for you and your students to discuss. Take time to talk about the operation of the entire circuit in detail, making sure students understand how every bit of it works.

If any of your students point out that there seem to be some power supply connections missing from the comparators (U_1 and U_2), discuss the fact that this notation is often used when multiple opamps or comparators are contained in the same integrated circuit. Often, the power supply connections will be omitted entirely for the sake of simplicity! Since everyone understands that opamps *need* DC power in order to function, the +V and -V (or ground) connections are simply assumed.

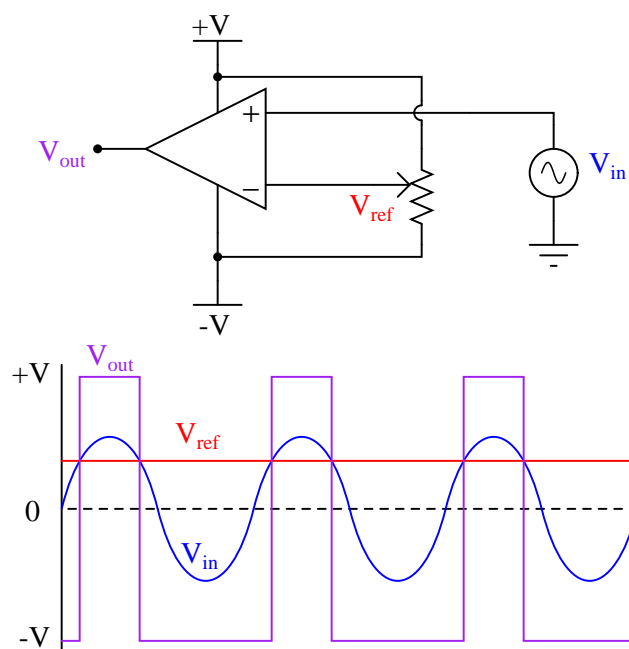
One misunderstanding I've seen with beginning students is to assume that signal input connections and power connections to an opamp are equivalent. That is, if an opamp does not receive +V/-V power through the normal power terminals, it will operate off of whatever voltages appear at its inverting and noninverting inputs. Nothing could be further from the truth! An "input" connection to a circuit denotes a signal to be detected, measured, or manipulated. A "power" connection is completely different. To use a stereo analogy, this is confusing the audio patch cable connections with the power cord.

Question 35

Trace the output waveform of this comparator circuit:



file 00878



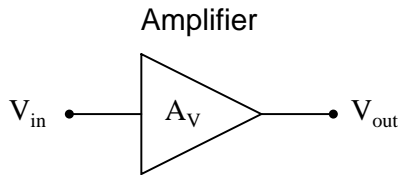
Follow-up question: explain what the phrase *duty cycle* means with reference to a "square" or "pulse" waveform.

Notes 35

During discussion, ask your students to explain how the output waveform of this comparator circuit comes to be, step by step. Ask them how they arrived at their solution, and if there is a way this AC/DC problem can be simplified to one that is DC only for easier analysis (determining what the output voltage will do for a certain set of input conditions).

Question 36

The *voltage gain* of a single-ended amplifier is defined as the ratio of output voltage to input voltage:



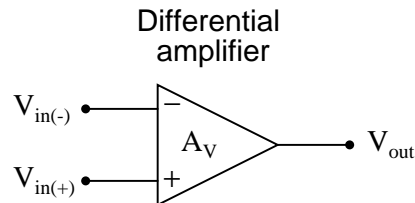
$$A_V = \frac{V_{out}}{V_{in}}$$

Often voltage gain is defined more specifically as the ratio of output voltage change to input voltage change. This is generally known as the *AC* voltage gain of an amplifier:

$$A_{V(AC)} = \frac{\Delta V_{out}}{\Delta V_{in}}$$

In either case, though, gain is a ratio of a single output voltage to a single input voltage.

How then do we generally define the voltage gain of a *differential* amplifier, where there are two inputs, not just one?



file 02287

Answer 36

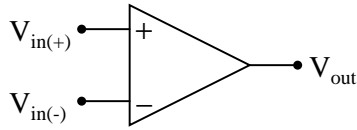
Voltage gain for a differential amplifier is defined as the ratio of output voltage to the *difference* in voltage between the two inputs.

Notes 36

This is a very important concept for students to grasp, especially before they proceed to study operational amplifiers, which are nothing more than differential amplifiers with extremely high voltage gains.

Question 37

Write the transfer function (input/output equation) for an operational amplifier with an open-loop voltage gain of 100,000. In other words, write an equation describing the output voltage of this op-amp (V_{out}) for any combination of input voltages ($V_{in(+)}$ and $V_{in(-)}$):



file 00925

Answer 37

$$V_{out} = 100,000(V_{in(+)} - V_{in(-)})$$

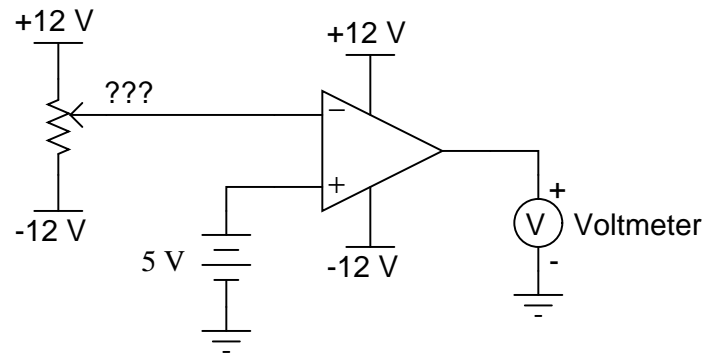
Notes 37

The concept of a "transfer function" is very useful, and this may be your students' first exposure to the idea. It is a phrase used quite often in engineering applications, and may denote an equation, a table of numbers, or a graph.

In this particular question, it is important that students know how to derive and use the basic transfer function for a differential amplifier. Challenge your students to express this function in a more general form, so that calculations may be made with different open-loop voltage gains.

Question 38

How much voltage would have to be "dialed up" at the potentiometer in order to stabilize the output at exactly 0 volts, assuming the opamp has no input offset voltage?



file 00924

Answer 38

5 volts

Notes 38

This question is a basic review of an ideal differential amplifier's function. Ask your students what voltage must be "dialed up" at the potentiometer to produce 0 volts at the output of the op-amp for several different voltages at the other input. If they don't understand at first, they soon will after discussing these alternate scenarios.

Question 39

An op-amp has +3 volts applied to the inverting input and +3.002 volts applied to the noninverting input. Its open-loop voltage gain is 220,000. Calculate the output voltage as predicted by the following formula:

$$V_{out} = A_V (V_{in(+)} - V_{in(-)})$$

How much differential voltage (input) is necessary to drive the output of the op-amp to a voltage of -4.5 volts?

[file 00926](#)

Answer 39

$$V_{out} = 440 \text{ volts}$$

Follow-up question: is this voltage figure realistic? Is it possible for an op-amp such as the model 741 to output 440 volts? Why or why not?

The differential input voltage necessary to drive the output of this op-amp to -4.5 volts is -20.455 μV .

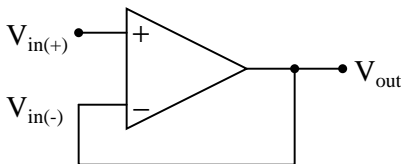
Follow-up question: what does it mean for the input voltage differential to be *negative* 20.455 microvolts? Provide an example of two input voltages ($V_{in(+)}$ and $V_{in(-)}$) that would generate this much differential voltage.

Notes 39

Obviously, there are limitations to the op-amp formula for calculating output voltage, given input voltages and open-loop voltage gain. Students need to realize the practical limits of an op-amp's output voltage range, and what sets those limits.

Question 40

Write the transfer function (input/output equation) for an operational amplifier with an open-loop voltage gain of 100,000, and the inverting input connected directly to its output terminal. In other words, write an equation describing the output voltage of this op-amp (V_{out}) for any given input voltage at the noninverting input ($V_{in(+)}$):



Then, once you have an equation written, solve for the over-all voltage gain ($A_V = \frac{V_{out}}{V_{in(+)}}$) of this amplifier circuit, and calculate the output voltage for a noninverting input voltage of +6 volts.

file 00927

Answer 40

$$V_{out} = 100,000(V_{in(+)} - V_{out})$$

(I've left it up to you to perform the algebraic simplification here!)

$$A_V = \frac{100,000}{100,001} = 0.99999$$

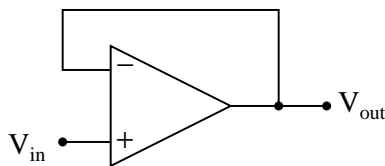
For an input voltage of +6 volts, the output voltage will be +5.99994 volts.

Notes 40

The significant point of this question is that students see the over-all voltage gain of the opamp radically attenuated from 100,000 to approximately 1. What is not so evident is just how *stable* this new voltage gain is, which is one of the purposes for employing negative feedback.

Question 41

How much effect will a change in the op-amp's open-loop voltage gain have on the *overall* voltage gain of a negative-feedback circuit such as this?



If the open-loop gain of this operational amplifier were to change from 100,000 to 200,000, for example, how big of an effect would it have on the voltage gain as measured from the noninverting input to the output?
[file 02288](#)

Answer 41

The different in overall voltage gain will be trivial.

Follow-up question: what advantage is there in building voltage amplifier circuits in this manner, applying negative feedback to a "core" amplifier with very high intrinsic gain?

Notes 41

Work with your students to calculate a few example scenarios, with the old open-loop gain versus the new open-loop gain. Have the students validate their conclusions with numbers!

Negative feedback is an extremely useful engineering principle, and one that allows us to build very precise amplifiers using imprecise components. Credit for this idea goes to Harold Black, an electrical engineer, in 1920's. Mr. Black was looking for a way to improve the linearity and stability of amplifiers in telephone systems, and (as legend has it) the idea came to him in a flash of insight as he was commuting on a ferry boat.

An interesting historical side-note is that Black's 1928 patent application was initially rejected on the grounds that he was trying to submit a perpetual motion device! The concept of negative feedback in an amplifier circuit was so contrary to established engineering thought at the time, that Black experienced significant resistance to the idea within the engineering community. The United States patent office, on the other hand, was inundated with fraudulent "perpetual motion" claims, and so dismissed Black's invention at first sight.

Question 42

For all practical purposes, how much voltage exists between the inverting and noninverting input terminals of an op-amp in a functioning negative-feedback circuit?

file 00930

Answer 42

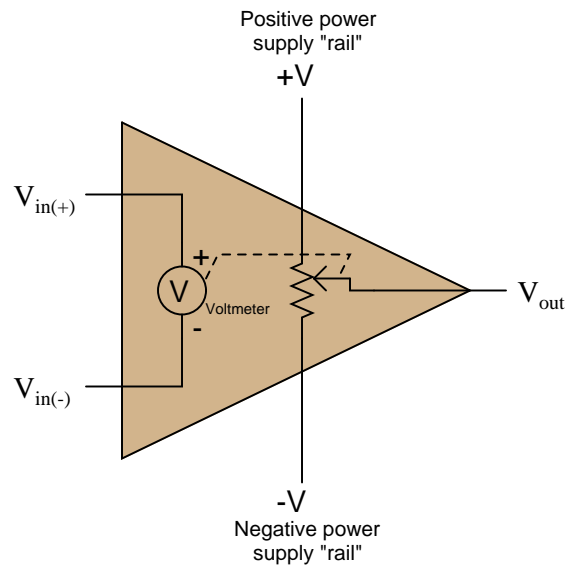
Zero volts

Notes 42

Ask your students to explain why there will be (practically) no voltage between the input terminals of an operational amplifier when it is used in a negative feedback circuit.

Question 43

A helpful model for understanding opamp function is one where the output of an opamp is thought of as being the wiper of a potentiometer, the wiper position automatically adjusted according to the difference in voltage measured between the two inputs:



To elaborate further, imagine an extremely sensitive, analog, zero-center voltmeter inside the opamp, where the moving-coil mechanism of the voltmeter mechanically drives the potentiometer wiper. The wiper's position would then be proportional to both the magnitude and polarity of the difference in voltage between the two input terminals.

Realistically, building such a voltmeter/potentiometer mechanism with the same sensitivity and dynamic performance as a solid-state opamp circuit would be impossible, but the point here is to *model* the opamp in terms of components that we are already very familiar with, not to suggest an alternative construction for real opamps.

Describe how this model helps to explain the output voltage limits of an opamp, and also where the opamp sources or sinks load current from.

file 02290

Answer 43

The output voltage of an opamp *cannot* exceed either power supply "rail" voltage, and it is these "rail" connections that either source or sink load current.

Follow-up question: does this model realistically depict the input characteristics (especially input *impedance*) of an opamp? Why or why not?

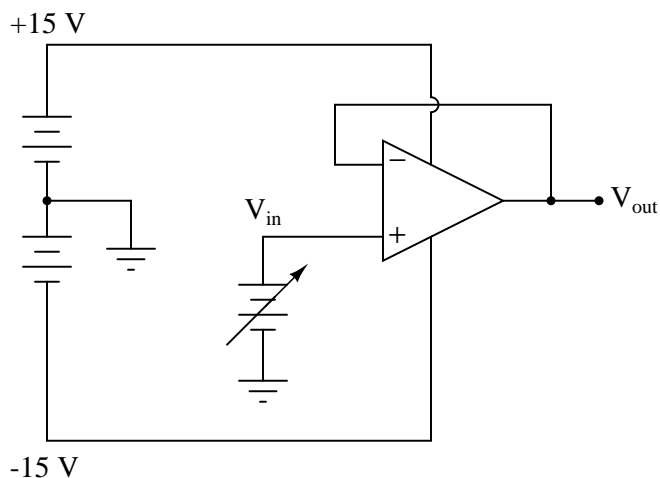
Students have told me that this opamp model "opened their eyes" to the behavior of opamp outputs, especially in situations where they would have otherwise expected an opamp to deliver an output voltage exceeding one of the rail voltages, or where the path of load current was critical. One of the common fallacies new students have about opamps is that output current somehow originates from current at one or both of the input terminals. This model also helps to shatter that illusion.

As a new instructor, I used to be shocked to see such misunderstandings in my students' thinking. Surely from their previous experience with single-transistor amplifier circuits they *knew* the DC output voltage could never exceed the power supply rail voltages, right? Surely they *understood* that the current gain provided by multiple transistor stages effectively isolated output loading from the input(s), so that increased load at the output had negligible effect on input current, right? Well, not necessarily so!

The major reasons I am so adamant about having students expose their conceptions and thinking processes in a classroom discussion (rather than quietly listen to me lecture) is to be able to detect and correct these kinds of misunderstandings, and to be able to instill a sense of internal dialogue so that students learn to detect and correct the same kinds of misunderstandings on their own. Deep and critical thought does not seem to be a natural tendency in most human beings. To the contrary, a great many people seem perfectly content with meager and shallow comprehensions of the world around them, and must be prodded into assessing what they think they know. Pose questions to your students that challenge shallow thinking, that expose misunderstandings, and that force students to think more deeply than they are used to. In my opinion, building these metacognitive skills and habits is the very essence of higher education.

Question 44

Complete the table of voltages for this opamp "voltage follower" circuit:



V_{in}	V_{out}
0 volts	0 volts
+5 volts	
+10 volts	
+15 volts	
+20 volts	
-5 volts	
-10 volts	
-15 volts	
-20 volts	

[file 02289](#)

Answer 44

V_{in}	V_{out}
0 volts	0 volts
+5 volts	+5 volts
+10 volts	+10 volts
+15 volts	+15 volts
+20 volts	+15 volts
-5 volts	-5 volts
-10 volts	-10 volts
-15 volts	-15 volts
-20 volts	-15 volts

Follow-up question: the output voltage values given in this table are ideal. A real opamp would probably not be able to achieve even what is shown here, due to idiosyncrasies of these amplifier circuits. Explain what would probably be different in a *real* opamp circuit from what is shown here.

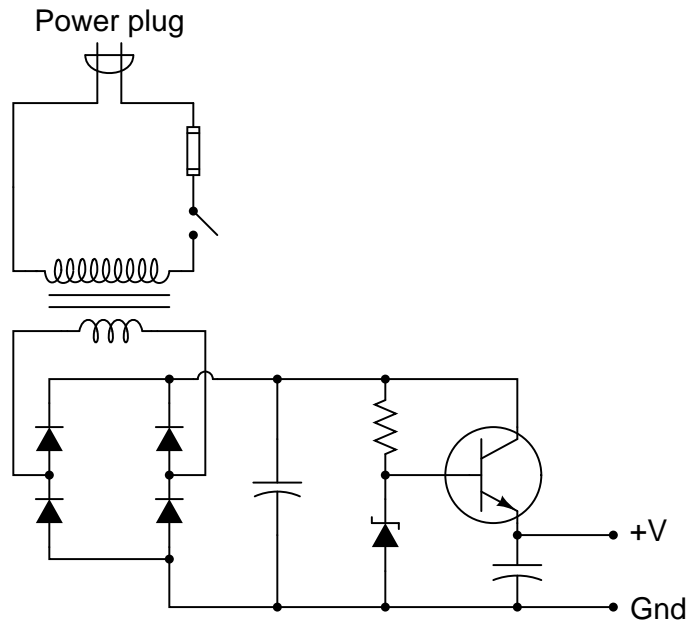
A common mistake I see students new to opamps make is assuming that the output voltage will magically attain whatever value the gain equation predicts, with no regard for power supply rail voltage limits.

Another good follow-up question to ask your students is this: "How much voltage is there between the two input terminals in each of the situations described in the table?" They will find that the "golden rule" of closed-loop opamp circuits can be violated!

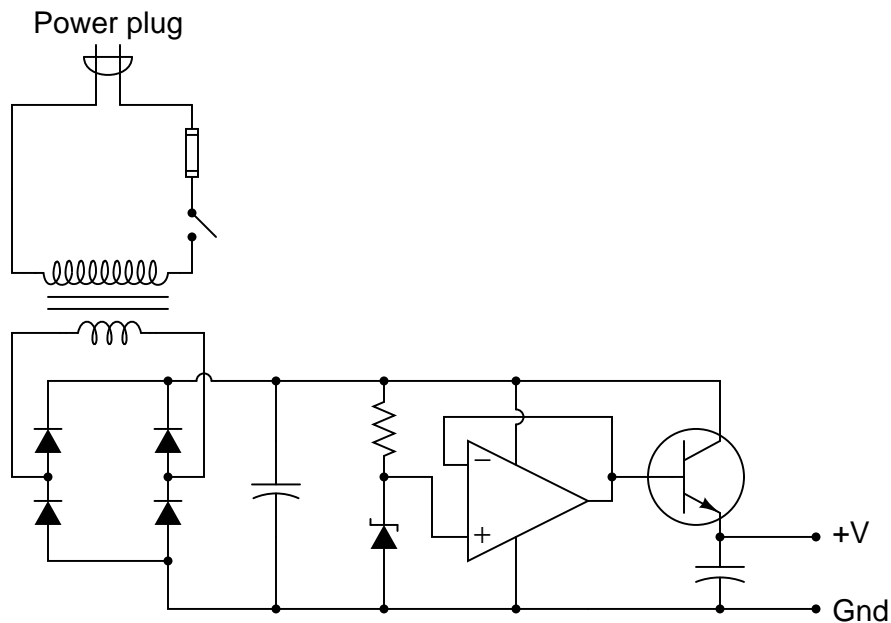
If students have difficulty answering the follow-up question, drop these two hints: (1) *Rail-to-rail output swing* and (2) *Latch-up*.

