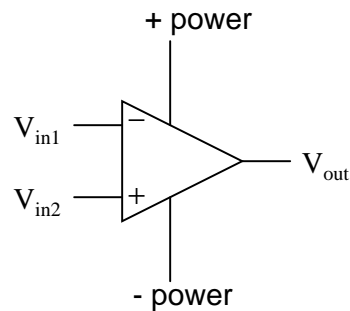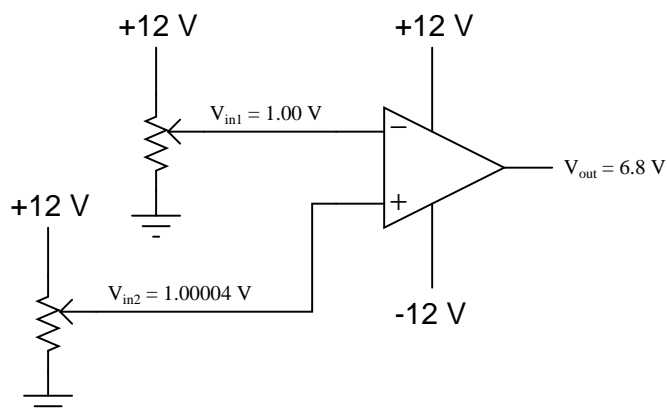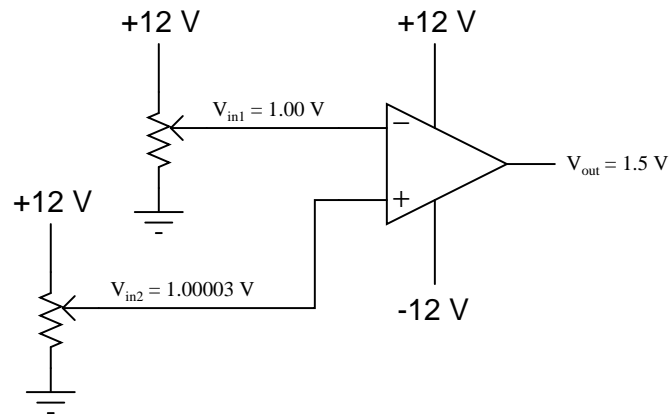Question 1

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 1

$A_V = 530{,}000$

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

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

Notes 1

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.
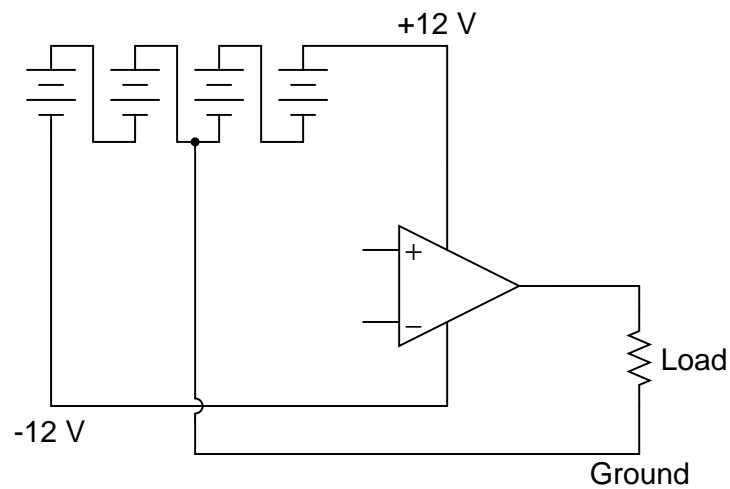
Question 2

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 V, -12 V, and Ground to this op-amp:
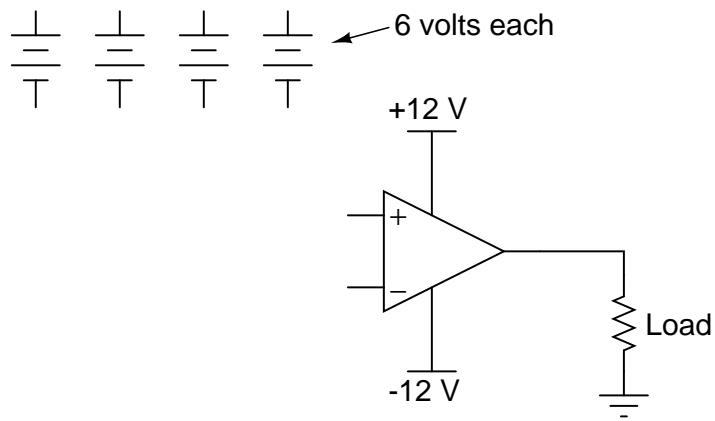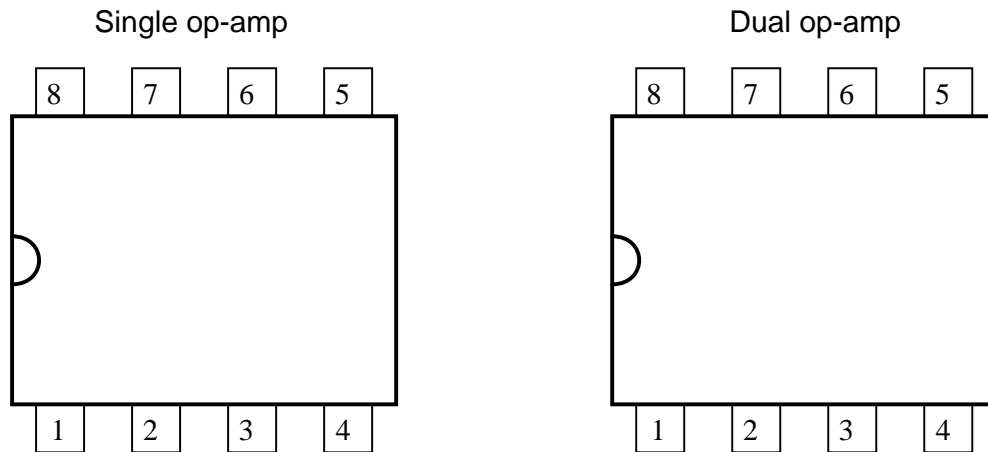

file 00880

Answer 2

Notes 2

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.
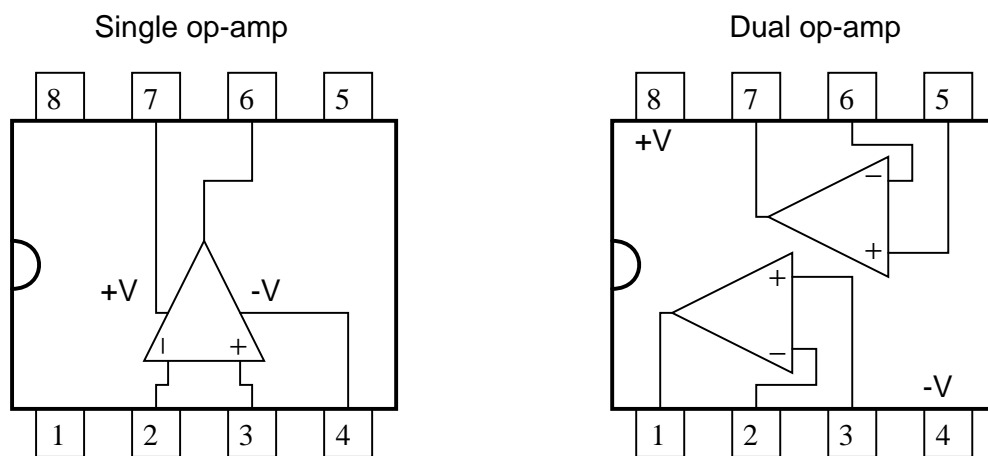
Question 3

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:

Single op-amp

Dual op-amp

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 3
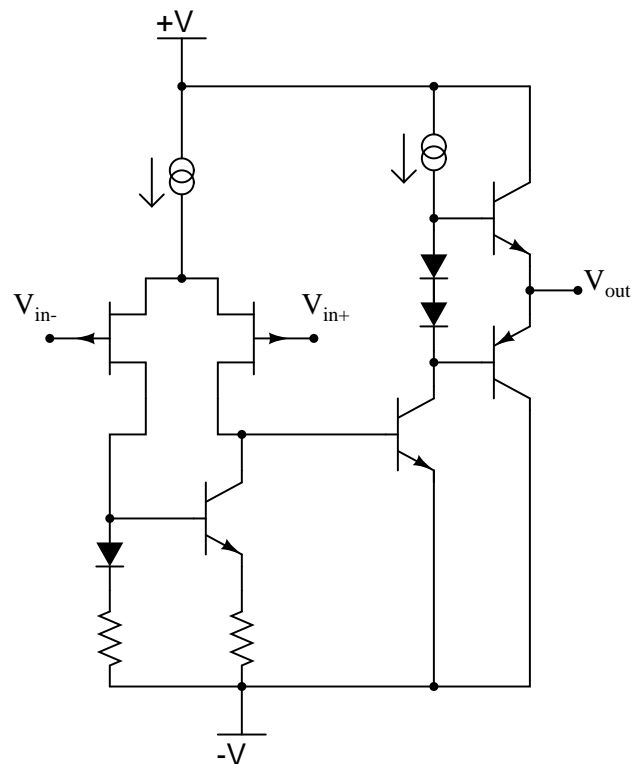
Single op-amp