Question 45

A student builds the following regulated AC-DC power supply circuit, but is dissatisfied with its performance:



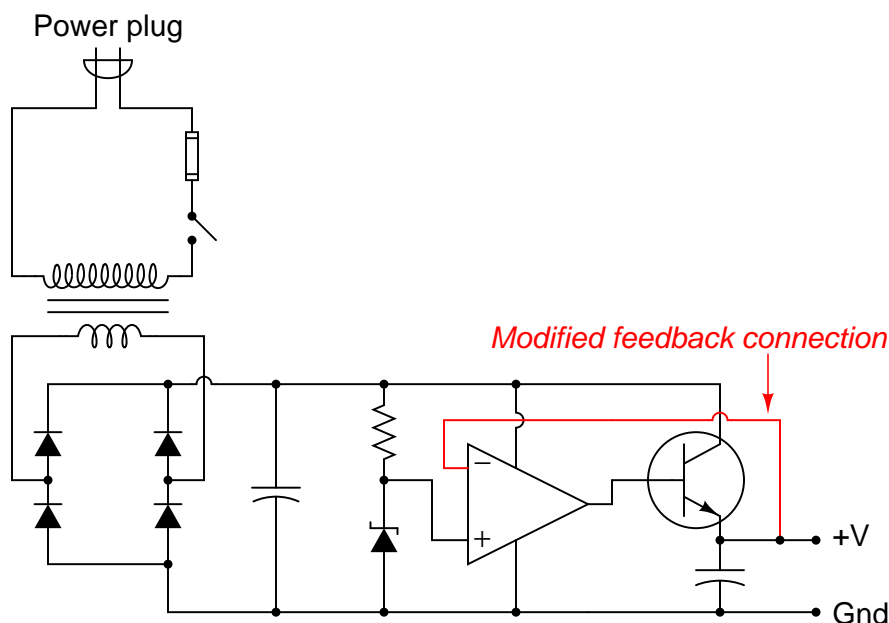
The voltage regulation is not as good as the student hoped. When loaded, the output voltage "sags" more than the student wants. When the zener diode's voltage is measured under the same conditions (unloaded output, versus loaded output), its voltage is noted to sag a bit as well. The student realizes that part of the problem here is loading of the zener diode through the transistor. In an effort to improve the voltage regulation of this circuit, the student inserts an opamp "voltage follower" circuit between the zener diode and the transistor:



Now the zener diode is effectively isolated from the loading effects of the transistor, and by extension

from the output load as well. The opamp simply takes the zener's voltage and reproduces it at the transistor base, delivering as much current to the transistor as necessary without imposing any additional load on the zener diode.

This modification does indeed improve the circuit's ability to hold a steady output voltage under changing load conditions, but there is still room for improvement. Another student looks at the modified circuit, and suggests one small change that dramatically improves the voltage regulation:



Now the output voltage holds steady at the zener diode's voltage with almost no "sag" under load! The second student is pleased with the success, but the first student does not understand why this version of the circuit functions any better than previous version. How would you explain this circuit's improved performance to the first student? How is an understanding of negative feedback essential to being able to comprehend the operation of this circuit?

[file 02286](#)

Answer 45

With the relocated feedback connection, the opamp now "senses" the load voltage at the output terminals, and is able to correct for *any* voltage losses in the power transistor.

Follow-up question: the new, improved circuit certainly exhibits better voltage regulation, but it also introduces something that the first student finds surprising: now the output voltage is approximately 0.7 volts greater than it used to be. Explain why.

Notes 45

This is one of my favorite questions to ask students as they begin to learn how negative feedback works. It is an excellent "litmus test" for comprehension of negative feedback: those students who understand how and why negative feedback works will immediately grasp the significance of the modified feedback connection; those who do not understand negative feedback will fail to grasp why this circuit works at all. Spend as much time as you need discussing this circuit, because it holds the key to student understanding of a great many opamp circuits!

Question 46

Amplifier *distortion* occurs when its gain varies as a function of the instantaneous signal amplitude. That is, some parts of the signal waveform become amplified more than others, and this results in the waveform taking on a slightly different shape.

All active devices, bipolar junction transistors included, are *nonlinear* to some extent. This term means that their gain varies throughout their operating ranges. During the 1920's, an electrical engineer named Harold Black was pondering this problem in the design of telephone system amplifiers. His solution came to him in a flash of insight one day, as he was commuting from work on a ferry boat. Explain what his solution to this problem was.

file 01244

Answer 46

Harold Black is credited as the first to apply *negative feedback* as a solution to the problem of nonlinearity in electronic amplifiers.

Challenge question: since negative feedback has the undesirable effect of diminishing overall amplifier gain, it would seem at first that low distortion and high gain are mutually exclusive design goals for an amplifier. Is this true, or is there a way to obtain both low distortion and high gain from an amplifier? If so, how?

Notes 46

Although Black's solution has been wildly successful in amplifier design, it also finds application in a wide range of processes. Control theory, for example, where machines are automated in such a way as to stabilize physical variables such as pressure, flow, temperature, etc., depends heavily on negative feedback as an operating principle.

An interesting historical side-note is that Black's 1928 patent application was initially rejected on the grounds that he was trying to submit a perpetual motion device! The concept of negative feedback in an amplifier circuit was so contrary to established engineering thought at the time, that Black experienced significant resistance to the idea within the engineering community. At that time the United States patent office was inundated with fraudulent "perpetual motion" claims, and so dismissed Black's invention at first sight.

Question 47

A very important concept in electronics is that of *negative feedback*. This is an extremely important concept to grasp, as a great many electronic systems exploit this principle for their operation and cannot be properly understood without a comprehension of it.

However important negative feedback might be, it is not the easiest concept to understand. In fact, it is quite a conceptual leap for some. The following is a list of examples – some electronic, some not – exhibiting negative feedback:

- A voltage regulating circuit
- An auto-pilot system for an aircraft or boat
- A thermostatic temperature control system ("thermostat")
- Emitter resistor in a BJT amplifier circuit
- Lenz's Law demonstration (magnetic damping of a moving object)
- Body temperature of a mammal
- Natural regulation of prices in a free market economy (Adam Smith's "invisible hand")
- A scientist learning about the behavior of a natural system through experimentation.

For each case, answer the following questions:

- What variable is being stabilized by negative feedback?
- How is the feedback taking place (step by step)?
- What would the system's response be like if negative feedback were not present?

file 02253

Answer 47

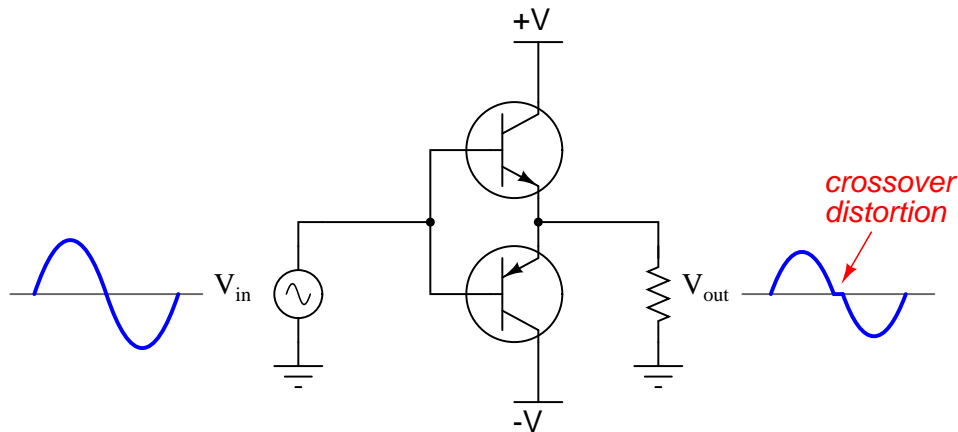
I will provide answers for only one of the examples, the voltage regulator:

- What variable is being stabilized by negative feedback?
Output voltage.
- How is the feedback taking place (step by step)?
When output voltage rises, the system takes action to drop more voltage internally, leaving less for the output.
- What would the system's response be like if negative feedback were not present?
Without negative feedback, the output voltage would rise and fall directly with the input voltage, and inversely with the load current.

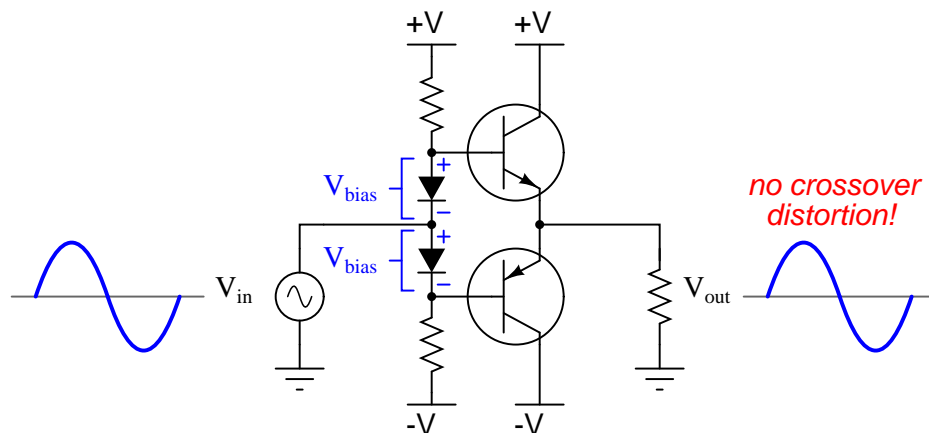
Notes 47

It is difficult to overstate the importance of grasping negative feedback in the study of electronics. So many different types of systems depend on it for their operation that it cannot be omitted from any serious electronics curriculum. Yet I see many textbooks fail to explore this principle in adequate depth, or discuss it in a mathematical sense only where students are likely to miss the basic concept because they will be too focused on solving the equations.

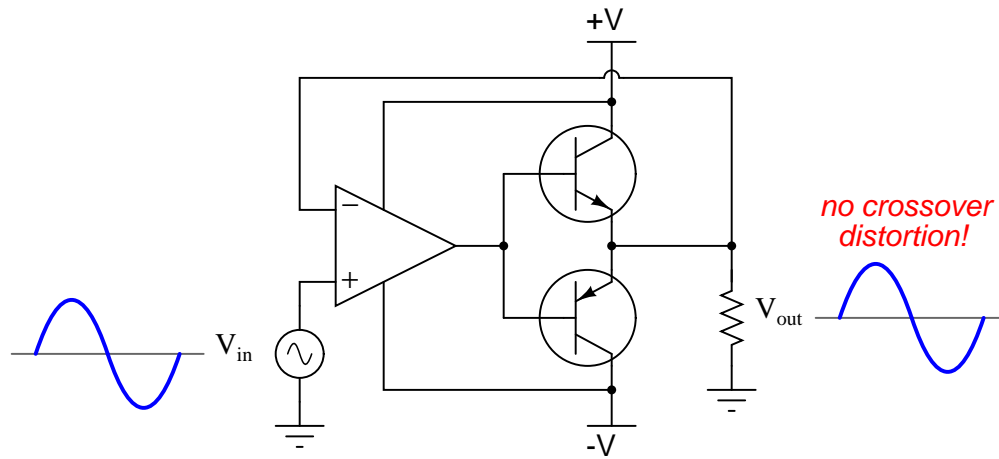
A complementary push-pull transistor amplifier built exactly as shown would perform rather poorly, exhibiting crossover distortion:



The simplest way to reduce or eliminate this distortion is by adding some bias voltage to each of the transistors' inputs, so there will never be a period of time when the two transistors are simultaneously cutoff:



One problem with this solution is that just a little too much bias voltage will result in overheating of the transistors, as they simultaneously conduct current near the zero-crossing point of the AC signal. A more sophisticated method of mitigating crossover distortion is to use an opamp with negative feedback, like this:



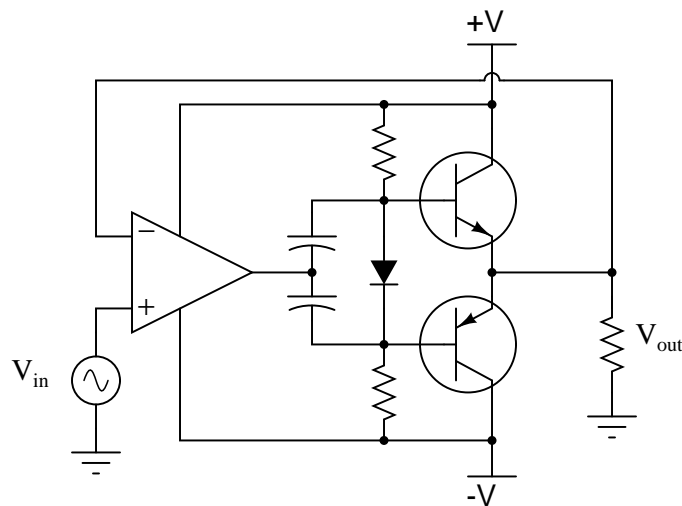
Explain how the opamp is able to eliminate crossover distortion in this push-pull amplifier circuit without the need for biasing.

file 02291

Answer 48

By sensing V_{out} , the opamp is able to "tell" whether or not the output voltage matches the input voltage, so it can drive the transistors as hard as they need to be driven to get the output voltage where it should be.

Challenge question: a more practical design blends the two strategies like this:



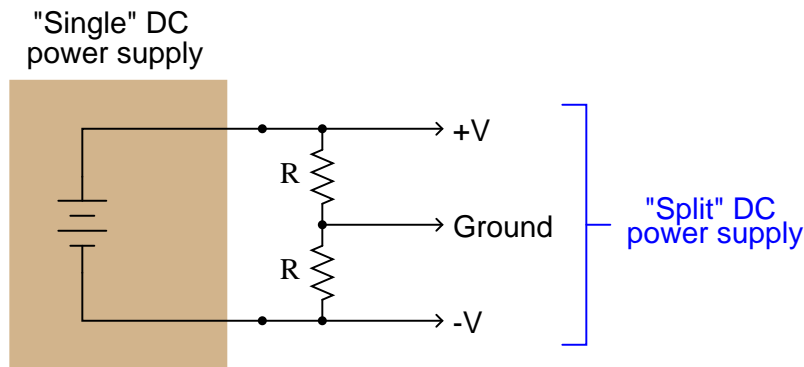
Explain why using less bias voltage *and* negative feedback with an opamp results in better performance than either method used alone.

Much could be said about good amplifier circuit design in this question, but the fundamental point is for students to see how negative feedback coupled with the extremely high gain of the opamp minimizes crossover distortion. Be sure to focus students' attention on that point until they understand it well before launching into a discussion about the finer points of amplifier design.

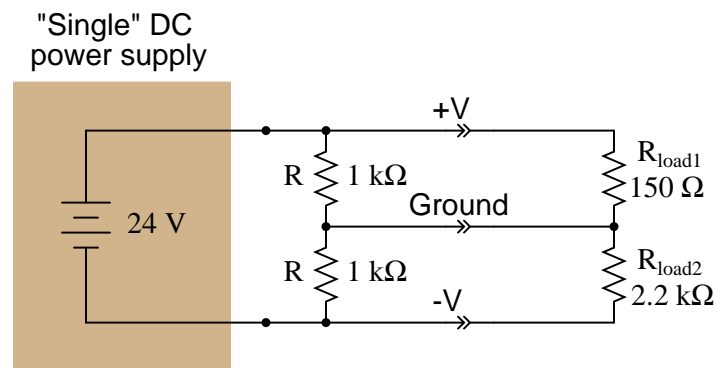
It should be noted that this solution to crossover distortion in a push-pull amplifier circuit does not always yield the best results. In order for the opamp to ensure a smooth transition between half-cycles, its output must jump about 1.4 volts *instantaneously* to go from turning one transistor off to turning the other transistor on. Of course, no opamp can do this, because all have slew rate limitations. So, there *will* still be some crossover distortion, but not nearly as much as without the opamp (and with far less quiescent power dissipation than the two-diode solution!).

Question 49

"Split" or "dual" DC power supplies are essential for powering many types of electronic circuits, especially certain types of operational amplifier circuits. If only a "single" DC power supply is not available, a "split" power supply may be roughly simulated through the use of a resistive voltage divider:



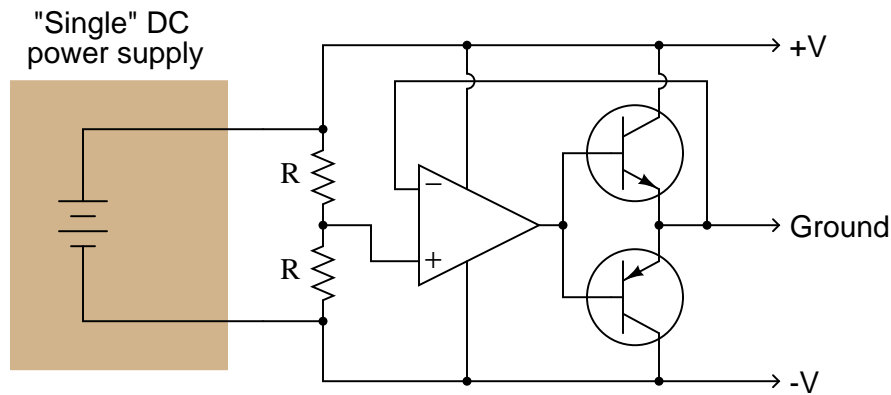
The problem with doing this is loading: if more current is drawn from one of the power supply rails than from the other, the "split" of voltage will become uneven. The only way that $+V$ and $-V$ will have the same (absolute) voltage value at the load is if the load impedance is balanced evenly between those rails and ground. This scenario is unlikely. Take for instance this example:



Voltage from $+V$ to Ground = 3.827 V

Voltage from $-V$ to Ground = -20.173 V

A simple opamp circuit, though, can correct this problem and maintain an even "split" of voltage between $+V$, Ground, and $-V$:



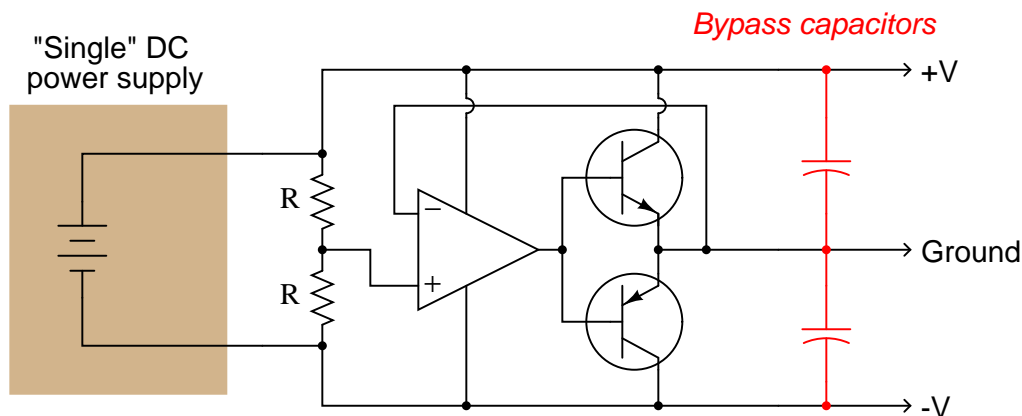
Explain how this circuit works. What function do the two resistors perform? How is negative feedback being used in this circuit?

[file 02293](#)

Answer 49

The two resistors establish a reference voltage exactly between +V and -V, which will be the "Ground" voltage seen by the load. The opamp keeps the actual Ground conductor at that reference potential through negative feedback, driving either transistor as hard as necessary to keep Ground potential centered between +V and -V.

Challenge question: if you plan on building this sort of circuit, placing a pair of bypass capacitors across the outputs is highly recommended. Explain why:

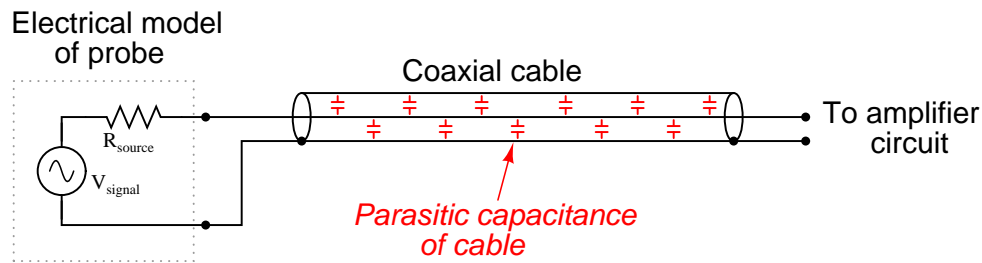


Notes 49

This circuit is not only worthwhile to discuss with your students as an example of negative feedback in action, but it is also practical for them to use as an impromptu power supply "splitter" when only a single supply is available. If you do decide to build this circuit, be careful of the transistors' power dissipations! Determine the maximum imbalance current to the load (how much current will be drawn through the Ground terminal), and then multiply that current by +V (or -V, absolute). This will be the maximum power dissipation value either transistor may have to safely handle.

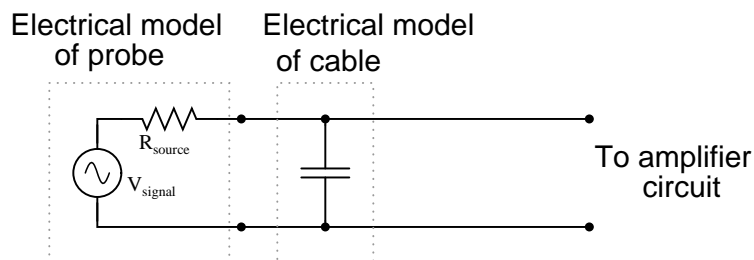
In response to the challenge question, the wisdom of the bypass capacitors will be evident if a pulsating load (such as a brush-type DC motor) is placed between either "rail" and Ground. The opamp must swing its output back and forth very rapidly to turn on each transistor fast enough to counter dips in voltage caused by the pulsating load. Capacitors naturally resist change in voltage, and so are ideal for mitigating such voltage dips, easing the burden placed on the opamp.

The parasitic capacitance naturally existing in two-wire cables can cause problems when connected to high-impedance electronic devices. Take for instance certain biomedical probes used to detect electrochemical events in living tissue. Such probes may be modeled as voltage sources in series with resistances, those resistances usually being rather large due to the probes' very small surface (contact) areas:



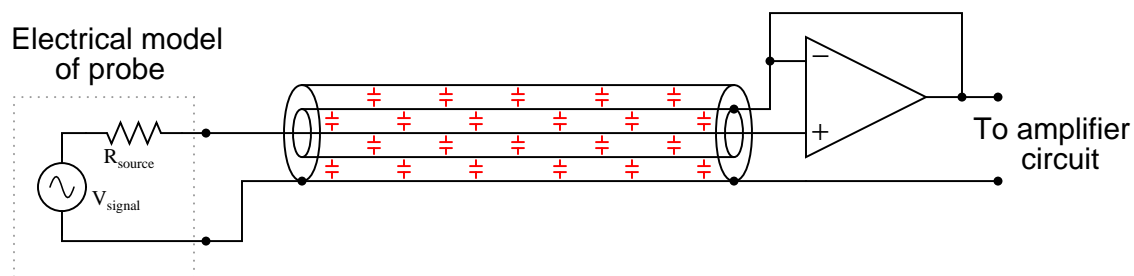
When connected to a cable with parasitic capacitance, a low-pass RC filter circuit is formed:

A low-pass filter is formed . . .

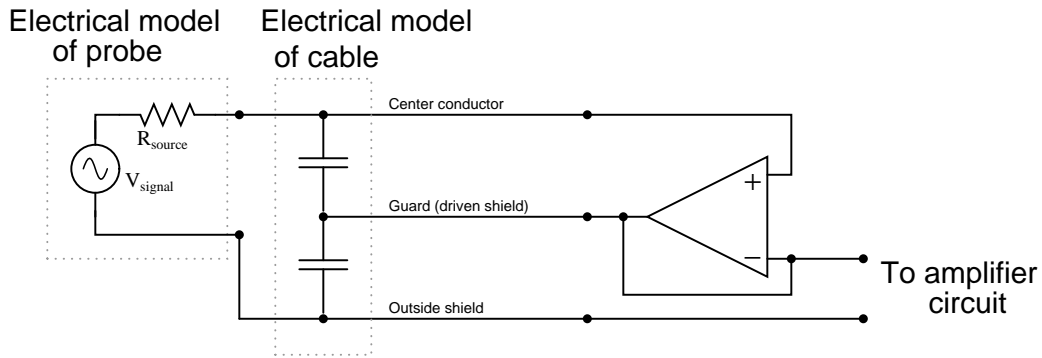


This low-pass filter (or passive integrator, if you wish) is purely unintentional. No one asked for it to be there, but it is there anyway just due to the natural resistance of the probe and the natural capacitance of the cable. Ideally, of course, we would like to be able to send the signal voltage (V_{signal}) straight to the amplifier with no interference or filtering of any kind so we can see exactly what it is we're trying to measure.

One clever way of practically eliminating the effects of cable capacitance is to encase the signal wire in its own shield, and then drive that shield with the exact same amount of voltage from a voltage follower at the other end of the cable. This is called *guarding*:



An equivalent schematic may make this technique more understandable:



Explain why guarding the signal wire effectively eliminates the effects of the cable's capacitance. Certainly the capacitance is still present, so how can it not have any effect on the weak signal any more?
[file 02292](#)

Answer 50

The guarding opamp holds the guard shield at the same potential as the center conductor, maintaining 0 volts across the parasitic capacitance between those two conductors. With no voltage across that capacitance, it might as well not even be there!

Follow-up question: although the center-to-guard capacitance may have zero volts across it at all times thanks to the opamp, the guard-to-(outer) shield capacitance still has the full signal voltage across it. Explain why this is of no concern to us, and why its presence does not form a low-pass filter as the original (unguarded) cable capacitance once did.

Notes 50

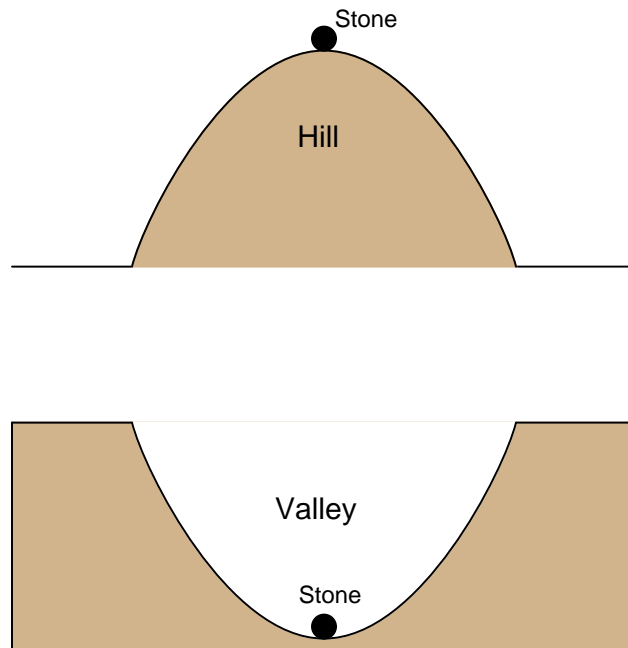
Guarding is a technique used in many test and measurement scenarios, and it serves as a great example of opamps used as voltage followers.

If students are not convinced of the seriousness of cable capacitance in an application such as the one described, suggest these values to them and ask them to calculate the cutoff frequency of the low-pass filter formed by R_{signal} and C_{cable} :

- $R_{\text{signal}} = 20 \text{ M}\Omega$
- $C_{\text{cable}} = 175 \text{ pF}$

Question 51

One analogy used to explain and contrast negative feedback versus positive feedback is that of a round stone, placed on either a hilltop or a valley:



The stability of the stone in each of these scenarios represents the stability of a specific type of electrical feedback system. Which of these scenarios represents negative feedback, which represents positive feedback, and why?

file 01149

Answer 51

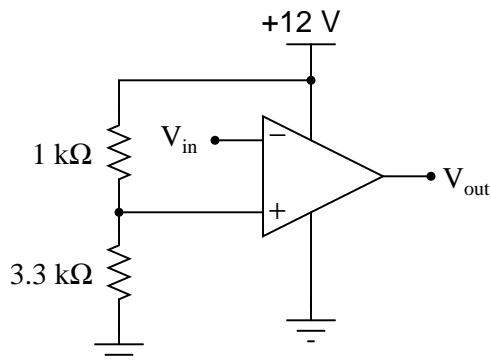
The valley represents negative feedback, while the hill represents positive feedback.

Notes 51

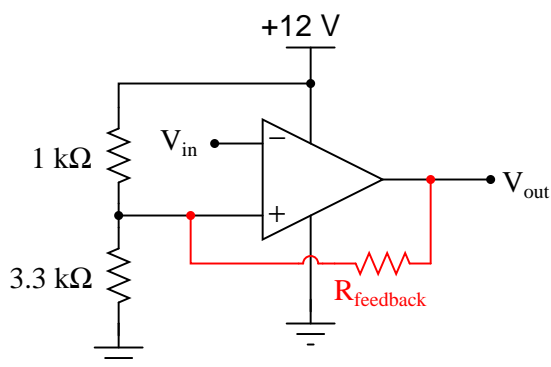
I have found this simple analogy to be most helpful when explaining feedback systems to students, because the behavior of each is intuitively obvious.

Question 52

Determine the "trip" voltage of this comparator circuit: the value of input voltage at which the opamp's output changes state from fully positive to fully negative or visa-versa:



Now, what do you suppose would happen if the output were fed back to the noninverting input through a resistor? Your answer merely has to be qualitative, not quantitative:



For your information, this circuit configuration is often referred to as a *Schmitt trigger*.
[file 02294](#)

Answer 52

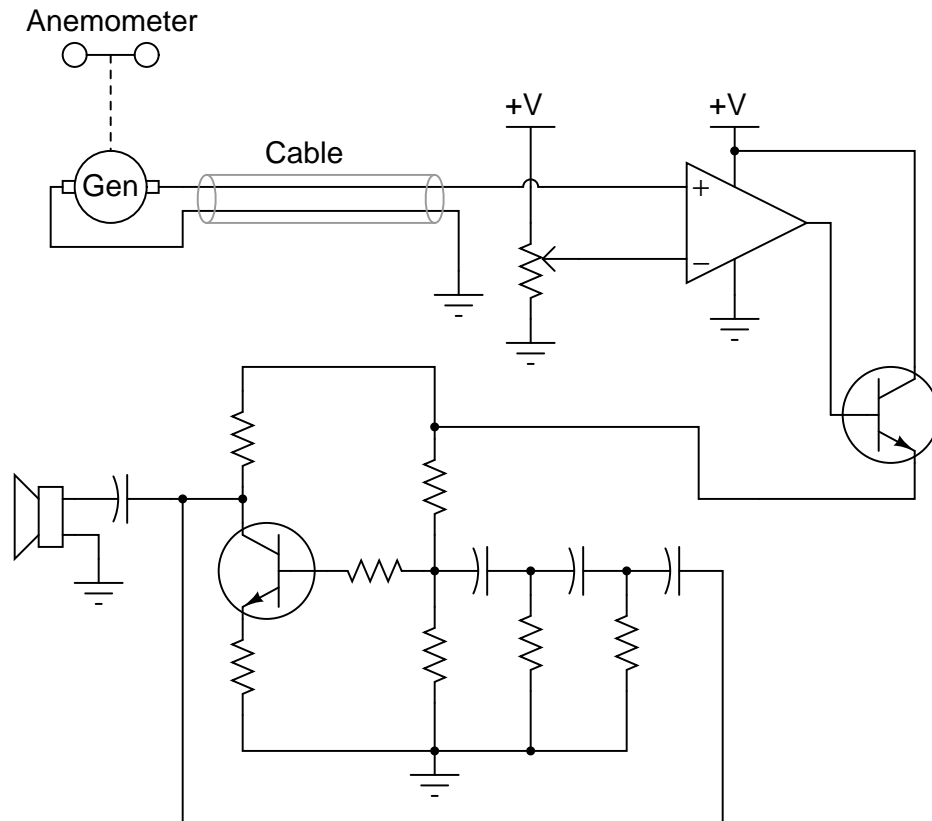
With no feedback resistor, the "trip" voltage would be 9.21 volts. With the feedback resistor in place, the "trip" voltage would change depending on the state of the opamp's output!

Follow-up question: describe what effect this changing "trip" voltage value will have on the operation of this comparator circuit.

Notes 52

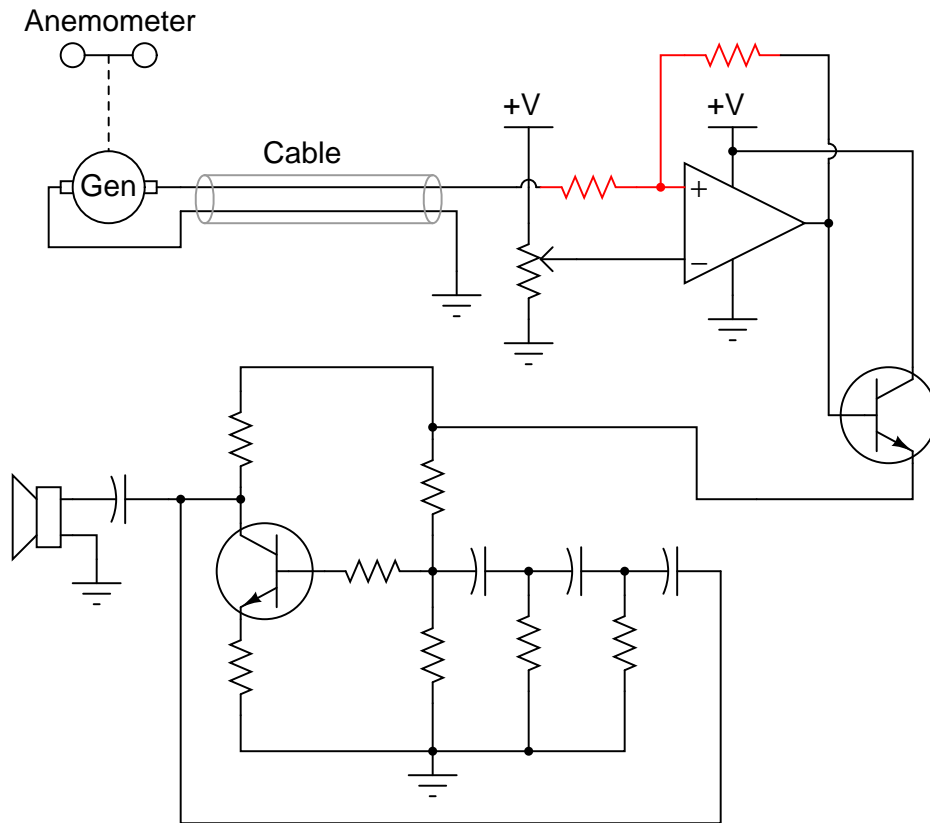
Schmitt trigger circuits are very popular for their ability to "cleanly" change states given a noisy input signal. I have intentionally avoided numerical calculations in this question, so that students may concentrate on the *concept* of positive feedback and how it affects this circuit.

A comparator is used as a high wind speed alarm in this circuit, triggering an audio tone to sound whenever the wind speed exceeds a pre-set alarm point:



The circuit works well to warn of high wind speed, but when the wind speed is just near the threshold level, every little gust causes the alarm to briefly sound, then turn off again. What would be better is for the alarm to sound at a set wind speed, then *stay on* until the wind speed falls below a substantially lower threshold value (example: alarm at 60 km/h, reset at 50 km/h).

An experienced electronics technician decides to add this functionality to the circuit by adding two resistors:



Explain why this circuit alteration works to solve the problem.
[file 01168](#)

Answer 53

The added resistors provide *positive feedback* to the opamp circuit, causing it to exhibit hysteresis.

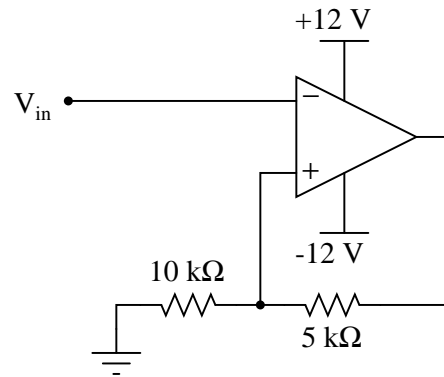
Challenge question: suppose you wished to increase the gap between the upper and lower alarm thresholds. What resistor value(s) would you have to alter to accomplish this adjustment?

Notes 53

A practical illustration for positive feedback in an opamp circuit. There is much to discuss here, even beyond the immediate context of positive feedback. Take for instance the oscillator circuit and on/off control transistor. For review, ask your students to explain how both these circuit sections function.

Question 54

Assume that the comparator in this circuit is capable of "swinging" its output fully from rail to rail. Calculate the upper and lower threshold voltages, given the resistor values shown:



$$V_{UT} = \qquad V_{LT} =$$

[file 01169](#)

Answer 54

$$V_{UT} = +8 \text{ volts}$$

$$V_{LT} = -8 \text{ volts}$$

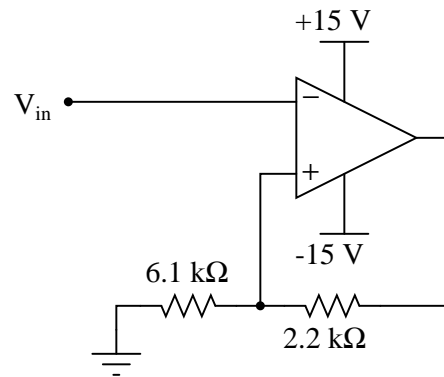
Challenge question: how would you recommend we change the circuit to give threshold voltages of +6 volts and -6 volts, respectively?