Dual op-amp

Notes 3

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

Question 4

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

5

Answer 4

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 4

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 5

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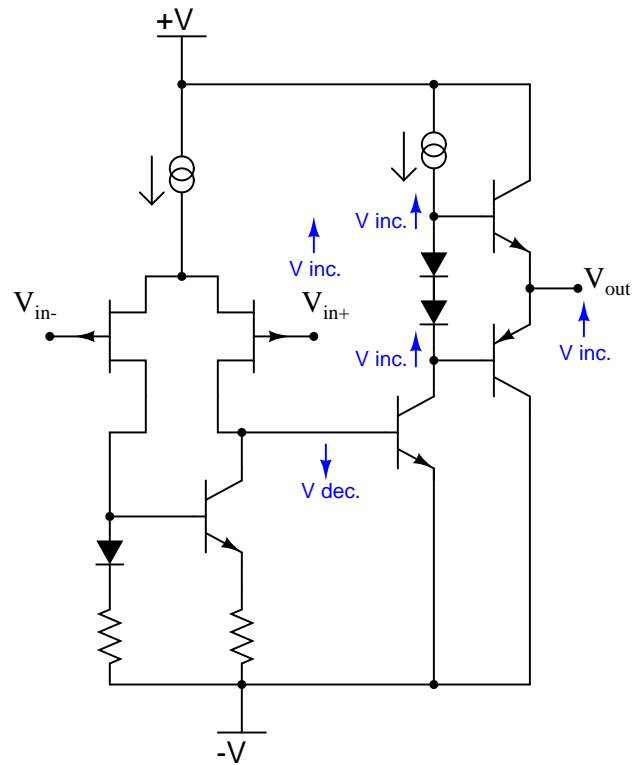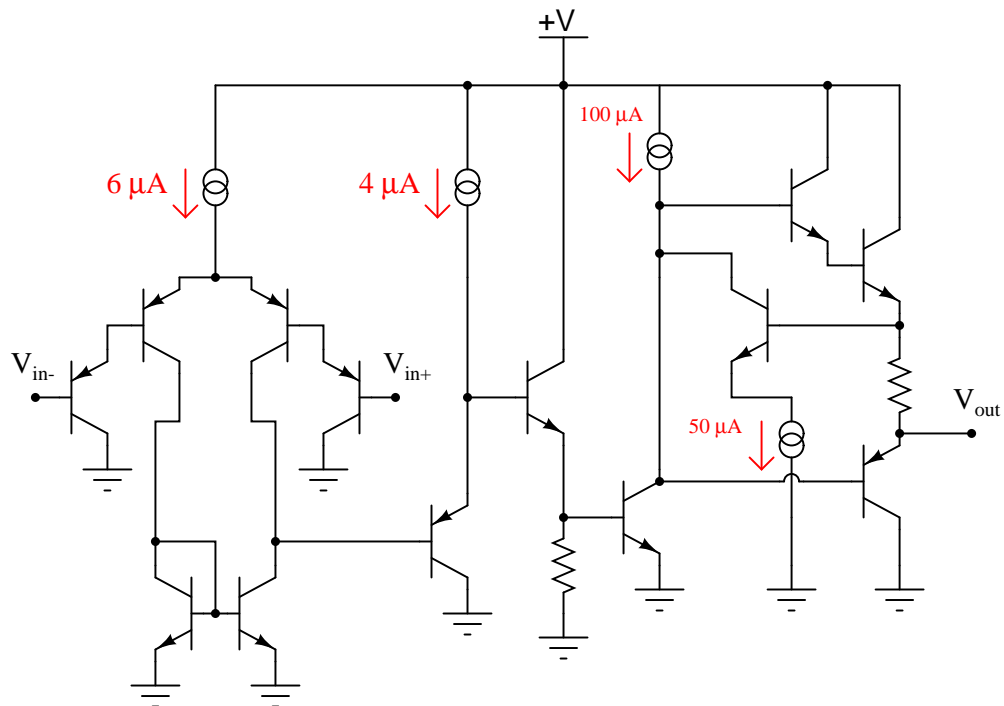

Qualitatively determine what will happen to the output voltage (V_{out}) if the voltage on the inverting input (V_{in-}) increases, and the voltage on the noninverting input (V_{in+}) remains the same (all voltages are positive quantities, referenced to ground). Explain what happens at every stage of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

file 00799

Answer 5

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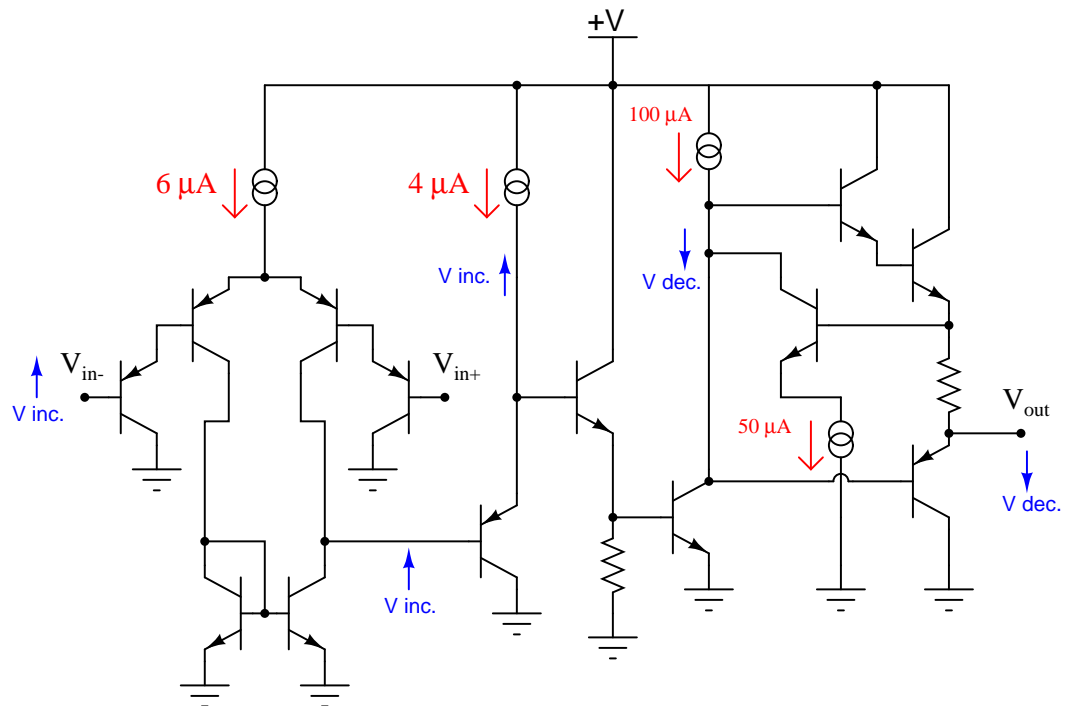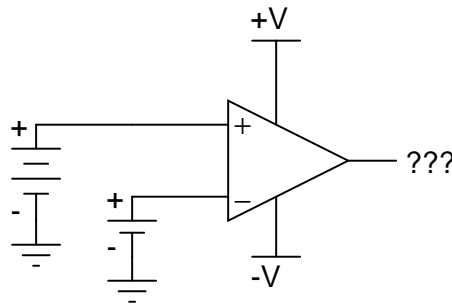

Notes 5

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 6

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

Answer 6

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:
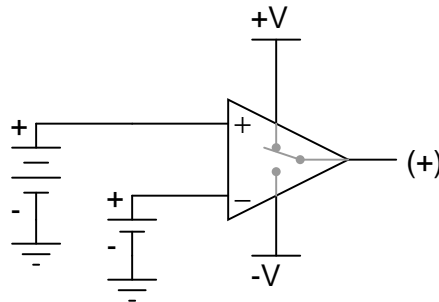
Notes 6

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 7

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

10

Answer 7

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.
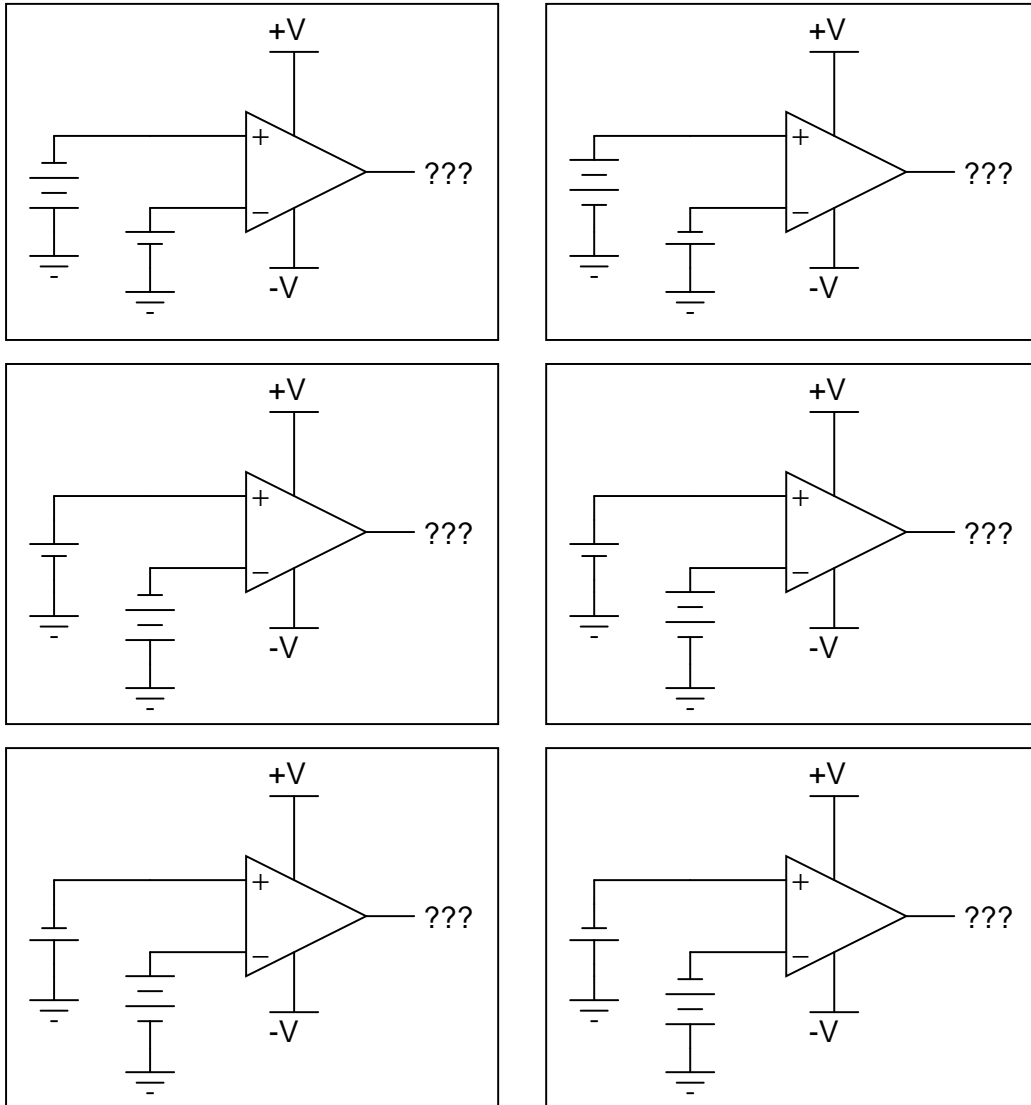