Notes 54

Ask your students to explain what the terms "upper threshold" and "lower threshold" mean with regard to input voltage in a circuit such as this.

Question 55

Assume that the comparator in this circuit is only capable of "swinging" its output to within 1 volt of its power supply rail voltages. Calculate the upper and lower threshold voltages, given the resistor values shown:



$$V_{UT} = \qquad V_{LT} =$$

file 01170

Answer 55

$$V_{UT} = +10.29 \text{ volts}$$

$$V_{LT} = -10.29 \text{ volts}$$

Challenge question: how would you recommend we change the circuit so that its threshold voltages are centered around some voltage value other than zero?

Notes 55

As many opamps and comparators are incapable of rail-to-rail output swings, this question is quite realistic.

Competency: BJT differential amplifier		Version:												
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Schematic</div>														
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Given conditions</div> <div style="display: flex; justify-content: space-around; align-items: flex-start;"> <div style="text-align: center;"> $V_{CC} =$ </div> <div style="text-align: center;"> $R_1 = R_2 =$ </div> <div style="text-align: center;"> $R_{prg} =$ </div> </div> <div style="text-align: center; margin-top: 10px;"> $R_{pot1} = R_{pot2} =$ </div>														
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Parameters</div> <table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 15%;"></th> <th style="width: 20%; text-align: center;">Predicted</th> <th style="width: 20%; text-align: center;">Measured</th> </tr> </thead> <tbody> <tr> <td>$I_C (Q_6)$</td> <td style="border: 1px solid black; height: 25px;"></td> <td style="border: 1px solid black; height: 25px;"></td> </tr> <tr> <td colspan="3" style="padding-top: 10px;"> Which transistor does the inverting input belong to? </td> </tr> <tr> <td colspan="3" style="padding-top: 10px;"> Which transistor does the non-inverting input belong to? </td> </tr> </tbody> </table>				Predicted	Measured	$I_C (Q_6)$			Which transistor does the inverting input belong to? 			Which transistor does the non-inverting input belong to? 		
	Predicted	Measured												
$I_C (Q_6)$														
Which transistor does the inverting input belong to? 														
Which transistor does the non-inverting input belong to? 														

file 01997

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

Notes 56

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

I suggest using ordinary (general-purpose) signal transistors in this circuit, such as the 2N2222 and 2N3403 (NPN), and the 2N2907 and 2N3906 (PNP) models, operating with a V_{CC} of 12 volts. When constructed as shown, this circuit has sufficient gain to be used as a crude operational amplifier (connect the inverting input to the output through various feedback networks).

These values have worked well for me:

- $V_{CC} = 12$ volts
- $R_1 = 10$ k Ω
- $R_2 = 10$ k Ω
- $R_{prg} = 10$ k Ω
- $R_{pot1} = 10$ k Ω
- $R_{pot2} = 10$ k Ω

I recommend instructing students to set each potentiometer near its mid-position of travel, then slightly adjusting each one to see the sharp change in output voltage as one input voltage crosses the other. If students wish to monitor each of the input voltages to check for a condition of crossing, they should measure right at the transistor base terminals, not at the potentiometer wiper terminals, so as to not incur error resulting from current through protection resistors R_1 or R_2 .

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: Voltage comparator	Version:																									
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Schematic</div> <div style="text-align: center; margin-top: 20px;"> </div>																										
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Given conditions</div> <div style="margin-top: 20px;"> $+V =$ $R_{pot1} = R_{pot2} =$ </div>																										
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Parameters</div> <table style="width: 100%; border-collapse: collapse; margin-top: 10px;"> <thead> <tr> <th></th> <th style="text-align: center; padding: 5px;">Predicted</th> <th style="text-align: center; padding: 5px;">Measured</th> <th></th> <th></th> </tr> </thead> <tbody> <tr> <td style="text-align: right; padding: 5px;">V_{out}</td> <td style="border: 1px solid black; width: 80px; height: 30px;"></td> <td style="border: 1px solid black; width: 80px; height: 30px;"></td> <td style="padding: 5px;">$V_{in(+)} =$ _____</td> <td style="padding: 5px;">$V_{in(-)} =$ _____</td> </tr> <tr> <td style="text-align: right; padding: 5px;">V_{out}</td> <td style="border: 1px solid black; width: 80px; height: 30px;"></td> <td style="border: 1px solid black; width: 80px; height: 30px;"></td> <td style="padding: 5px;">$V_{in(+)} =$ _____</td> <td style="padding: 5px;">$V_{in(-)} =$ _____</td> </tr> <tr> <td style="text-align: right; padding: 5px;">V_{out}</td> <td style="border: 1px solid black; width: 80px; height: 30px;"></td> <td style="border: 1px solid black; width: 80px; height: 30px;"></td> <td style="padding: 5px;">$V_{in(+)} =$ _____</td> <td style="padding: 5px;">$V_{in(-)} =$ _____</td> </tr> <tr> <td style="text-align: right; padding: 5px;">V_{out}</td> <td style="border: 1px solid black; width: 80px; height: 30px;"></td> <td style="border: 1px solid black; width: 80px; height: 30px;"></td> <td style="padding: 5px;">$V_{in(+)} =$ _____</td> <td style="padding: 5px;">$V_{in(-)} =$ _____</td> </tr> </tbody> </table>			Predicted	Measured			V_{out}			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____	V_{out}			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____	V_{out}			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____	V_{out}			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____
	Predicted	Measured																								
V_{out}			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____																						
V_{out}			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____																						
V_{out}			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____																						
V_{out}			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____																						
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Fault analysis</div> <div style="margin-top: 10px;"> <p>Suppose component fails <input type="checkbox"/> open <input type="checkbox"/> other _____</p> <p><input type="checkbox"/> shorted</p> <p><i>What will happen in the circuit?</i></p> </div>																										

file 01999

Answer 57

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

Notes 57

You may wish to use either an operational amplifier or a true comparator for this exercise. Whether or not the specific device has rail-to-rail output swing capability is your choice as well.

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: Opamp voltage follower		Version:																										
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Schematic</div> <div style="text-align: center; margin-top: 20px;"> </div>																												
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Given conditions</div> <div style="display: flex; justify-content: space-around; margin-top: 10px;"> <div>$+V =$</div> <div>$R_{\text{pot}} =$</div> <div>$V_{\text{TP1}} =$</div> </div> <div style="margin-top: 10px;">$-V =$</div>																												
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Parameters</div> <table style="width: 100%; border-collapse: collapse; margin-top: 10px;"> <thead> <tr> <th style="width: 40%;"></th> <th style="width: 15%; text-align: center;">Predicted</th> <th style="width: 15%; text-align: center;">Measured</th> <th style="width: 30%;"></th> </tr> </thead> <tbody> <tr> <td>V_{out}</td> <td><input style="width: 80%;" type="text"/></td> <td><input style="width: 80%;" type="text"/></td> <td rowspan="3"> Inverting . . . <input style="width: 40px;" type="checkbox"/> or noninverting? <input style="width: 40px;" type="checkbox"/> </td> </tr> <tr> <td>A_V (ratio)</td> <td><input style="width: 80%;" type="text"/></td> <td><input style="width: 80%;" type="text"/></td> </tr> <tr> <td>A_V (dB)</td> <td><input style="width: 80%;" type="text"/></td> <td><input style="width: 80%;" type="text"/></td> </tr> <tr> <td>V_{TP1} resulting in <i>latch-up</i></td> <td colspan="2"><input style="width: 100%;" type="text"/></td> <td></td> </tr> <tr> <td colspan="4" style="text-align: center; margin-top: 10px;">Measured</td> </tr> <tr> <td>Rail-to-rail output swing?</td> <td colspan="3"> <input style="width: 60px;" type="text"/> (Yes/No) </td> </tr> </tbody> </table>				Predicted	Measured		V_{out}	<input style="width: 80%;" type="text"/>	<input style="width: 80%;" type="text"/>	Inverting . . . <input style="width: 40px;" type="checkbox"/> or noninverting? <input style="width: 40px;" type="checkbox"/>	A_V (ratio)	<input style="width: 80%;" type="text"/>	<input style="width: 80%;" type="text"/>	A_V (dB)	<input style="width: 80%;" type="text"/>	<input style="width: 80%;" type="text"/>	V_{TP1} resulting in <i>latch-up</i>	<input style="width: 100%;" type="text"/>			Measured				Rail-to-rail output swing?	<input style="width: 60px;" type="text"/> (Yes/No)		
	Predicted	Measured																										
V_{out}	<input style="width: 80%;" type="text"/>	<input style="width: 80%;" type="text"/>	Inverting . . . <input style="width: 40px;" type="checkbox"/> or noninverting? <input style="width: 40px;" type="checkbox"/>																									
A_V (ratio)	<input style="width: 80%;" type="text"/>	<input style="width: 80%;" type="text"/>																										
A_V (dB)	<input style="width: 80%;" type="text"/>	<input style="width: 80%;" type="text"/>																										
V_{TP1} resulting in <i>latch-up</i>	<input style="width: 100%;" type="text"/>																											
Measured																												
Rail-to-rail output swing?	<input style="width: 60px;" type="text"/> (Yes/No)																											

file 01968

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

Use a dual-voltage, regulated power supply to supply power to the opamp.

I have had good success using the following values:

- $+V = +12$ volts
- $-V = -12$ volts
- V_{TP1} = Any voltage well between $+V$ and $-V$
- $R_{pot} = 10$ k Ω linear potentiometer
- U_1 = TL081 BiFET operational amplifier (or one-half of a TL082)

In order to demonstrate latch-up, you must have an op-amp capable of latching up. Thus, you should avoid op-amps such as the LM741 and LM1458. I recommend using an op-amp such as the TL082 for this exercise because it not only latches up, but also does not swing its output voltage rail-to-rail. Students need to see both these common limitations when they first learn how to use op-amps.

In case your students ask, test point **TP1** is for measuring the output of the potentiometer rather than as a place to inject external signals into. All you need to connect to **TP1** is a voltmeter!

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: Linear voltage regulator circuit		Version:
Schematic		
Given conditions		
$V_{\text{supply}} (\text{min}) =$	$R_1 =$	Load =
$V_{\text{supply}} (\text{max}) =$	$V_{\text{zener}} =$	$C_1 =$
Parameters		
	Predicted	Measured
$V_{\text{in}(+)}$		
V_{load}		
$V_{\text{B}} (Q_1)$		
		Calculated
		P_{Q1}
Fault analysis		
Suppose component fails <div style="display: inline-block; vertical-align: middle; margin-left: 10px;"> <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted </div>		
<i>What will happen in the circuit?</i>		

file 01998

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

Use a power transistor for this circuit, as general-purpose signal transistors may not have sufficient power dissipation ratings to survive the loading students may put them through! I recommend a small DC motor as a load. An electric motor offers an easy way to increase electrical loading by placing a mechanical load on the shaft. By doing this, students can see for themselves how well the circuit maintains load voltage (resisting voltage "sag" under increasing load current).

I have found that this circuit is excellent for getting students to understand how negative feedback really works. Here, the opamp adjusts the power transistor's base voltage to *whatever it needs to be* in order to maintain the load voltage at the same level as the reference set by the zener diode. Any sort of loss incurred by the transistor (most notably V_{BE}) is automatically compensated for by the opamp.

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. <i>What I did and/or noticed . . .</i>)	Conclusions (i.e. <i>What this tells me . . .</i>)

file 03933

Answer 60

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

Notes 60

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 61

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 61

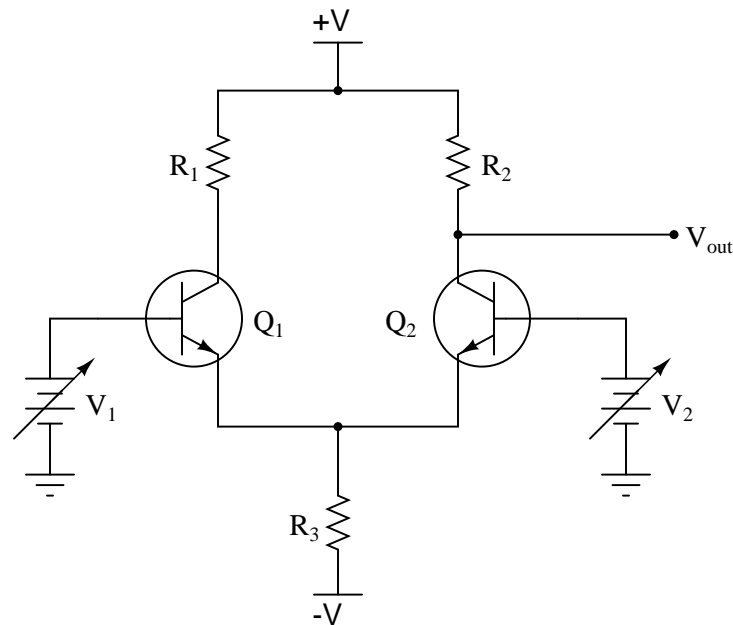
Be sure to document all steps taken and conclusions made in your troubleshooting!

Notes 61

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 62

Predict how the operation of this differential pair circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Resistor R_3 fails open:
- Solder bridge (short) across resistor R_3 :

For each of these conditions, explain *why* the resulting effects will occur.

[file 03764](#)

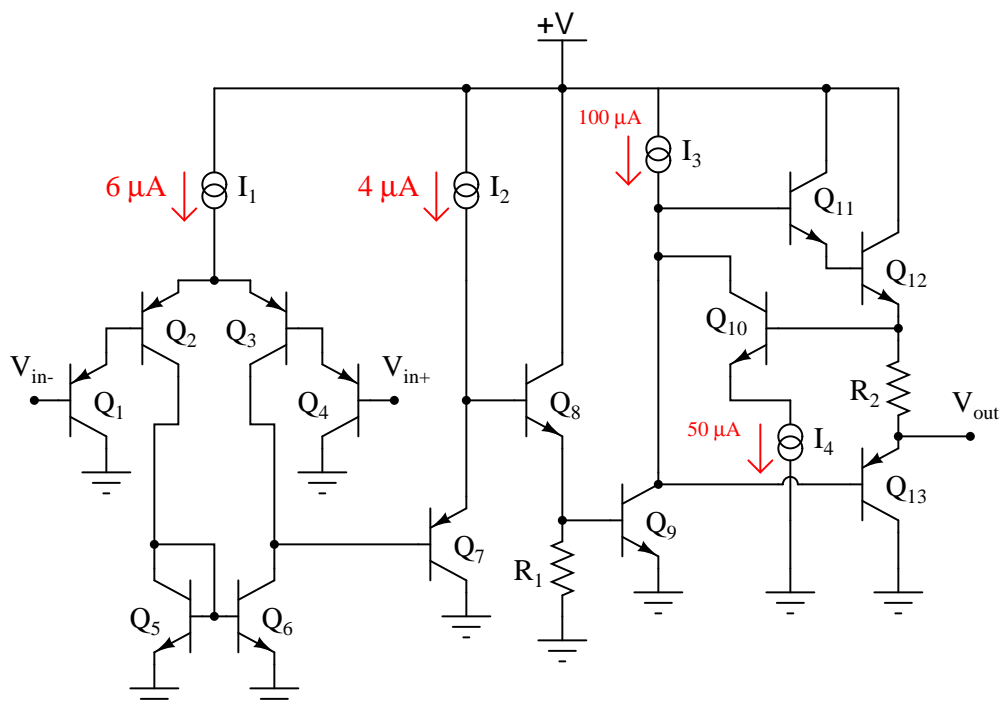
Answer 62

- Resistor R_1 fails open: *More current will be drawn from V_1 ; if V_1 sags as a result, V_{out} will decrease.*
- Resistor R_2 fails open: *V_{out} will assume a voltage level approximately equal to $V_2 - 0.7$ volts.*
- Resistor R_3 fails open: *V_{out} saturates to $+V$ (positive supply rail).*
- Solder bridge (short) across resistor R_3 : *V_{out} saturates to within a few tenths of a volt from $-V$ (negative supply rail).*

Notes 62

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

Predict how the operation of this operational amplifier circuit will be affected as a result of the following faults. Specifically, identify whether the output voltage (V_{out}) will move in a positive direction (closer to the +V rail) or in a negative direction (closer to ground). Consider each fault independently (i.e. one at a time, no multiple faults):



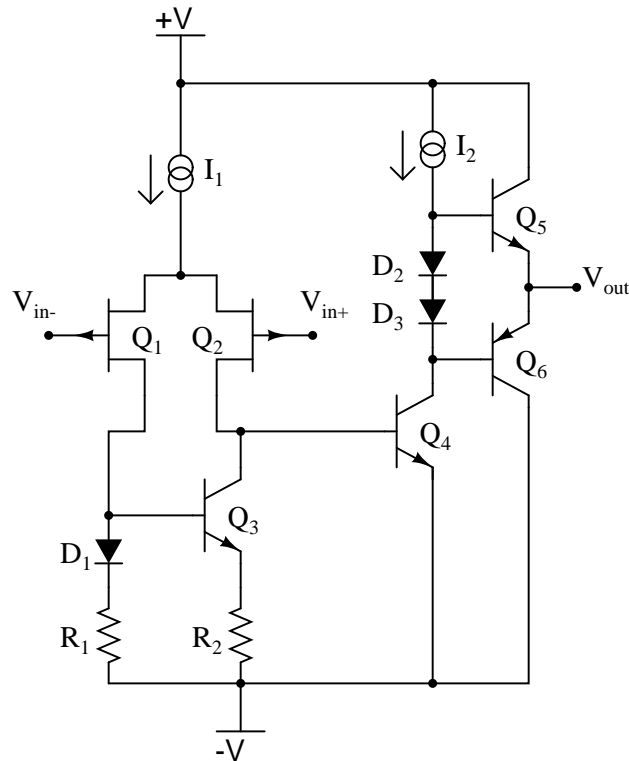
- For each of these conditions, explain *why* the resulting effects will occur.
- file 03765

- Transistor Q_5 fails shorted (collector-to-emitter): V_{out} goes negative.
- Transistor Q_6 fails shorted (collector-to-emitter): V_{out} goes positive.
- Resistor R_1 fails open: V_{out} goes negative.
- Current source I_2 fails shorted: V_{out} goes negative.

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

Question 64

Predict how the operation of this operational amplifier circuit will be affected as a result of the following faults. Specifically, identify whether the output voltage (V_{out}) will move in a positive direction (closer to the $+V$ rail) or in a negative direction (closer to the $-V$ rail). Consider each fault independently (i.e. one at a time, no multiple faults):



- Diode D_1 fails open:
- Resistor R_1 fails shorted:
- Transistor Q_2 fails shorted (drain-to-source):
- Transistor Q_5 fails shorted (collector-to-emitter):
- Resistor R_2 fails open:
- Current source I_2 fails open:

For each of these conditions, explain *why* the resulting effects will occur.
[file 03766](#)

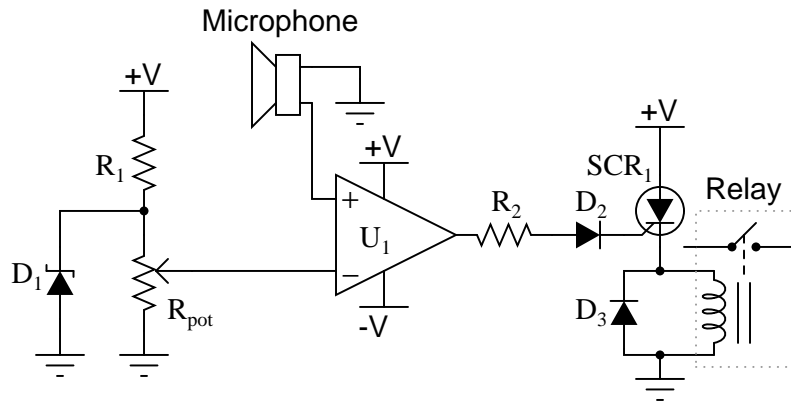
- Diode D_1 fails open: V_{out} goes positive.
- Resistor R_1 fails shorted: V_{out} goes negative.
- Transistor Q_2 fails shorted (drain-to-source): V_{out} goes negative.
- Transistor Q_5 fails shorted (collector-to-emitter): V_{out} goes positive.
- Resistor R_2 fails open: V_{out} goes negative.
- Current source I_2 fails open: V_{out} goes negative.

Notes 64

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

Question 65

Predict how the operation of this sound-activated relay circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



- Zener diode D_1 fails open:
- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Microphone voice coil fails open:
- Comparator U_1 fails with output saturated positive:
- Diode D_3 fails shorted:

For each of these conditions, explain *why* the resulting effects will occur.

file 03767

Answer 65

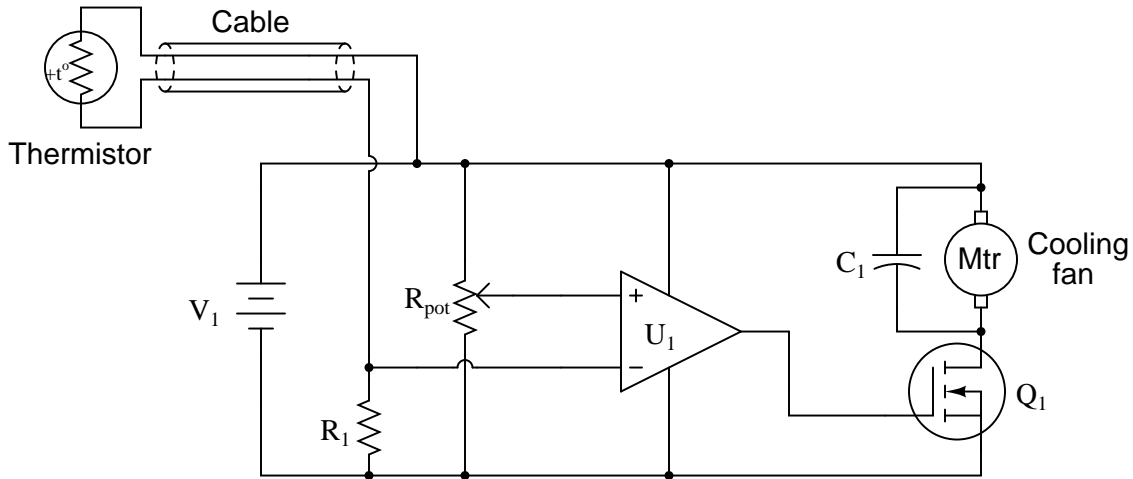
- Zener diode D_1 fails open: *Volume threshold increases (relay may not energize at all).*
- Resistor R_1 fails open: *Any sound at all will energize the relay.*
- Resistor R_2 fails open: *Relay refuses to energize.*
- Microphone voice coil fails open: *Relay energizes randomly, as comparator input is now sensitive to static electricity.*
- Comparator U_1 fails with output saturated positive: *Relay immediately energizes, whether or not there is sound.*
- Diode D_3 fails shorted: *Relay refuses to energize, SCR will likely be damaged due to overheating after a sound event.*

Notes 65

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

Question 66

Predict how the operation of this thermostat circuit (where the cooling fan motor is supposed to turn on when the temperature gets too high) will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



- Cable fails open:
- Comparator U_1 fails with output saturated positive:
- Resistor R_1 fails open:
- Capacitor C_1 fails shorted:
- Transistor Q_1 fails shorted (drain-to-source):

For each of these conditions, explain *why* the resulting effects will occur.

file 03768

Answer 66

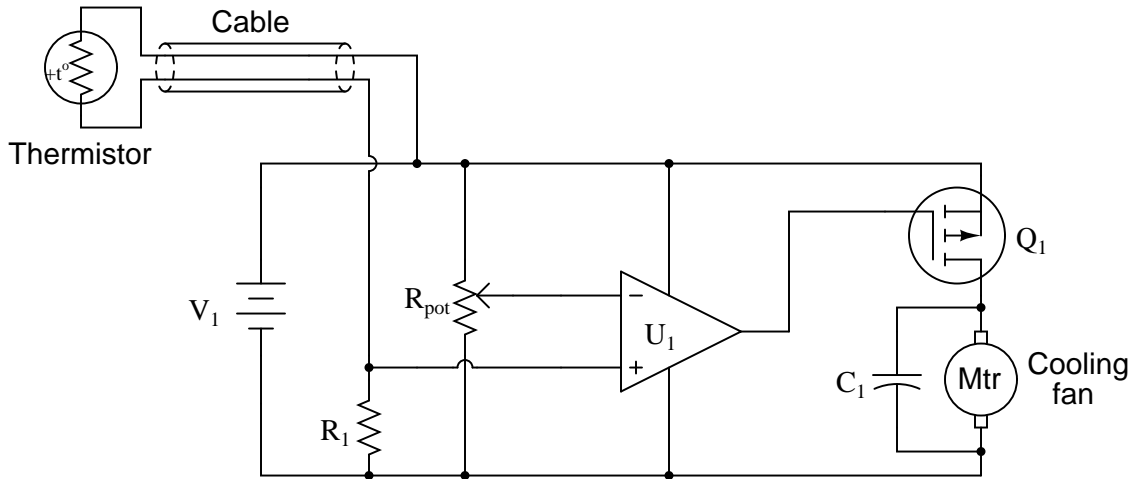
- Cable fails open: *Fan turns on and never turns off.*
- Comparator U_1 fails with output saturated positive: *Fan turns on and never turns off.*
- Resistor R_1 fails open: *Fan refuses to turn on.*
- Capacitor C_1 fails shorted: *Fan refuses to turn on, transistor Q_1 likely fails due to overheating when it tries to energize fan.*
- Transistor Q_1 fails shorted (drain-to-source): *Fan turns on and never turns off.*

Notes 66

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

Question 67

Predict how the operation of this thermostat circuit (where the cooling fan motor is supposed to turn on when the temperature gets too high) will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



- Cable fails open:
- Comparator U_1 fails with output saturated positive:
- Resistor R_1 fails open:
- Cable fails shorted:
- Transistor Q_1 fails shorted (drain-to-source):

For each of these conditions, explain *why* the resulting effects will occur.

file 03769

Answer 67

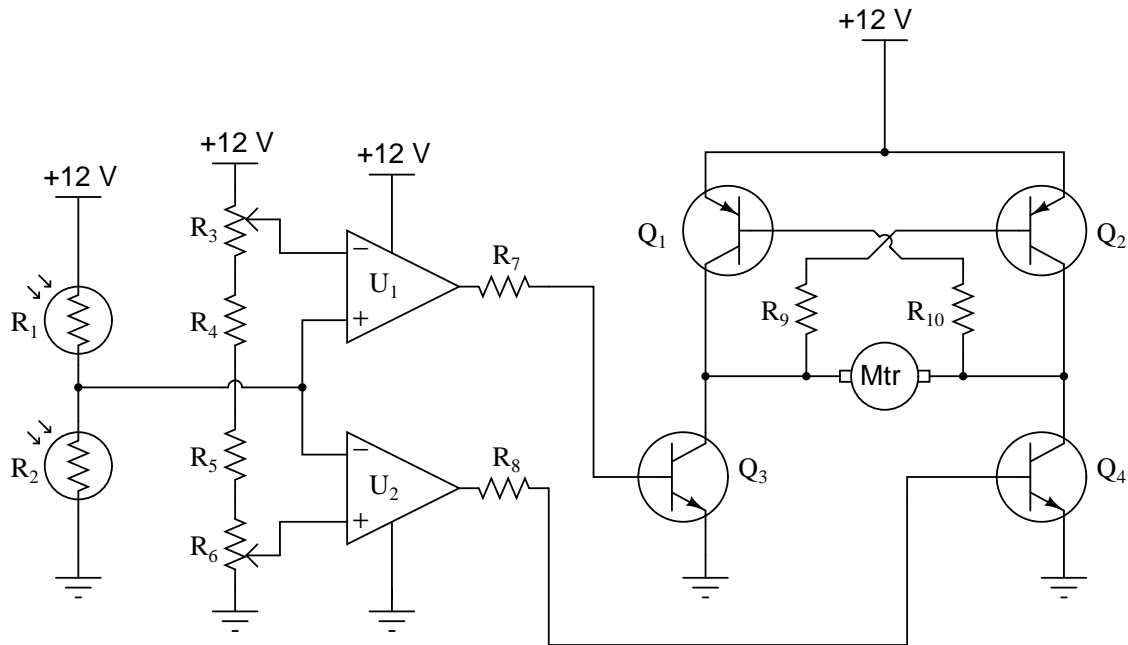
- Cable fails open: *Fan turns on and never turns off.*
- Comparator U_1 fails with output saturated positive: *Fan refuses to turn on.*
- Resistor R_1 fails open: *Fan refuses to turn on.*
- Cable fails shorted: *Fan refuses to turn on.*
- Transistor Q_1 fails shorted (drain-to-source): *Fan turns on and never turns off.*

Notes 67

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

Question 68

Predict how the operation of this solar panel tracking circuit (where the tracking motor turns in response to a difference in light sensed by the two photoresistors) will be affected as a result of the following faults. Assuming that the motor spins clockwise when its left terminal is negative and its right terminal is positive (when Q_2 and Q_3 are both on), specify the direction of rotation (or non-rotation) resulting from each fault. Consider each fault independently (i.e. one at a time, no multiple faults):



- Photoresistor R_1 fails open:
- Photoresistor R_2 fails open:
- Resistor R_4 fails open:
- Resistor R_5 fails open:
- Resistor R_7 fails open:
- Resistor R_{10} fails open:
- Transistor Q_3 fails open (collector-to-emitter):

For each of these conditions, explain *why* the resulting effects will occur.

file 03770

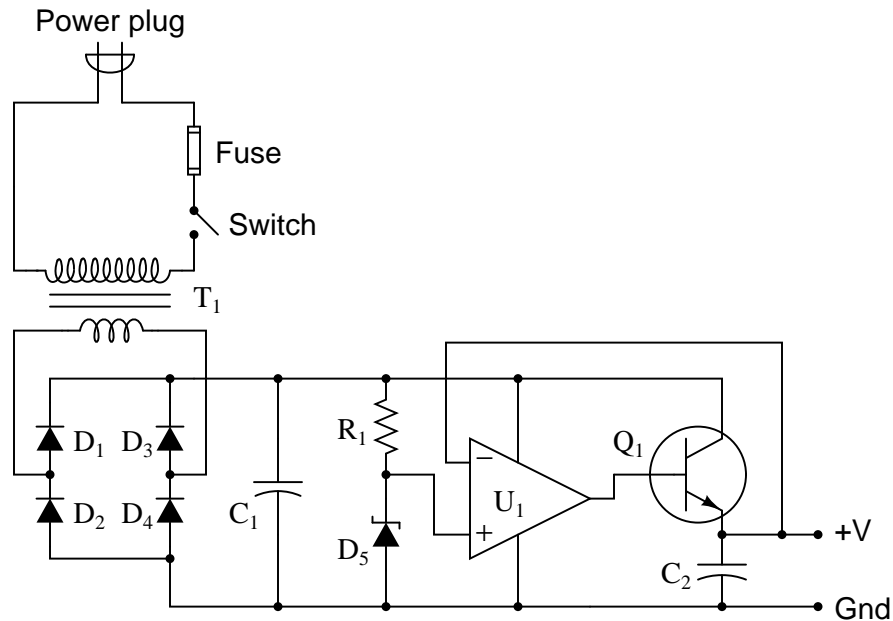
- Photoresistor R_1 fails open: *Motor continuously spins counter-clockwise.*
- Photoresistor R_2 fails open: *Motor continuously spins clockwise.*
- Resistor R_4 fails open: *Motor refuses to energize at all.*
- Resistor R_5 fails open: *Motor refuses to energize at all.*
- Resistor R_7 fails open: *Motor cannot spin clockwise, only counter-clockwise.*
- Resistor R_{10} fails open: *Motor cannot spin counter-clockwise, only clockwise.*
- Transistor Q_3 fails open (collector-to-emitter): *Motor cannot spin clockwise, only counter-clockwise.*

Notes 68

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

Question 69

Predict how the operation of this regulated power supply circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



- Transformer T_1 primary winding fails open:
- Rectifying diode D_3 fails open:
- Rectifying diode D_4 fails shorted:
- Resistor R_1 fails open:
- Zener diode D_5 fails open:
- Operational amplifier U_1 fails with output saturated positive:
- Transistor Q_1 fails open (collector-to-emitter):

For each of these conditions, explain *why* the resulting effects will occur.

file 03771

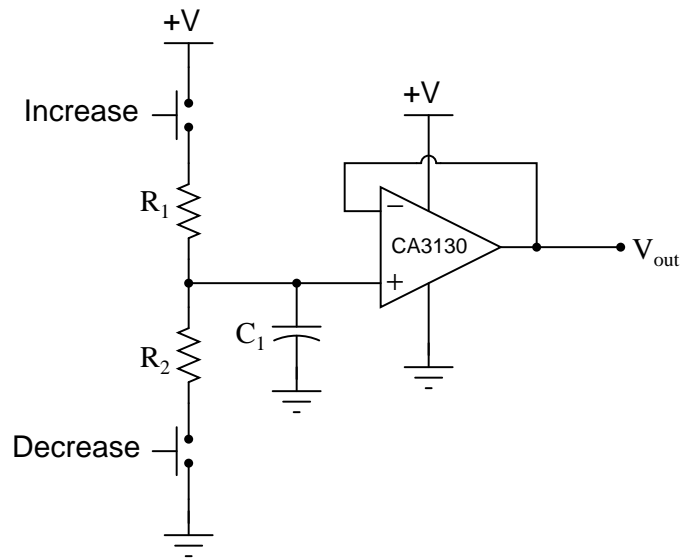
- Transformer T_1 primary winding fails open: *Output voltage falls to zero after filter capacitors C_1 and C_2 discharge.*
- Rectifying diode D_3 fails open: *No effect seen at no load, regulation falters sooner as load gets heavier.*
- Rectifying diode D_4 fails shorted: *Fuse may blow, diode D_2 may fail due to overheating (and quickly blow the fuse if it also fails shorted).*
- Resistor R_1 fails open: *Output voltage falls to zero after filter capacitor C_2 discharges.*
- Zener diode D_5 fails open: *Output voltage rises to nearly full (unregulated) value.*
- Operational amplifier U_1 fails with output saturated positive: *Output voltage rises to nearly full (unregulated) value.*
- Transistor Q_1 fails open (collector-to-emitter): *Output voltage falls to zero after filter capacitor C_2 discharges.*

Notes 69

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

Question 70

The purpose of this circuit is to provide a pushbutton-adjustable voltage. Pressing one button causes the output voltage to increase, while pressing the other button causes the output voltage to decrease. When neither button is pressed, the voltage remains stable:



After working just fine for quite a long while, the circuit suddenly fails: now it only outputs zero volts DC all the time.

An experienced technician first checks the power supply voltage to see if it is within normal limits, and it is. Then, the technician checks the voltage across the capacitor. Explain why this is a good test point to check, and what the results of that check would tell the technician about the nature of the fault.

file 03773

Answer 70

Checking for voltage across the capacitor will tell the technician what voltage the op-amp follower is being "told" to reproduce at the output.

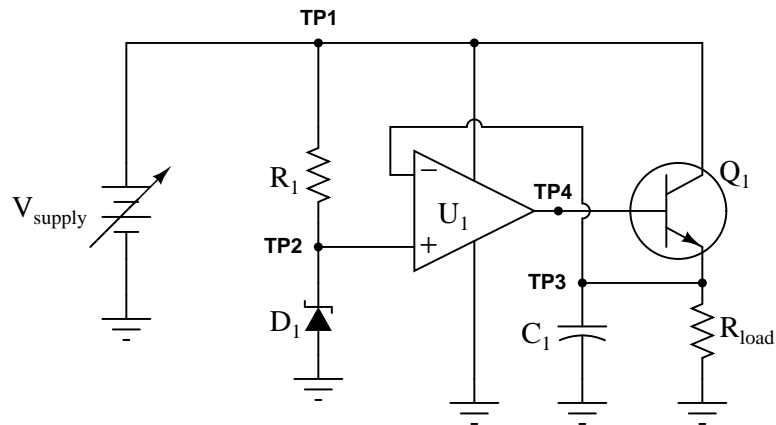
Challenge question: why do you suppose I specify a CA3130 operational amplifier for this particular circuit? What is special about this opamp that qualifies it for the task?

Notes 70

Knowing where to check for critical signals in a circuit is an important skill, because it usually means the difference between efficiently locating a fault and wasting time. Ask your students to explain in detail the rationale behind checking for voltage across the capacitor, and (again, in detail) what certain voltage measurements at that point would prove about the nature of the fault.

Question 71

This regulated power supply circuit has a problem. Instead of outputting 15 volts DC (exactly) as it should, it is outputting 0 volts DC to the load:



You measure 0.25 volts DC between TP4 and ground, and 20 volts between TP1 and ground, using your voltmeter. From this information, determine at least two independent faults that could cause this particular problem.

file 03772

Answer 71

Possible faults: (note that this list is not exhaustive)

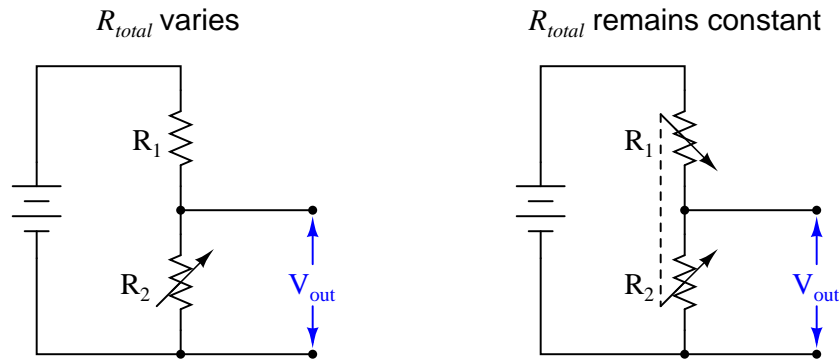
- Opamp (U_1) failed with output saturated negative.
- Zener diode (D_1) failed shorted.
- Resistor R_1 failed open.