Notes 7

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."
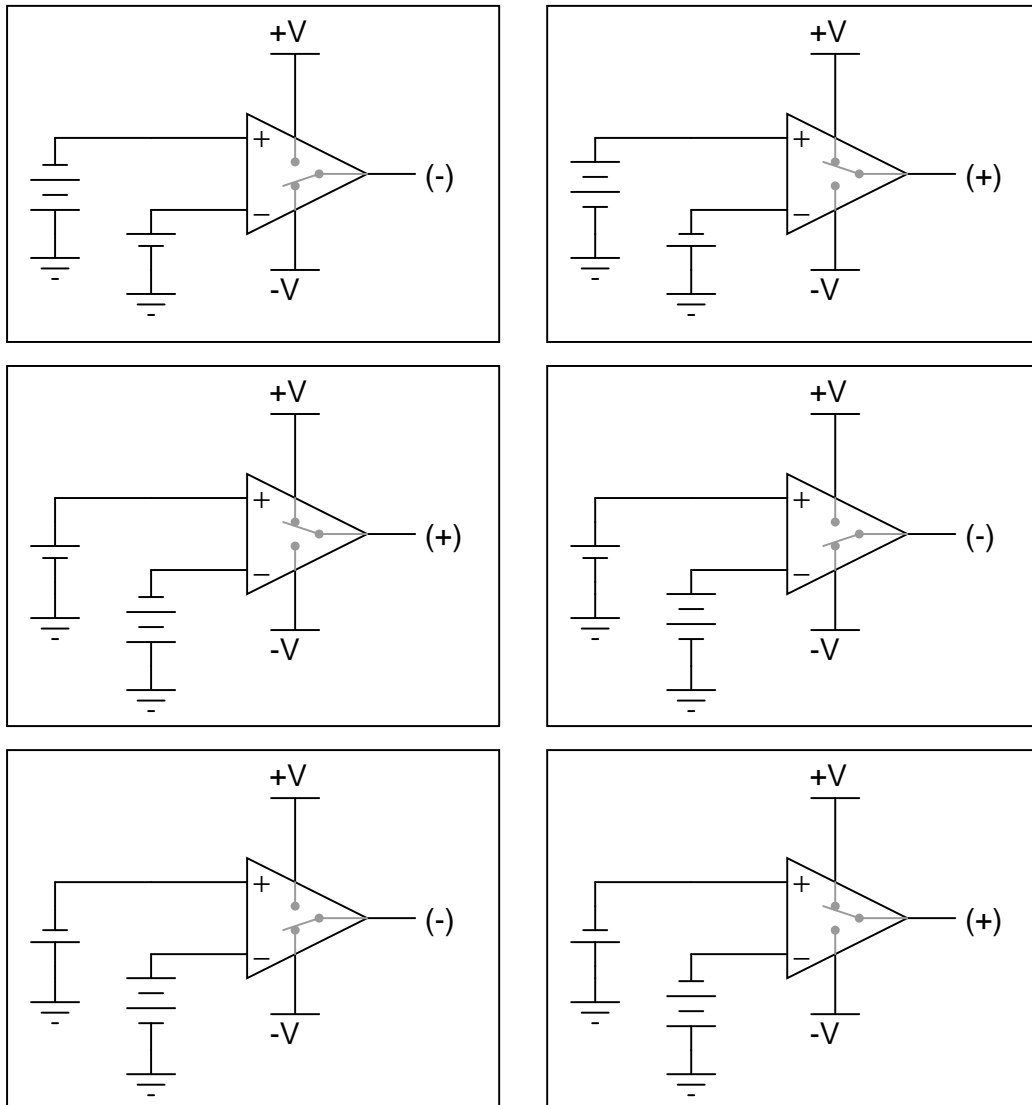
Question 8

In this circuit, an op-amp turns on an LED if the proper input voltage conditions are met:
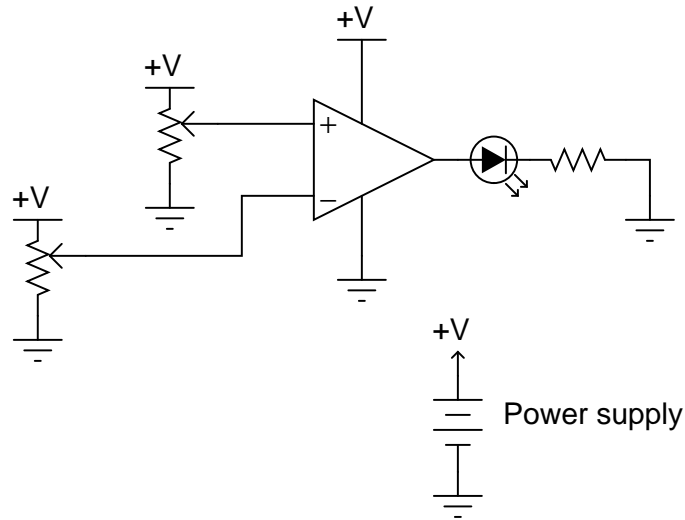
Trace the complete path of current powering the LED. Where, exactly, does the LED get its power from?

file 00801

Answer 8

The arrows shown in this diagram trace "conventional" current flow, not electron flow:
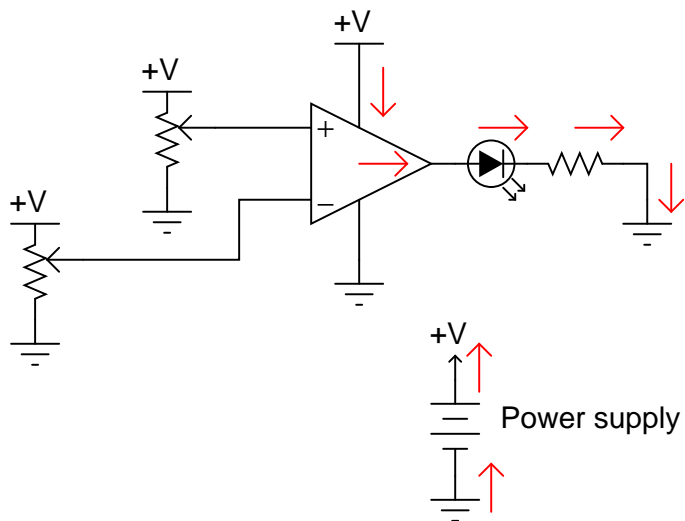
Notes 8

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 9

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?
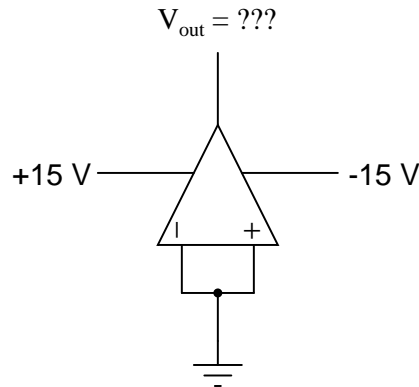
$$V_{out} = ???$$