Notes 71

Ask your students to explain their reasoning, as to why they chose the component faults that they did. Also, ask them to identify any components they think are working properly (beyond a doubt).

Question 72

Suppose we were to compare the performance of two voltage divider circuits side-by-side. The circuit on the left has one variable resistor (R_2), while the circuit on the right has two variable resistors (R_1 and R_2). The right-hand circuit's resistors are ganged together in such a way that as one resistance increases, the other will decrease by the same amount, keeping the circuit's total resistance constant:



Knowing that the voltage output by a voltage divider is described by the following formula, determine which voltage divider circuit yields the greatest change in output voltage for a given change in R_2 's resistance.

$$V_{out} = V_{battery} \left(\frac{R_2}{R_1 + R_2} \right)$$

file 02655

Answer 72

The voltage divider with the ganged rheostats will yield the greatest change in output voltage for a given change in R_2 's resistance, because only the numerator of the fraction in the voltage divider formula changes with R_2 , not the denominator as well.

Follow-up question #1: what happens to the amount of current in each circuit for a given change in R_2 resistance? Explain why.

Follow-up question #2: explain how a potentiometer performs the exact function as the second circuit with the two (complementarily) ganged rheostats.

Understanding the mathematical basis for the answer may be a significant leap for some students. If they experience trouble understanding how the voltage divider formula proves the answer, have them try a "thought experiment" with really simple numbers:

- Initial conditions:

$$R_1 = 1 \, \Omega$$

$$R_2 = 1 \, \Omega$$

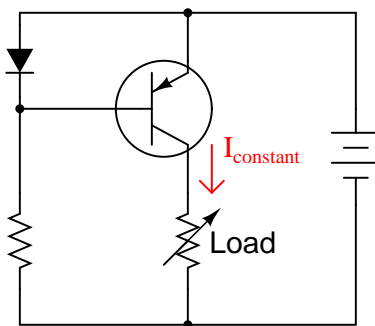
$$V_{battery} = 1 \text{ volt}$$

Now, increase R_2 from $1 \, \Omega$ to $2 \, \Omega$ and see which voltage divider circuit has experienced the greatest change in output voltage. Once these example quantities are placed into the respective formulae, it should become easy to see how the voltage divider formula explains the larger voltage swing of the second divider circuit.

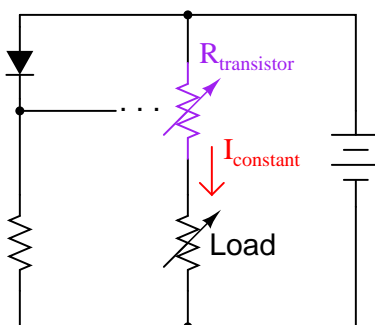
Point out to your students that this is an example of practical problem-solving: performing a "thought experiment" with really simple quantities to numerically explore how two different systems react to change. Although there is nothing particularly difficult about this technique, many students avoid it because they think there must be some easier way (a ready-made explanation, as opposed to a thought experiment of their own) to understand the concept. Getting students over this attitude barrier is a difficult yet crucial step in them developing self-teaching ability.

Question 73

The purpose of a *current mirror* circuit is to maintain constant current through a load despite changes in that load's resistance:



If we were to crudely model the transistor's behavior as an automatically-varied rheostat – constantly adjusting resistance as necessary to keep load current constant – how would you describe this rheostat's response to changes in load resistance?



In other words, as R_{load} increases, what does $R_{transistor}$ do – increase resistance, decrease resistance, or remain the same resistance it was before? How does the changing value of $R_{transistor}$ affect total circuit resistance?

[file 02656](#)

Answer 73

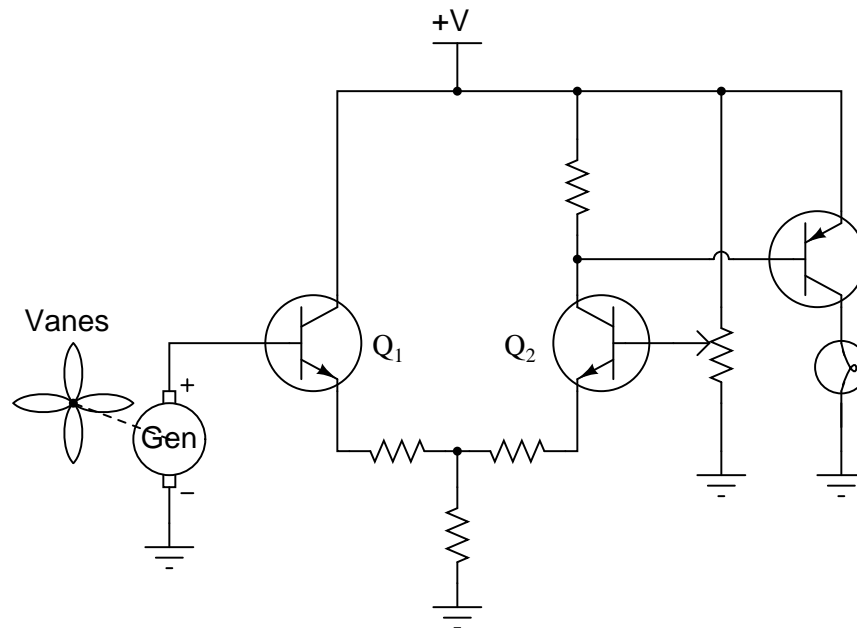
As R_{load} increases, $R_{transistor}$ will decrease in resistance so as to maintain a constant current through the load and a constant R_{total} .

Notes 73

This model of current mirror transistor behavior, albeit crude, serves as a good introduction to the subject of *active loads* in transistor amplifier circuits. This is where a transistor is configured to operate as a constant-current regulator, then placed in series with an amplifying transistor to yield much greater voltage gains than what is possible with a passive (fixed resistor) load.

Question 74

This circuit is part of a weather monitoring station. Wind speed is measured by the voltage output from a permanent-magnet DC generator, turned by a set of vanes. A light bulb lights up when the wind speed passes a threshold ("trip") value, established by the potentiometer:



Based on your understanding of differential pair circuits, is this a high-speed wind indicating circuit or a low-speed wind indicating circuit?

[file 00938](#)

Answer 74

The light bulb energizes when the wind speed decreases below the threshold value.

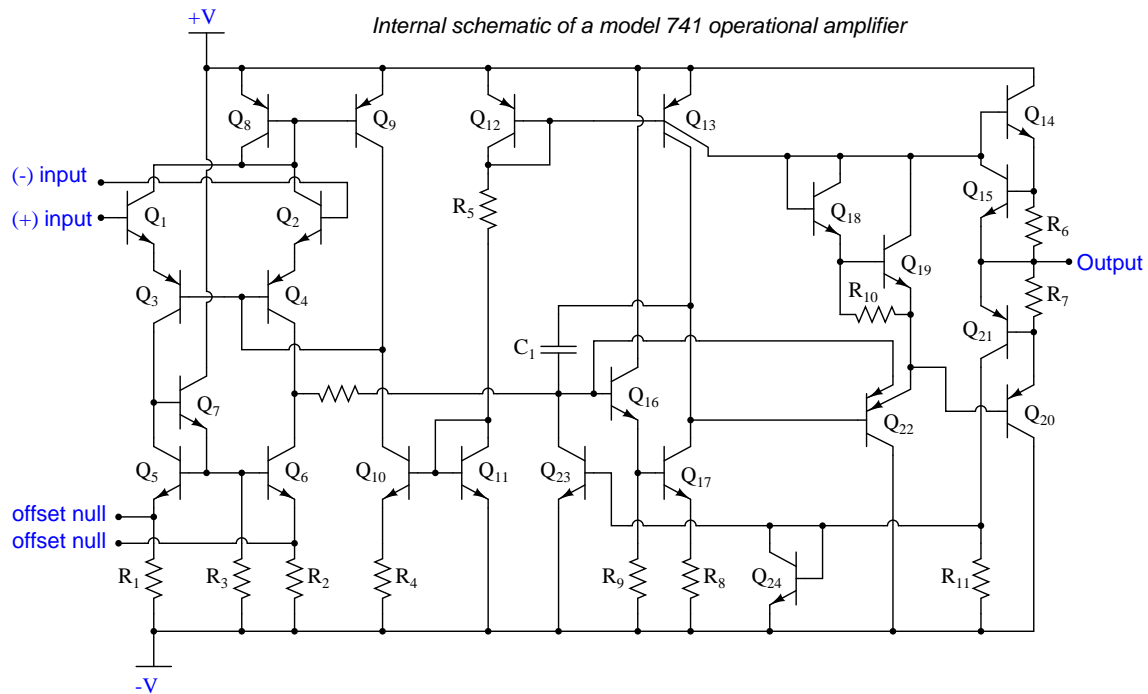
Notes 74

Ask your students to explain their reasoning in obtaining their answers. What happens in this circuit as the generator voltage increases, and as it decreases? Which way do we adjust the potentiometer to increase the trip point? How do we know this?

Let your students know that this circuit is a simple example of what is called a *comparator*: a circuit that compares two voltages against each other and generates an output corresponding to which voltage is greater.

Question 75

Identify as many active loads as you can in the following schematic of an LM741 operational amplifier circuit, along with their respective (amplifying) transistors:



[file 02659](#)

Answer 75

- Q_6 is an active load for Q_4
- Q_{23} is an active load for Q_{17}
- Q_{13} is an active load for Q_{17} and Q_{22}

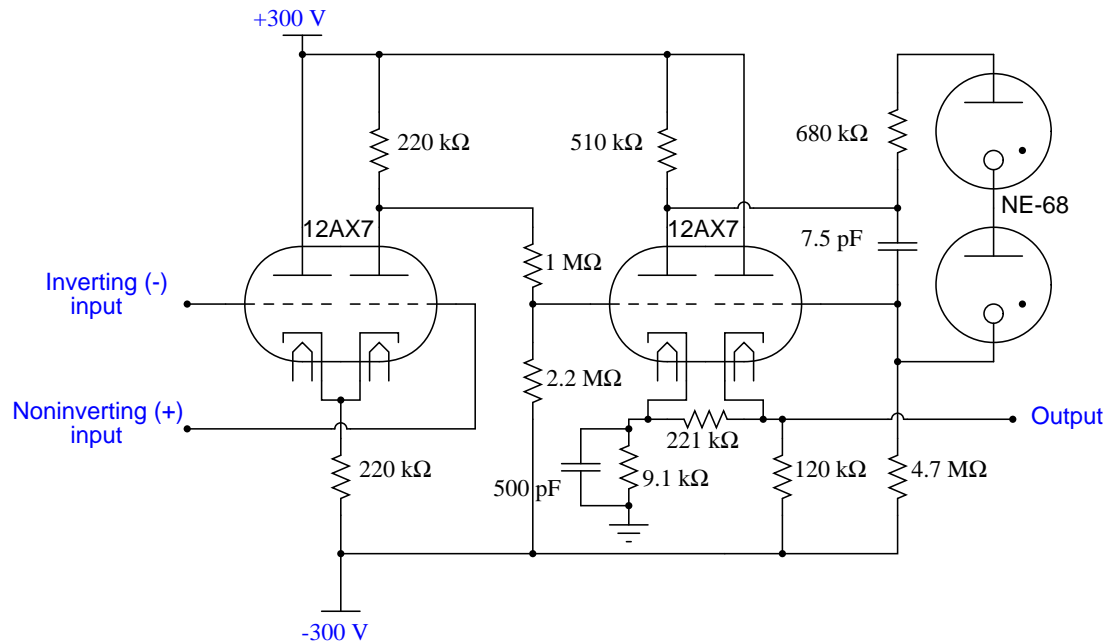
Notes 75

Even if students do not yet know what an "operational amplifier" circuit is, they should still be able to identify transistor stages, configurations, and active loads.

Question 76

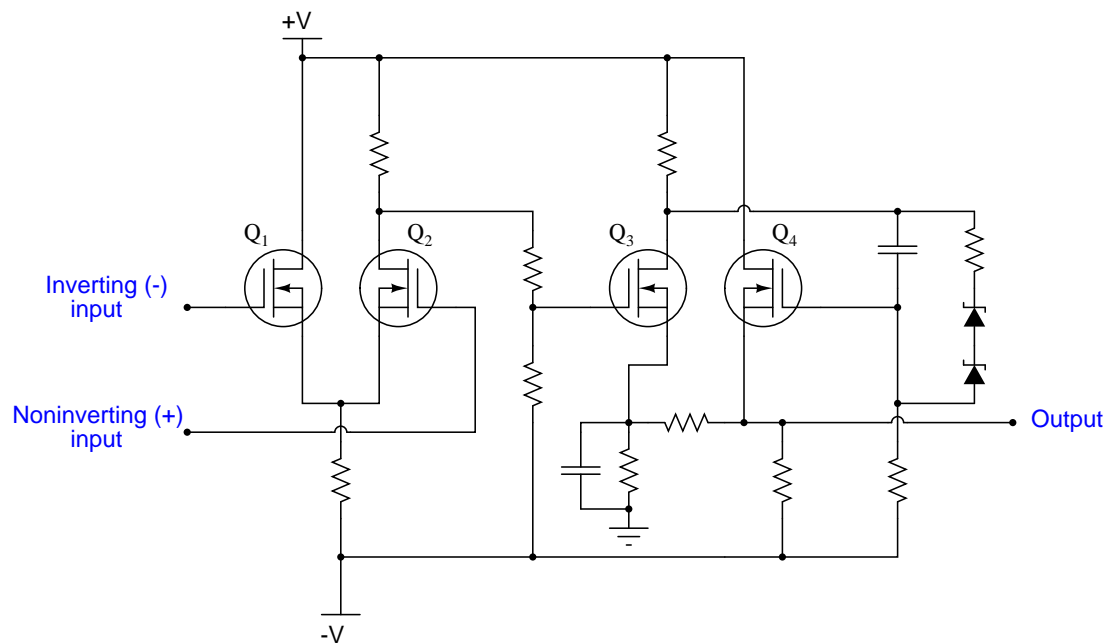
One of the first popular operational amplifiers was manufactured by Philbrick Researches, and it was called the K2-W. Built with two dual-triode vacuum tubes, its original schematic diagram looked like this:

The Philbrick Researches op-amp, model K2-W



To make this opamp circuit easier for modern students to understand, I'll substitute equivalent solid-state components for all tubes in the original design:

The Philbrick Researches op-amp, model K2-W, reborn



Explain the configuration (common-source, common-drain, or common-gate) of each transistor in the modernized schematic, identifying the function of each in the operational amplifier circuit.

file 02590

Answer 76

Q_1 and Q_2 form a *differential pair*, outputting a signal proportional to the difference in voltage between the two inputs. Q_3 is a (bypassed) common-source voltage amplifier, while Q_4 is a source-follower (common-drain), providing voltage gain and current gain, respectively.

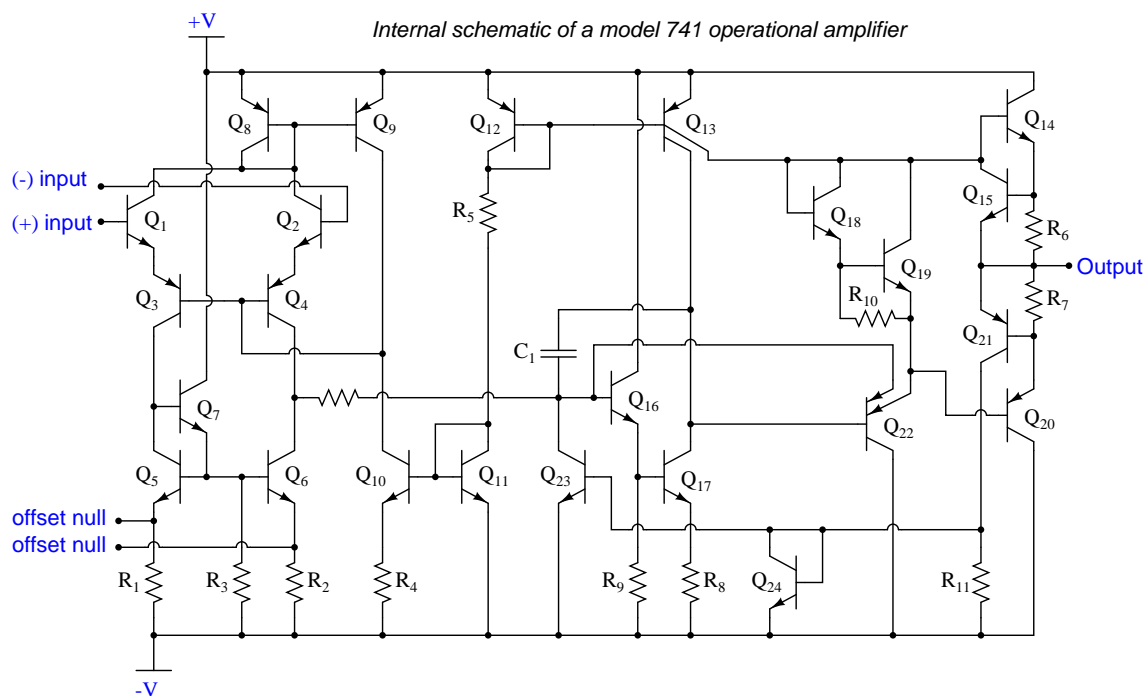
Notes 76

The answer as given is incomplete. One could elaborate more on the function of each transistor, and by doing so understand the original amplifier circuit a little better. Explore this circuit with your students, challenging them to follow through the logic of the design, trying to figure out what the designer(s) intended.

This question also provides the opportunity to draw parallels between D-type MOSFET operation and the behavior of triode-type vacuum tubes. As with D-type MOSFETs, triodes were "normally half-on" devices, whose plate-cathode current conduction could be enhanced or depleted by applying voltage to the grid (with respect to the cathode).