+15 V ———— ————— -15 V

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 9

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 9

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 10

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 10

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 10

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 11

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 11

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

Notes 11

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 12

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

file 00845

Answer 12

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 12

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 13

Determine the output voltage polarity of this op-amp (with reference to ground), given the following input conditions:
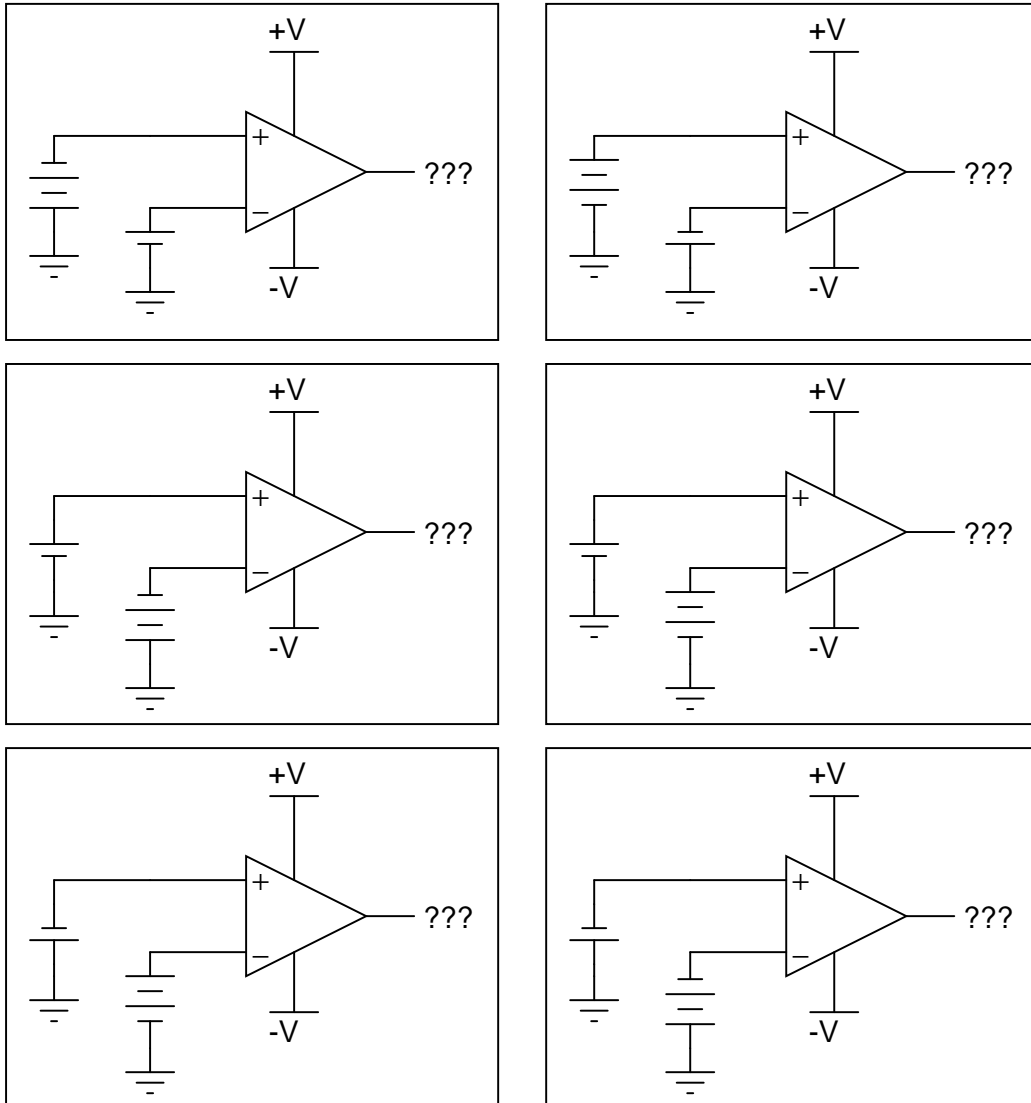
Answer 13

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.
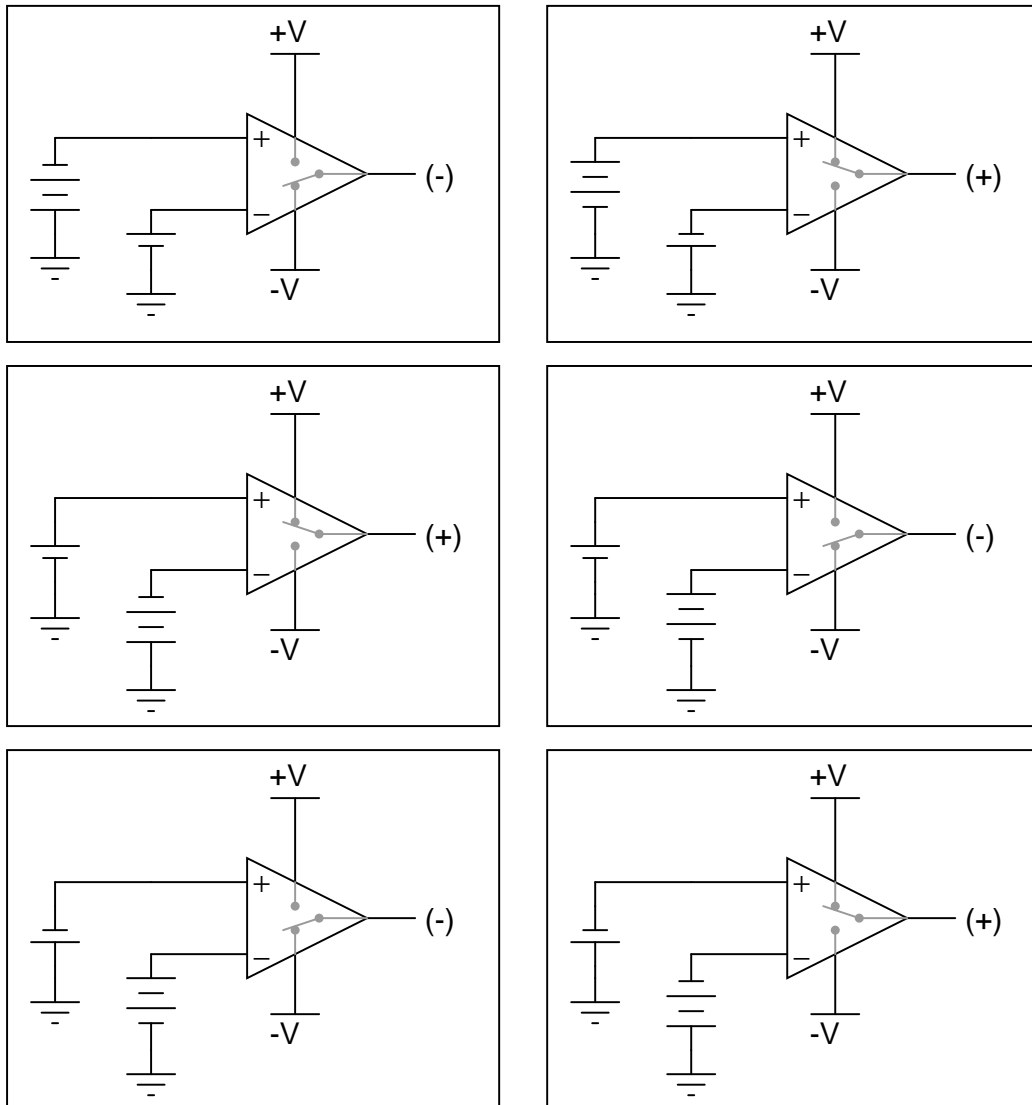
Notes 13

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 14

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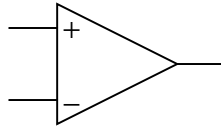

What is the difference between a comparator such as the model LM319, and a true operational amplifier such as the model LM324? Are the two devices interchangeable, or is there any significant difference despite the exact same schematic symbols? Explain your answer.

file 00875

Answer 14

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 14

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 15

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?
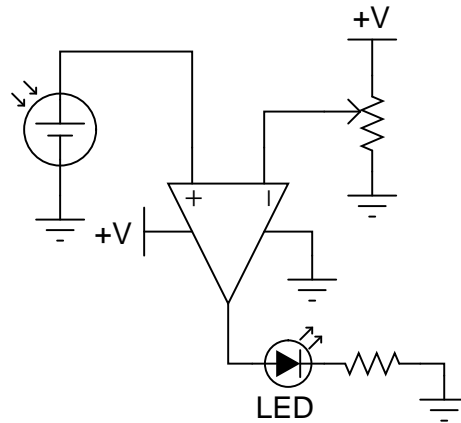
file 00872

Answer 15

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 15

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 16

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 16

"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 16

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.

A student is operating a simple comparator circuit and documenting the results in a table:
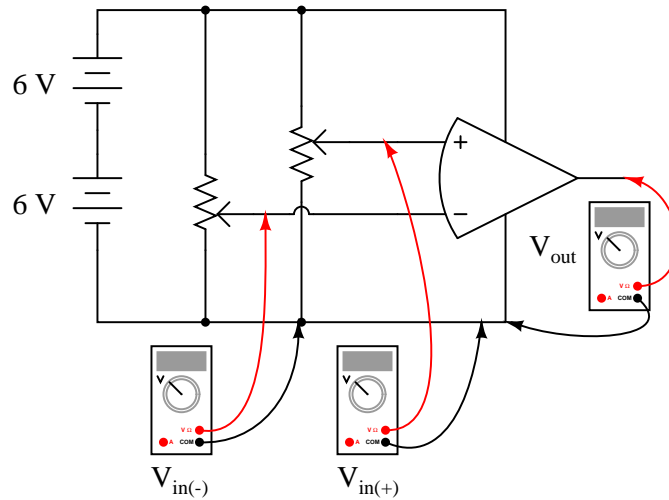
$V_{in(+)}$	$V_{in(-)}$	V_{out}
3.00 V	1.45 V	10.5 V
3.00 V	2.85 V	10.4 V
3.00 V	3.10 V	1.19 V
3.00 V	6.75 V	1.20 V

$V_{in(+)}$	$V_{in(-)}$	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 17

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 17

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 18

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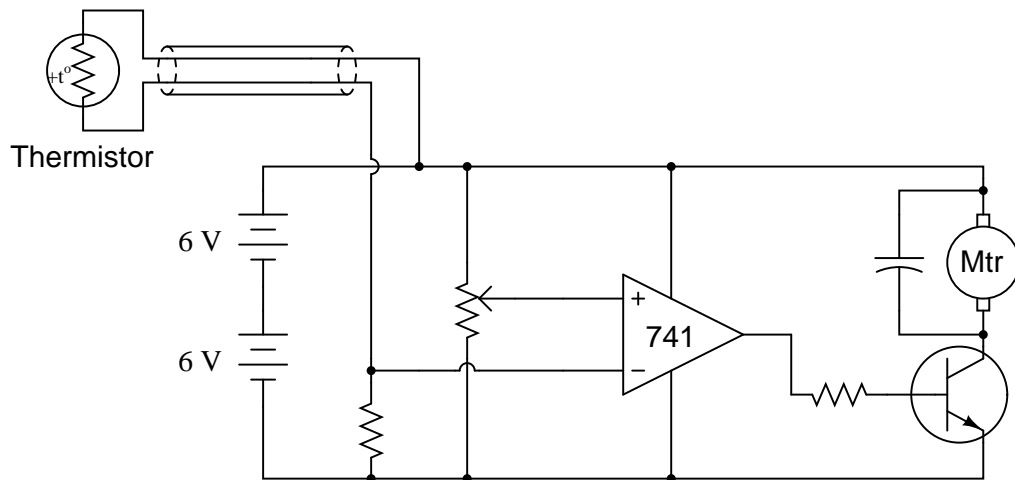
The circuit works just as it is supposed to in turning the motor on and off, but it has a strange problem: the transistor gets warm when the motor is *off*! Oddly enough, the transistor actually cools down when the motor turns on.

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 18

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 18

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 19

Explain the operation of this sound-activated relay circuit:
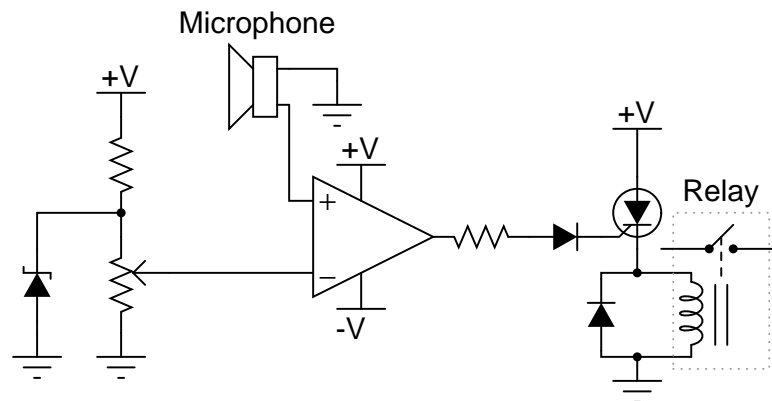
Answer 19

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 19

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 20

Trace the output waveform of this comparator circuit:


file 00878

Answer 20
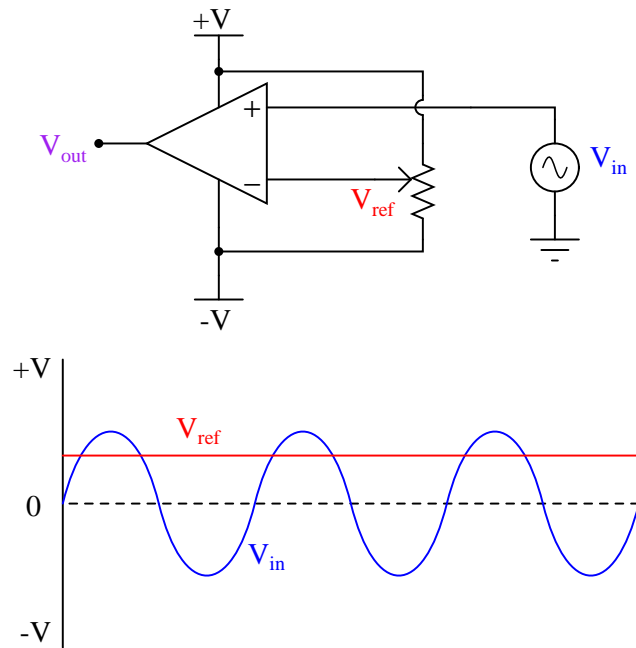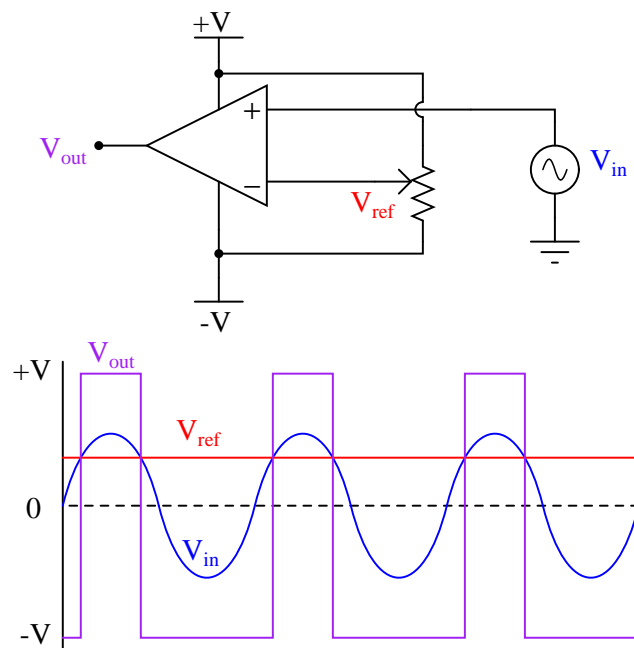
Follow-up question: explain what the phrase *duty cycle* means with reference to a "square" or "pulse" waveform.


Notes 20

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 21

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:
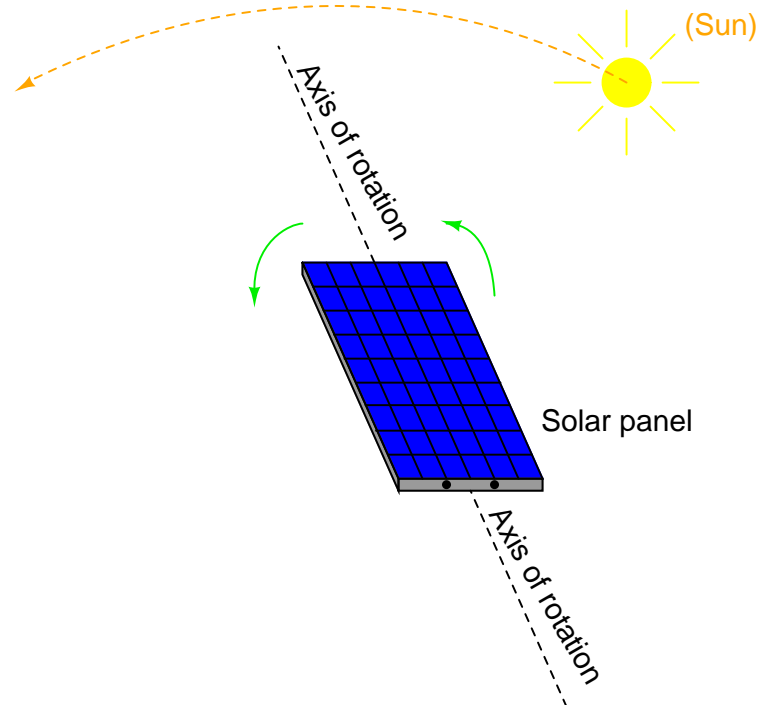
One way to detect the sun's position relative to the panel is to attach a pair of Light-Dependent Resistors (LDR's) to the solar panel in such a way that each LDR will receive an equal amount of light only if the panel is pointed directly at the sun:
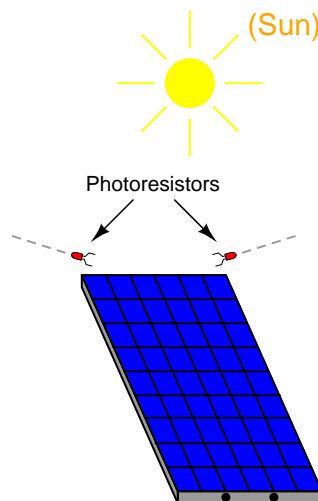
Two comparators are used to sense the differential resistance produced by these two LDR's, and activate a tracking motor to tilt the solar panel on its axis when the differential resistance becomes too great. An "H-drive" transistor switching circuit takes the comparators' output signals and amplifies them to drive a permanent-magnet DC motor one way or the other:
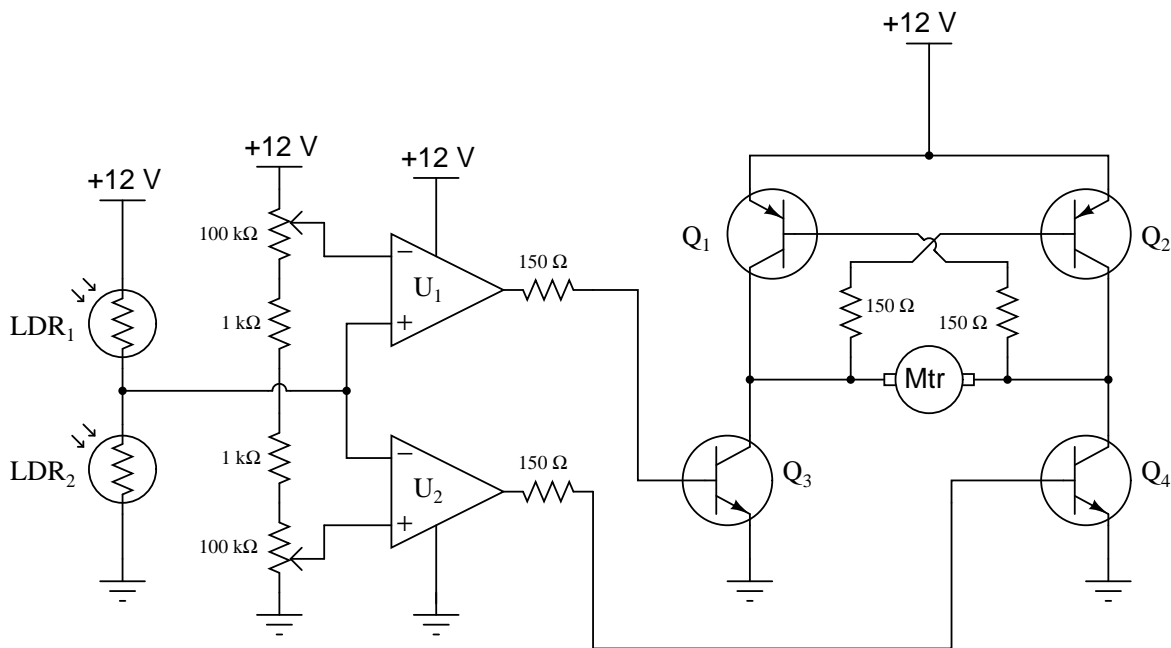
In this circuit, what guarantees that the two comparators never output a "high" (+V) voltage simultaneously, thus attempting to move the tracking motor clockwise and counter-clockwise at the same time?