Question 77

Determine the functions for as many components as you can in the following schematic diagram of a model 741 operational amplifier:



[file 02591](#)

Answer 77

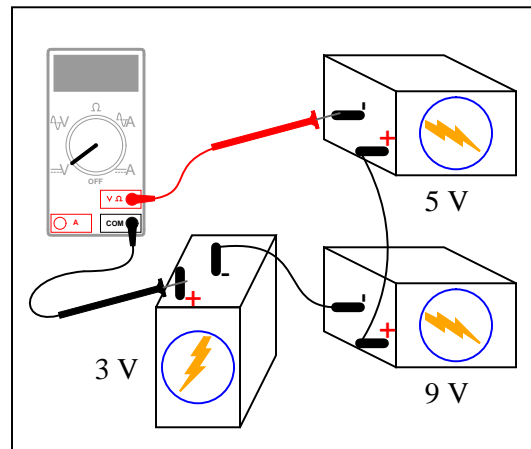
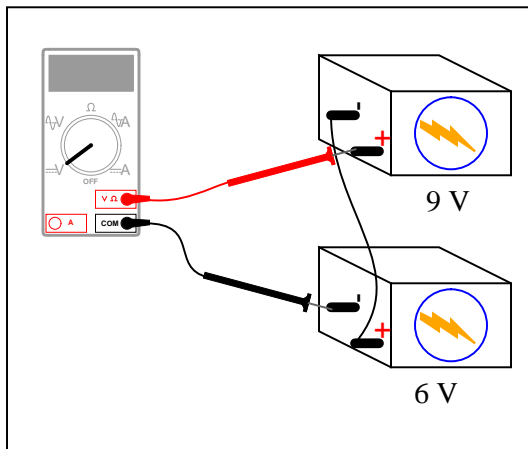
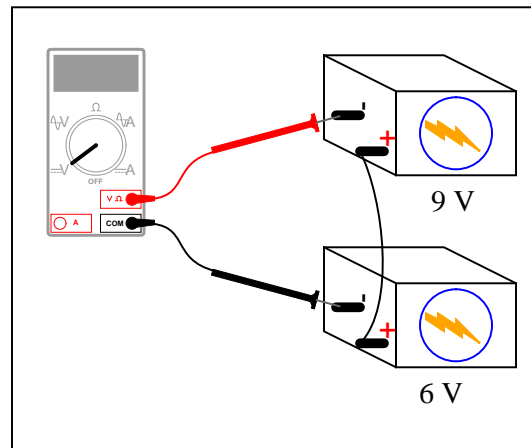
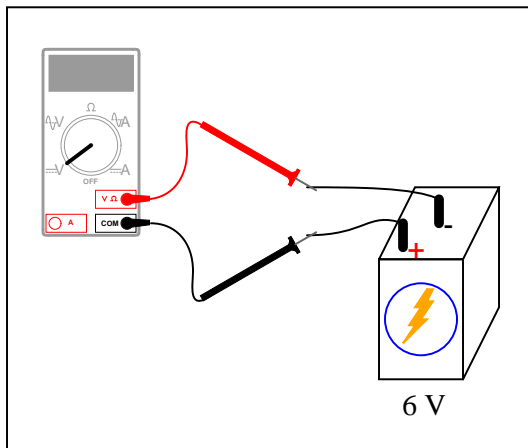
I'll let you and your classmates have fun with this question!

Notes 77

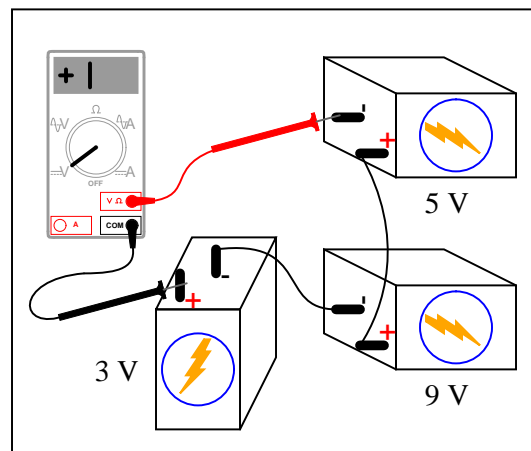
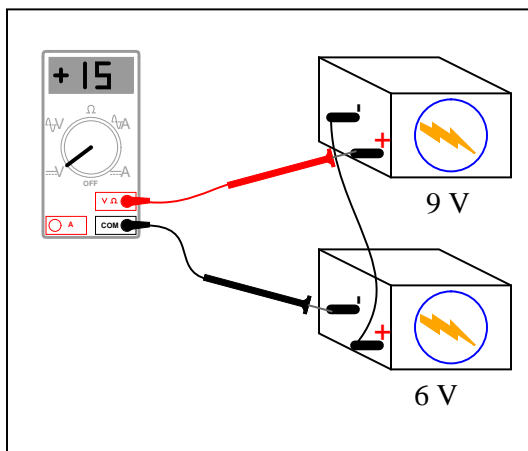
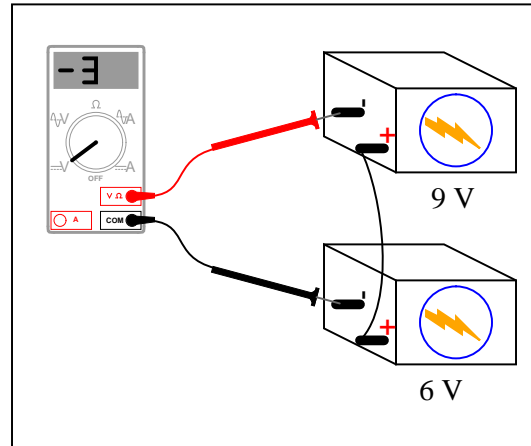
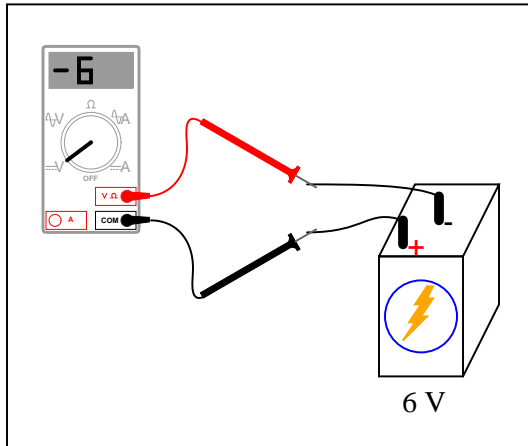
Although the model 741 operational amplifier is considered obsolete by many modern standards, it is still a suitable circuit for this kind of exploration with students. Being able to look over a schematic diagram and figure out what the components do is an important troubleshooting skill. The fact that human circuit designers tend to repeat specific circuit elements and "modules" (such as the common-collector amplifier or the current mirror) in their designs rather than invent something completely novel for each design simplifies the task of later interpretation.

Question 78

Determine what the magnitude and polarity of the voltmeter's indication will be in each case:



file 03763

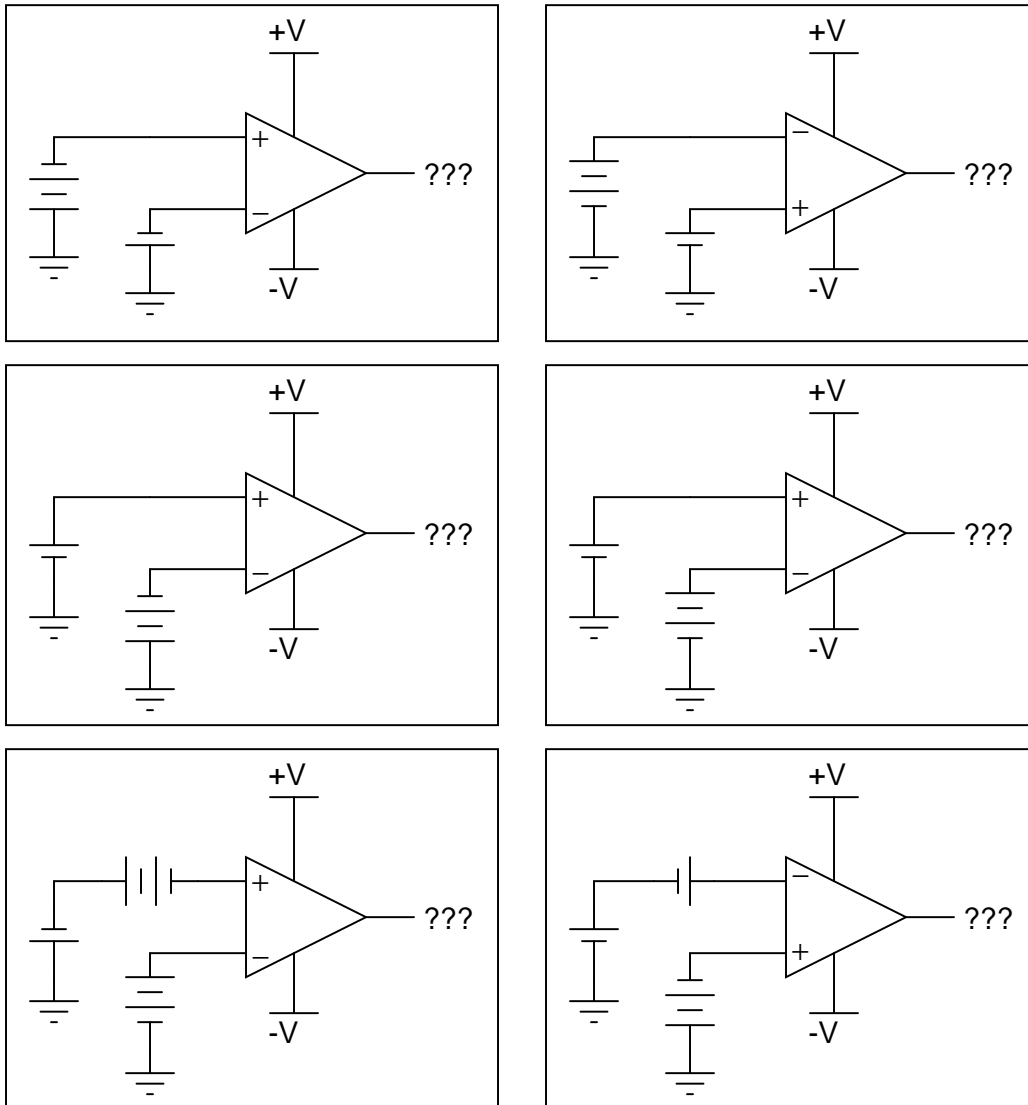


Notes 78

Here, students must apply Kirchhoff's Voltage Law to determine what the voltmeter's indication will be. This question works well as a prelude to determining comparator (open-loop opamp) output polarities.

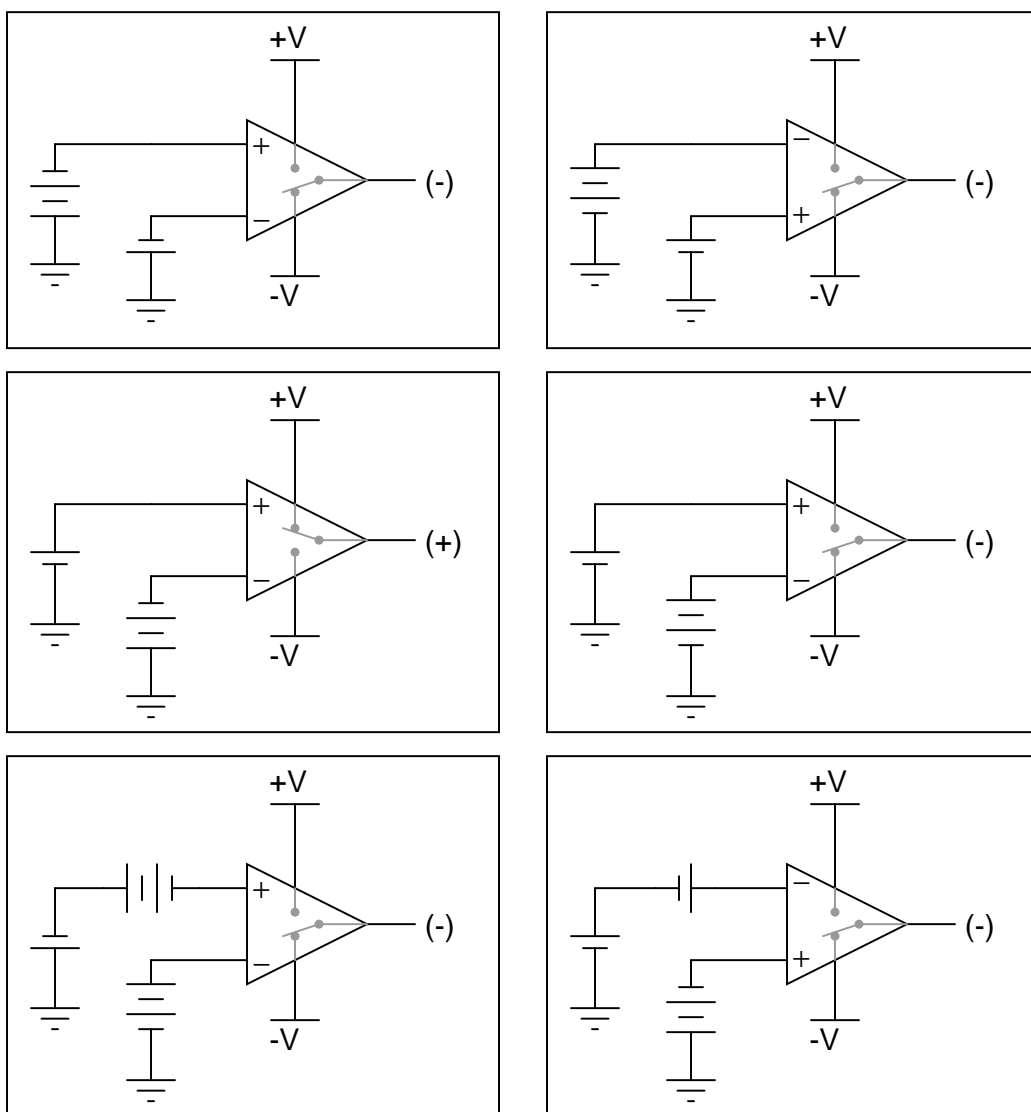
Question 79

Determine the output voltage polarity of this op-amp (with reference to ground), given the following input conditions:



file 03761

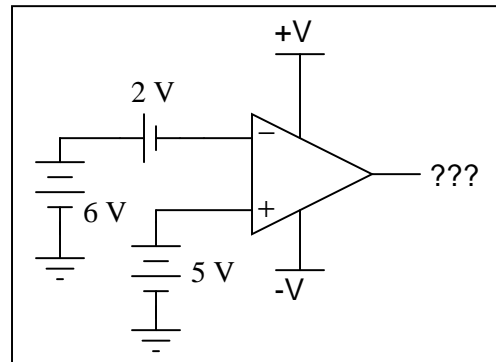
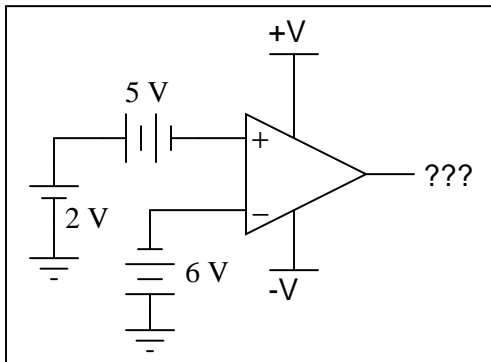
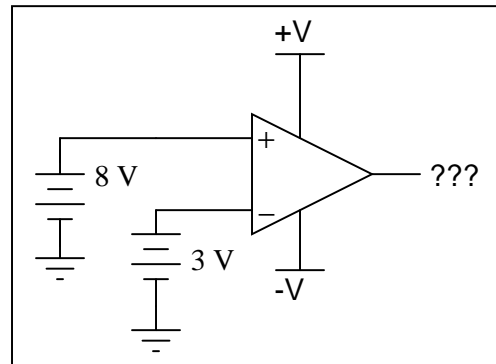
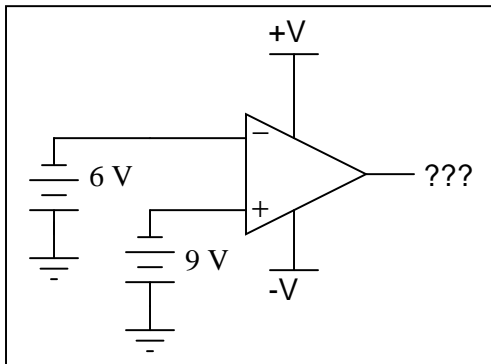
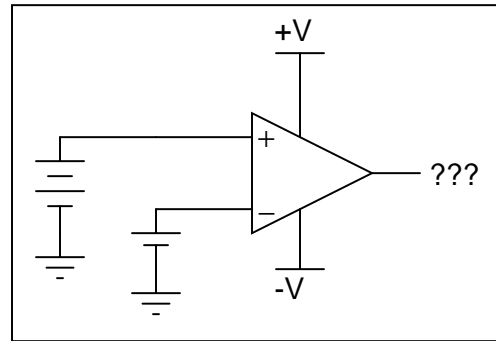
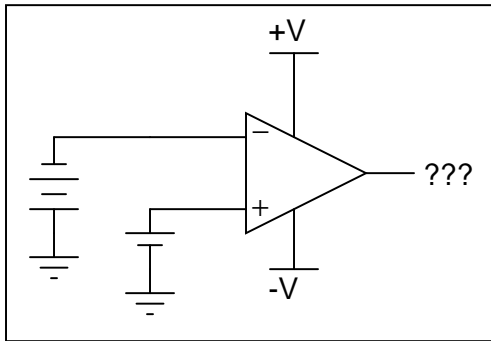
In these illustrations, I have likened the op-amp's action to that of a single-pole, double-throw switch, showing the "connection" made between power supply terminals and the output terminal.



Determining which "way" the output of an op-amp drives under different input voltage conditions is confusing to many students. Discuss this with them, and ask them to present any principles or analogies they use to remember "which way is which."