file 00881

Answer 21

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 then the lower potentiometer's voltage at the same time, which is an impossibility. This comparator configuration is commonly known as a *window comparator* circuit.
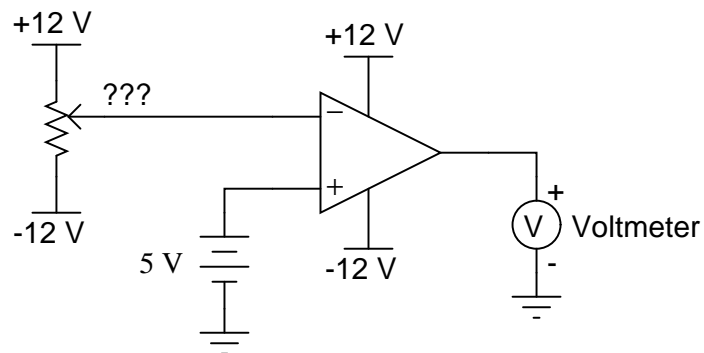

Notes 21

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.

29

Question 22

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?

Answer 22

5 volts

Notes 22

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 23

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:

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

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 23

$V_{out} = 440$ 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 23

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 24

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 $V_{in(-)}$):
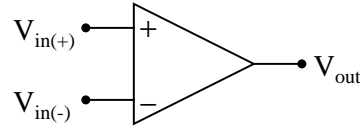
Answer 24

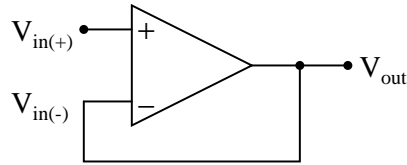$$V_{out} = 100,000(V_{in(+)} - V_{in(-)})$$

Notes 24

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 25

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 25

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

(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 25

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 26

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 to a voltage divider on its output terminal (so the inverting input receives exactly one-half the output voltage). 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 ($V_{in(+)}$):
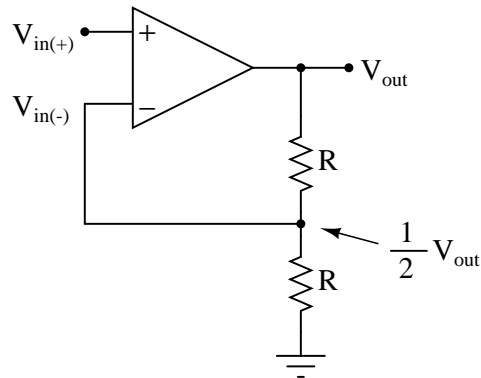
Then, once you have an equation written, solve for the output voltage if the noninverting input voltage is -2.4 volts.

file 00928

Answer 26

$$V_{out} = 100,000(V_{in(+)} - \tfrac{1}{2}V_{out})$$

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

For an input voltage of -2.4 volts, the output voltage will be -4.7999 volts.

Follow-up question: what do you notice about the output voltage in this circuit? What value is it very close to being, in relation to the input voltage? Does this pattern hold true for other input voltages as well?

Notes 26

Your students should see a definite pattern here as they calculate the output voltage for several different input voltage levels. Discuss this phenomenon with your students, asking them to explain it as best they can.

Question 27

A mechanic has an idea for upgrading the electrical system in an automobile originally designed for 6 volt operation. He wants to upgrade the 6 volt headlights, starter motor, battery, etc, to 12 volts, but wishes to retain the original 6-volt generator and regulator. Shown here is the original 6-volt electrical system:
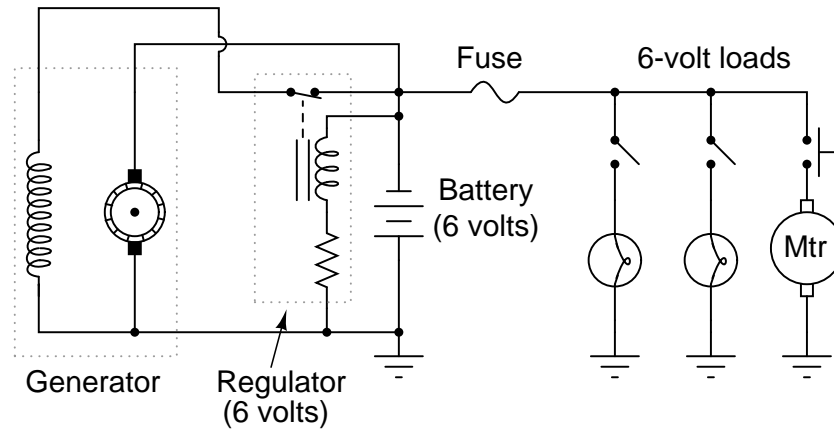
The mechanic's plan is to replace all the 6-volt loads with 12-volt loads, and use two 6-volt batteries connected in series, with the original (6-volt) regulator sensing voltage across only one of those batteries:
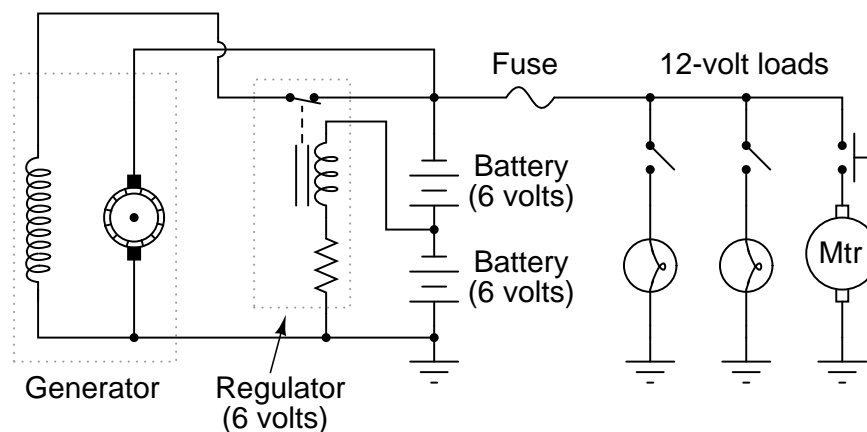
Explain how this system is supposed to work. Do you think the mechanic's plan is practical, or are there any problems with it?

file 01022

Answer 27

So long as the generator is capable of outputting 12 volts, this system will work!

Challenge question: identify factors that may prevent the generator from outputting enough voltage with the regulator connected as shown in the last diagram.

In this question, we see a foreshadowing of op-amp theory, with the regulator's negative feedback applied to what is essentially a voltage divider (two equal-voltage batteries being charged by the generator). The regulator circuit senses only 6 volts, but the generator outputs 12 volts.

Fundamentally, the focus of this question is *negative feedback* and one of its many practical applications in electrical engineering. The depth to which you discuss this concept will vary according to the students' readiness, but it is something you should at least mention during discussion on this question.

This idea actually came from one of the readers of my textbook series Lessons In Electric Circuits. He was trying to upgrade a vehicle from 12 volts to 24 volts, but the principle is the same. An important difference in his plan was that he was still planning on having some 12-volt loads in the vehicle (dashboard gauges, starter solenoid, etc.), with the full 24 volts supplying only the high-power loads (such as the starter motor itself):
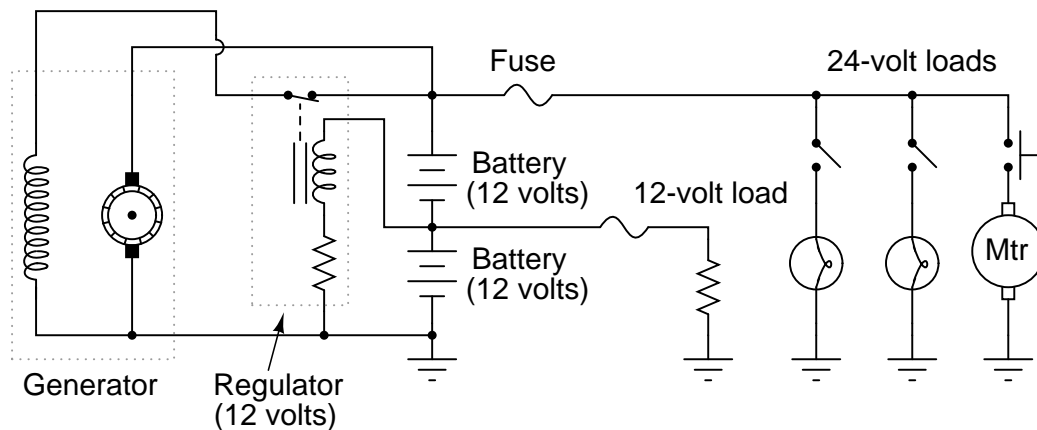
As a challenge for your students, ask them how well they think *this* system would work. It is a bit more complex than the system shown in the question, due to the two different load banks.

Question 28

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?
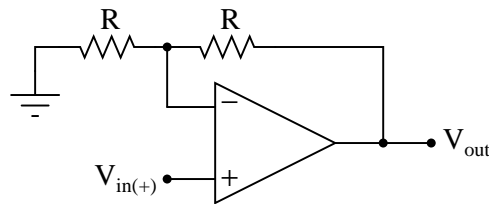
If the open-loop gain of this operational amplifier were to change from 100,000 to 200,000, for example, how big of an effect would it have on the voltage gain as measured from the noninverting input to the output?
file 00929

Answer 28

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?
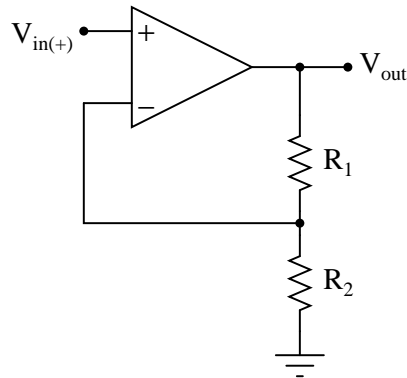
Notes 28

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 29

What would have to be altered in this circuit to increase its overall voltage gain?

Answer 29

The voltage divider would have to altered so as to send a smaller proportion of the output voltage to the inverting input.

Notes 29

Ask your students to explain how they would modify the voltage divider in this circuit to achieve the goal of a smaller voltage division ratio. This should be trivial, but it is always good to review basic principles of electricity even when "deep" into a more advanced topic.

Question 30

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?
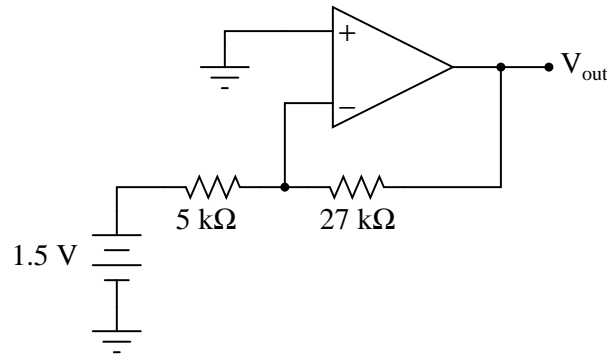
file 00930

Answer 30

Zero volts

Notes 30

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 31

Calculate the output voltage of this op-amp circuit (using negative feedback):

Also, calculate the DC voltage gain of this circuit.

file 00932

Answer 31

V_{out} = -8.1 volts

$A_V = 5.4$

Follow-up question: the midpoint of the voltage divider (connecting to the inverting input of the op-amp) is often called a *virtual ground* in a circuit like this. Explain why.

Notes 31

It is important that students learn to analyze the op-amp circuit in terms of voltage drops and currents for each resistor, rather than just calculate the output using a gain formula. Detailed, Ohm's Law analysis of op-amp circuits is essential for analyzing more complex circuitry.

The "virtual ground" question is an important one for the sake of rapid analysis. Once students understand how and why there is such a thing as a "virtual ground" in an op-amp circuit like this, their analysis of op-amp circuits will be much more efficient.

Question 32

Operational amplifier circuits employing negative feedback are sometimes referred to as "electronic levers," because their voltage gains may be understood through the mechanical analogy of a lever. Explain this analogy in your own words, identifying how the lengths and fulcrum location of a lever relate to the component values of an op-amp circuit:
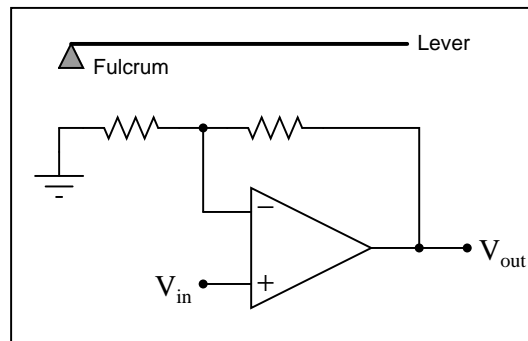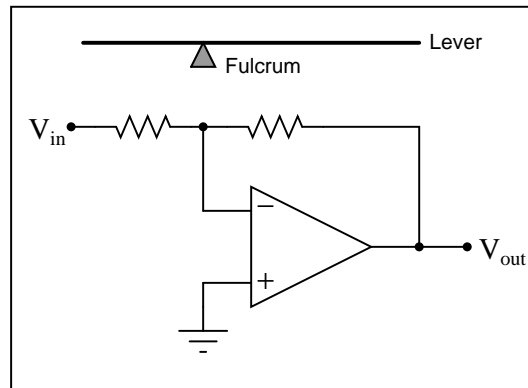

file 00933

Answer 32

The analogy of a lever works well to explain how the output voltage of an op-amp circuit relates to the input voltage, in terms of both magnitude and polarity. Resistor values correspond to *moment arm* lengths, while direction of lever motion (up versus down) corresponds to polarity. The position of the fulcrum represents the location of ground potential in the feedback network.

Notes 32

I found this analogy in one of the best books I've ever read on op-amp circuits: John I. Smith's <u>Modern Operational Circuit Design</u>. Unfortunately, this book is out of print, but if you can possibly obtain a copy for your library, I highly recommend it!

Question 33

A simple "follower" circuit that boosts the current-output ability of this noninverting amplifier circuit is a set of bipolar junction transistors, connected together in a "push-pull" fashion like this:
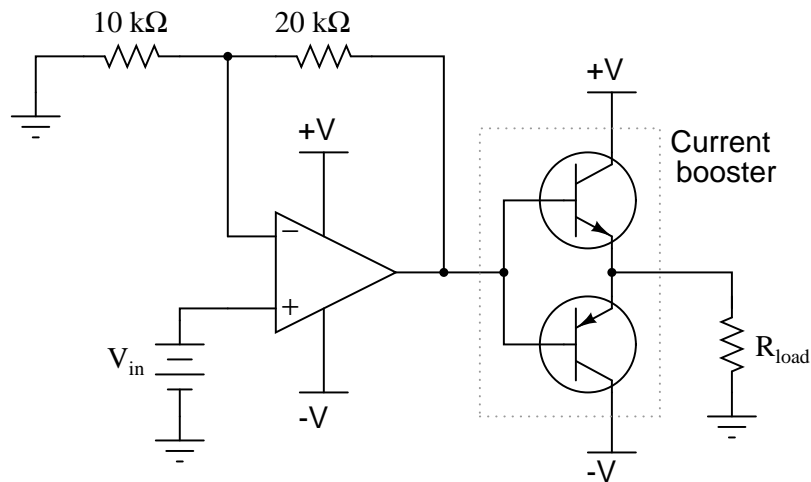

However, if connected exactly as shown, there will be a significant voltage error introduced to the opamp's output. No longer will the final output voltage (measured across the load) be an exact 3:1 multiple of the input voltage, due to the 0.7 volts dropped by the transistor in active mode:
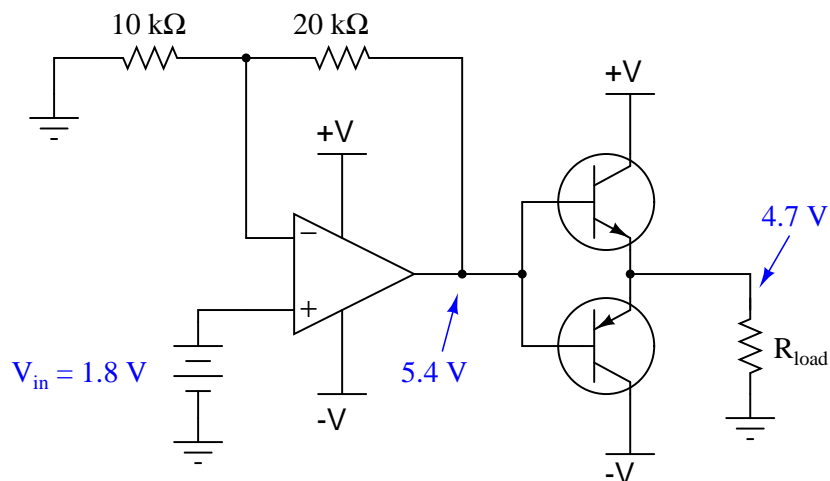
There is a very simple way to completely eliminate this error, without adding any additional components. Modify the circuit accordingly.

file 00935

42
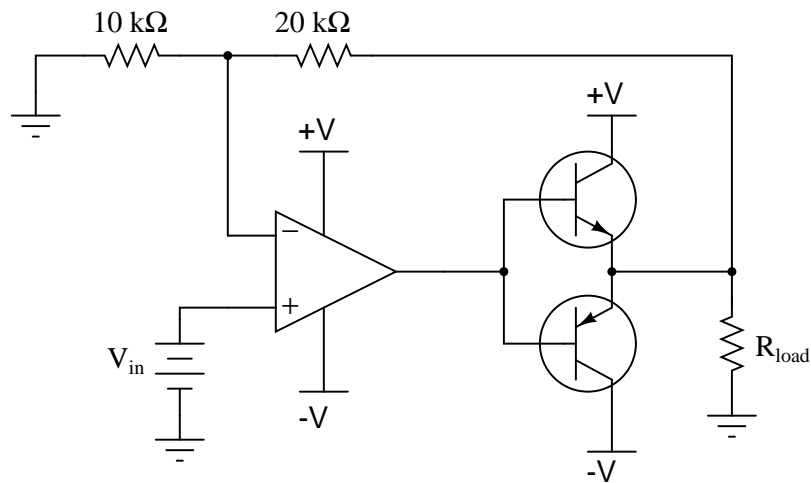
Answer 33

If you understand why this circuit works, pat yourself on the back: you truly understand the self-correcting nature of negative feedback. If not, you have a bit more studying to do!