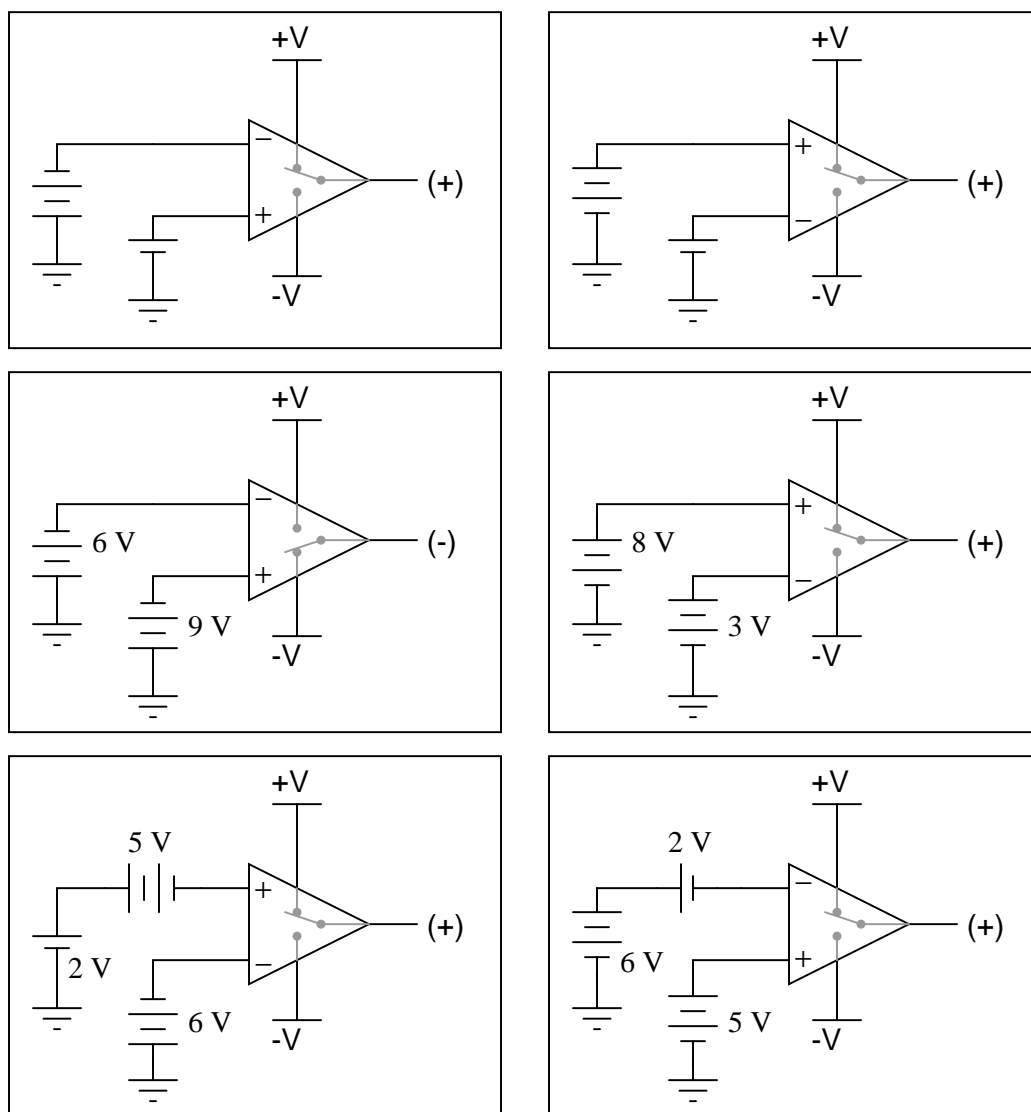
Question 80

Determine the output voltage polarity of this op-amp (with reference to ground), given the following input conditions:



file 03762

In these illustrations, I have likened the op-amp's action to that of a single-pole, double-throw switch, showing the "connection" made between power supply terminals and the output terminal.



Determining which "way" the output of an op-amp drives under different input voltage conditions is confusing to many students. Discuss this with them, and ask them to present any principles or analogies they use to remember "which way is which."

Question 81

Just as certain assumptions are often made for bipolar transistors in order to simplify their analysis in circuits (an ideal BJT has negligible base current, $I_C = I_E$, constant β , etc.), we often make assumptions about operational amplifiers so we may more easily analyze their behavior in closed-loop circuits. Identify some of these ideal opamp assumptions as they relate to the following parameters:

- Magnitude of input terminal currents:
- Input impedance:
- Output impedance:
- Input voltage range:
- Output voltage range:
- Differential voltage (between input terminals) with negative feedback:

file 02749

Answer 81

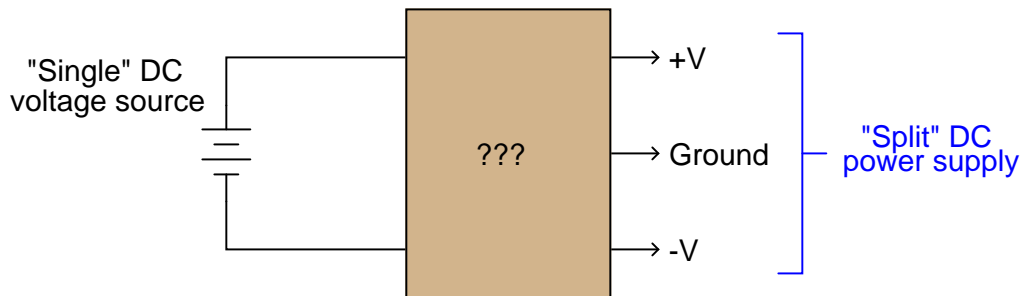
- Magnitude of input terminal currents: *infinitesimal*
- Input impedance: *infinite*
- Output impedance: *infinitesimal*
- Input voltage range: *never exceeding $+V/-V$*
- Output voltage range: *never exceeding $+V/-V$*
- Differential voltage (between input terminals) with negative feedback: *infinitesimal*

Notes 81

Just in case your students are unfamiliar with the words *infinite* and *infinitesimal*, tell them they simply mean "bigger than big" and "smaller than small", respectively.

Question 82

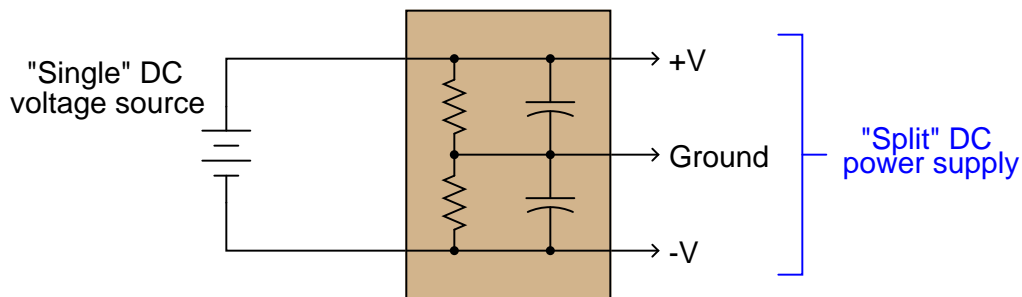
Design a passive circuit that will create a "split" (+V/-V) power supply from a single voltage source:



file 02748

Answer 82

For low-current applications, the following resistor/capacitor network works remarkably well:



Follow-up question: what design constraints will dictate the sizes of the resistors and capacitors?

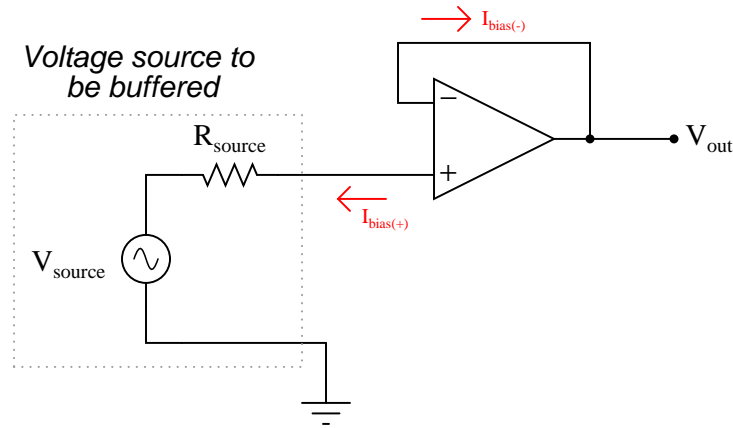
Notes 82

This simple filtered voltage divider circuit works well when the current draws are low, or at least very close to being equal, on the +V and -V load rails. It does not work so well for highly asymmetrical loads, or where low quiescent current draw is important (low-power battery circuits, for example). In applications requiring better +V/-V voltage stability, an opamp "follower" circuit is recommended after the voltage divider.

Question 83

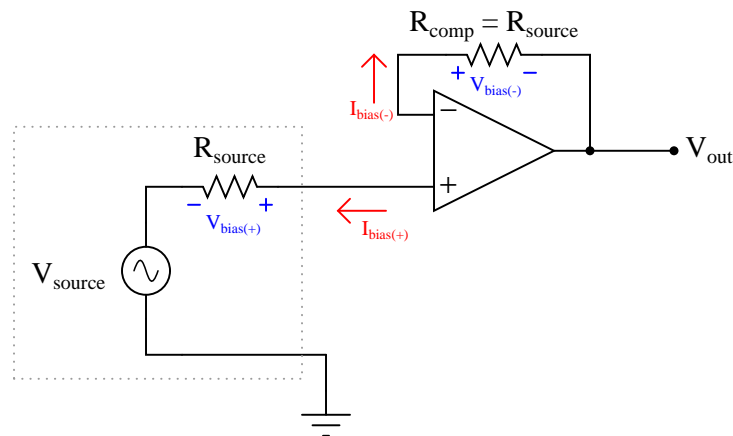
Ideally, the input terminals of an operational amplifier conduct zero current, allowing us to simplify the analysis of many opamp circuits. However, in actuality there is a very small amount of current going through each of the input terminals of any opamp with BJT input circuitry. This may cause unexpected voltage errors in circuits.

Consider the following voltage buffer circuit:



$I_{bias(-)}$ does not cause any trouble for us, because it is completely supplied by the opamp's output. The other bias current, though, *does* cause trouble, because it must go through the source's Thévenin resistance. When it does, it drops some voltage across that intrinsic source resistance, skewing the amount of voltage actually seen at the noninverting terminal of the opamp.

A common solution to this is to add another resistor to the circuit, like this:



Explain why the addition of a resistor fixes the problem.

[file 02462](#)

Answer 83

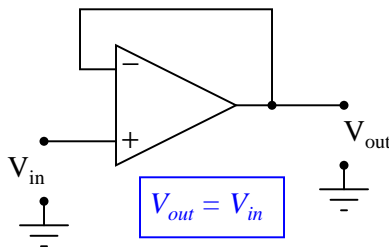
The additional resistor should drop an equal amount of voltage, thus canceling out any bias voltage introduced by the bias current passing through the source's internal resistance. Sizing this "compensating" resistor equal to the source's Thévenin resistance assumes zero input *offset* current.

A simple voltage buffer circuit is the easiest context in which to understand the function of a bias current compensating resistor, and so it is presented here to allow students to see its impact.

Question 84

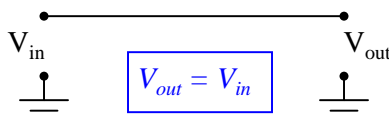
This operational amplifier circuit is often referred to as a *voltage buffer*, because it has unity gain (0 dB) and therefore simply reproduces, or "buffers," the input voltage:

Voltage buffer circuit



What possible use is a circuit such as this, which offers no voltage gain or any other form of signal modification? Wouldn't a straight piece of wire do the same thing? Explain your answers.

A simpler voltage buffer?



file 03801

Answer 84

While this circuit offers no voltage gain, it does offer *current gain* and *impedance transformation*. Much like the common-collector (or common-drain) single transistor amplifier circuits which also had voltage gains of (near) unity, opamp buffer circuits are useful whenever one must drive a relatively "heavy" (low impedance) load with a signal coming from a "weak" (high impedance) source.

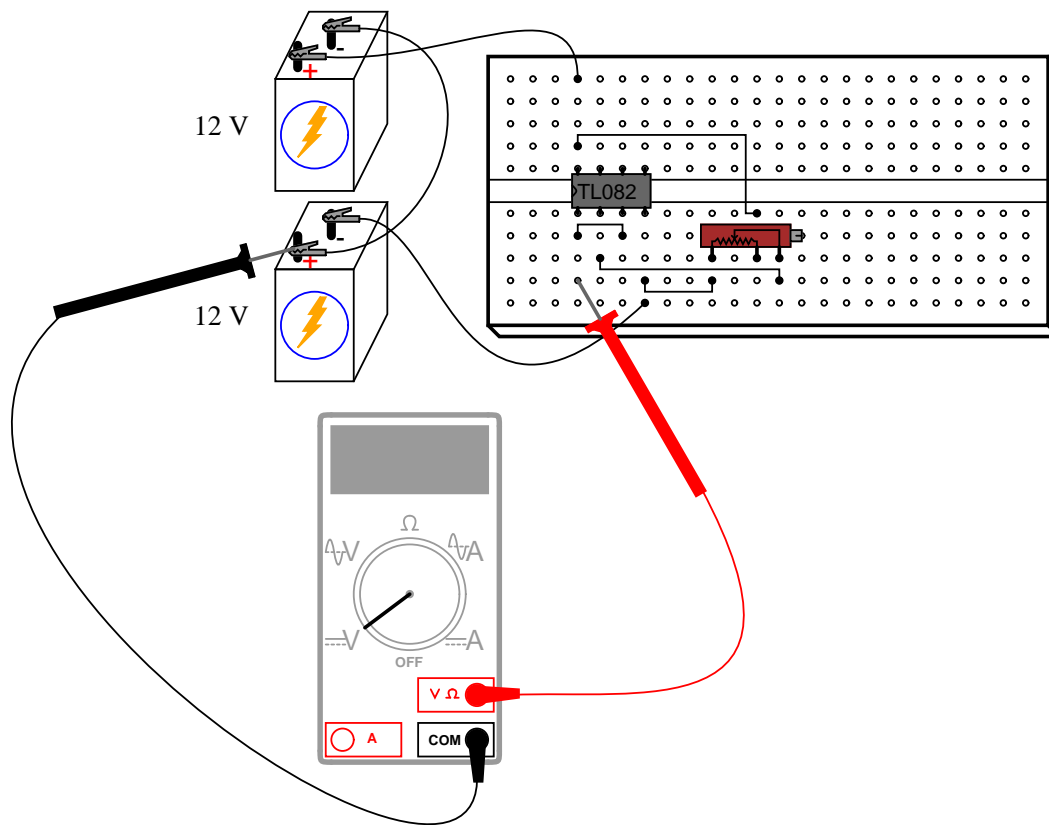
Notes 84

I have found that some students have difficulty with the terms "heavy" and "light" in reference to load characteristics. That a "heavy" load would have very few ohms of impedance, and a "light" load would have many ohms of impedance seems counter-intuitive to some. It all makes sense, though, once students realize the terms "heavy" and "light" refer to the amount of *current* drawn by the respective loads.

Ask your students to explain why the straight piece of wire fails to "buffer" the voltage signal in the same way the the opamp follower circuit does.

Question 85

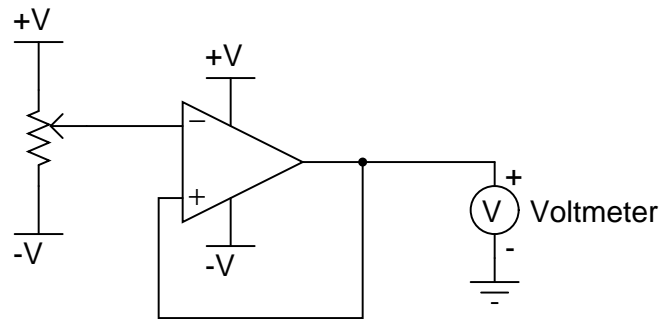
A student intends to connect a TL082 opamp as a voltage follower, to "follow" the voltage generated by a potentiometer, but makes a mistake in the breadboard wiring:



Draw a schematic diagram of this faulty circuit, and determine what the voltmeter's indication will be, explaining why it is such.

file 01148

Circuit schematic, as wired:



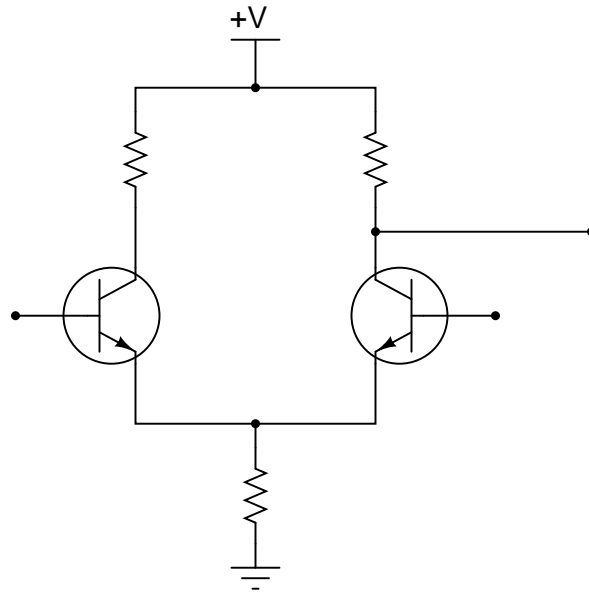
The output voltage will saturate at approximately +11 volts, or -11 volts, with the potentiometer having little or no effect.

Notes 85

Ask your students to characterize the type of feedback exhibited in this circuit. How does this type of feedback affect the opamp's behavior? Is it possible for the opamp to function as a voltage follower, connected like this?

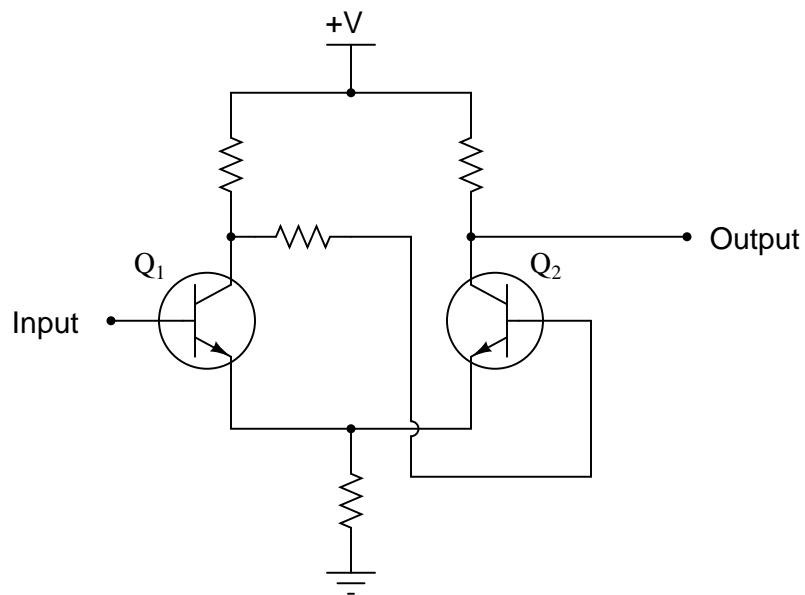
Question 86

Comparators with positive feedback are sometimes referred to as *Schmitt triggers*. Suppose you needed a Schmitt trigger for a circuit you were building, but did not have any more integrated circuit comparators or op-amps to use. All you have available to you are discrete components. Is there any way you can think of to modify the following discrete transistor differential pair so that it behaves as a Schmitt trigger?



[file 01243](#)

Answer 86



Ask your students to determine whether this Schmitt trigger circuit is inverting or non-inverting. Have them explain their reasoning step-by-step.

Authors Paul Horowitz and Winfield Hill, in their book The Art of Electronics, say that Q_1 's collector resistor must be larger than Q_2 's collector resistor in order for this circuit to work properly (page 232, second edition).

Question 87

Positive or *regenerative* feedback is an essential characteristic of all oscillator circuits. Why, then, do comparator circuits utilizing positive feedback not oscillate? Instead of oscillating, the output of a comparator circuit with positive feedback simply saturates to one of its two rail voltage values. Explain this.

file 01172

Answer 87

The positive feedback used in oscillator circuits is always phase-shifted 360° , while the positive feedback used in comparator circuits has no phase shift at all, being direct-coupled.

Notes 87

This is a challenging question, and may not be suitable for all students. Basically, what I'm trying to get students to do here is think carefully about the nature of positive feedback as used in comparator circuits, versus as it's used in oscillator circuits. Students who have simply memorized the concept of "positive feedback causing oscillation" will fail to understand what is being asked in this question, much less understand the given answer.