Notes 33

The answer is not meant to be discouraging for those students of yours who do not understand how the solution works. It is simply a "litmus test" of whether or not your students really comprehend the concept of negative feedback. Although the change made in the circuit is simple, the principle is a bit of a conceptual leap for some people.

It might help your students understand if you label the new wire with the word *sense*, to indicate its purpose of providing feedback from the very output of the circuit, back to the opamp so it can sense how much voltage the load is receiving.
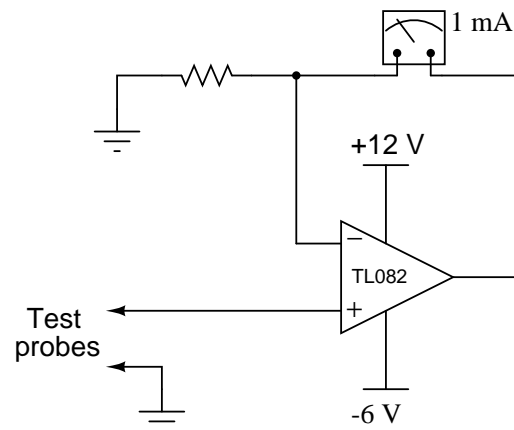
Question 34

Shown here is a simple circuit for constructing an extremely high input impedance voltmeter on a wireless breadboard, using one half of a TL082 dual op-amp:
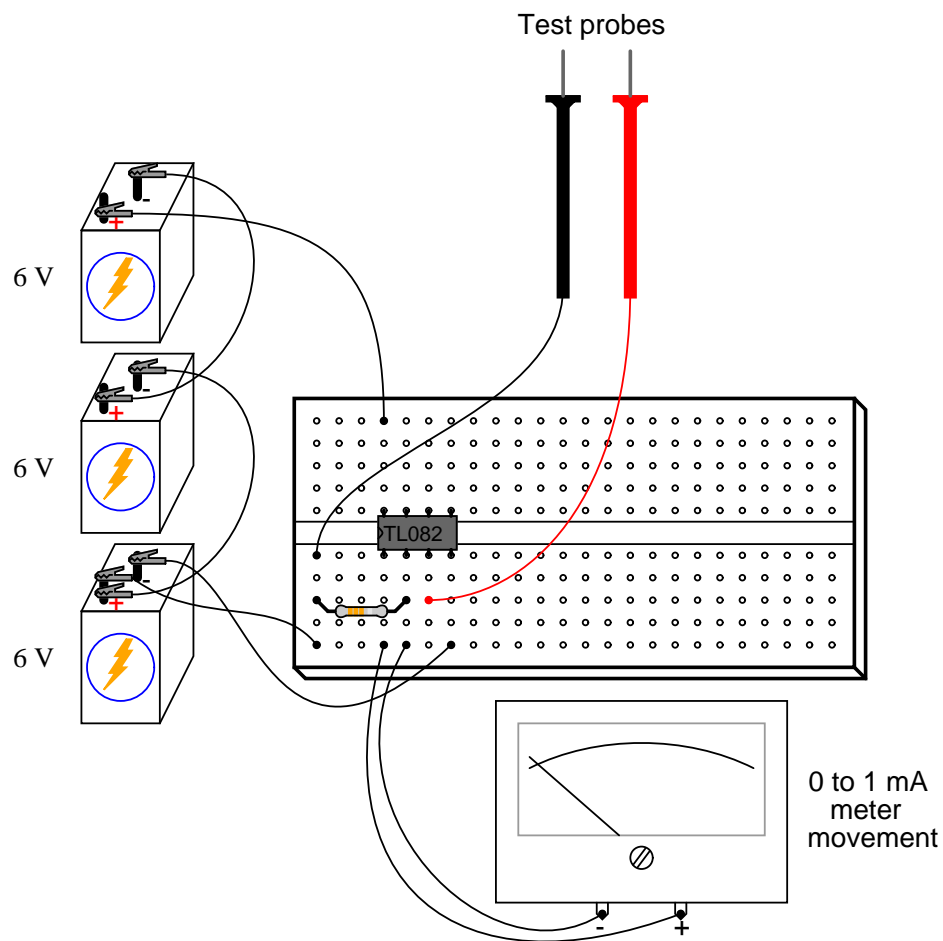
Draw a schematic diagram of this circuit, a calculate the resistor value necessary to give the meter a voltage measurement range of 0 to 5 volts.

file 00934

Answer 34

$R = 5$ kΩ

Follow-up question: determine the approximate input impedance of this voltmeter, and also the maximum voltage it is able to measure with *any* size resistor in the circuit.

Notes 34

This is a very practical circuit for your students to build, and they may find it outperforms their own (purchased) voltmeters in the parameter of input impedance! Be sure to ask them where they found the information on input impedance for the TL082 op-amp, and how they were able to determine the maximum input voltage for a circuit like this.

Question 35

This opamp circuit is called a *precision rectifier*. Analyze its output voltage as the input voltage smoothly increases from -5 volts to +5 volts, and explain why the circuit is worthy of its name:
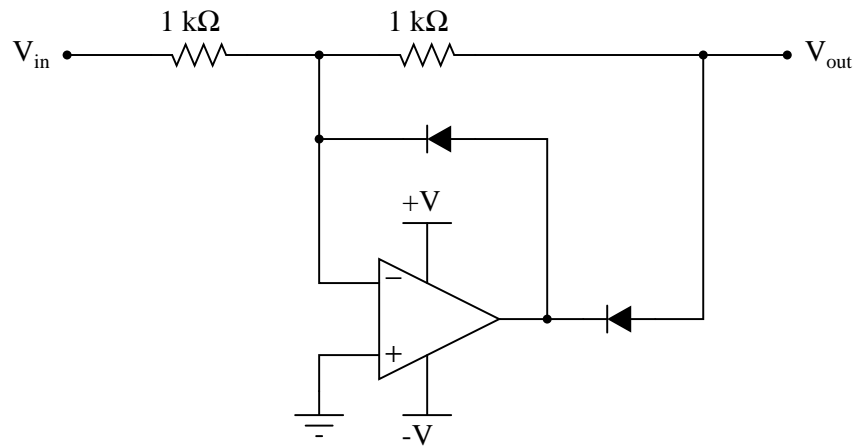
Assume that both diodes in this circuit are silicon switching diodes, with a nominal forward voltage drop of 0.7 volts.

file 01173

Answer 35

Any positive input voltage, no matter how small, is "reflected" on the output as a negative voltage of equal (absolute) magnitude. The output of this circuit remains exactly at 0 volts for any negative input voltage.

Follow-up question: would it affect the output voltage if the forward voltage drop of either diode increased? Explain why or why not.

Notes 35

Precision rectifier circuits tend to be more difficult for students to comprehend than non-rectifying inverting or noninverting amplifier circuits. Spend time analyzing this circuit together in class with your students, asking them to determine the magnitudes of all voltages in the circuit (and directions of current) for given input voltage conditions.

Understanding whether or not changes in diode forward voltage drop affect a precision rectifier circuit's function is fundamental. If students comprehend nothing else about this circuit, it is the relationship between diode voltage drop and input/output transfer characteristics.

Question 36

Suppose that diode D1 in this precision rectifier circuit fails open. What effect will this have on the output voltage?
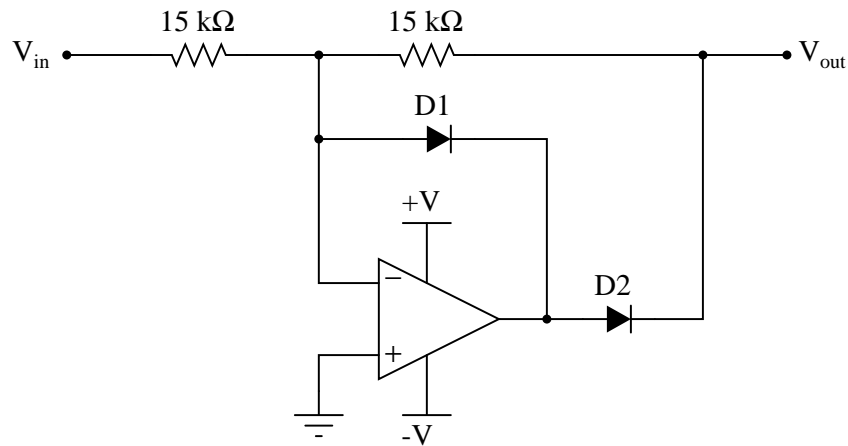
Hint: if it helps, draw a table of figures relating V_{in} with V_{out}, and base your answer on the tabulated results.

file 01174

Answer 36

Instead of the output voltage remaining at exactly 0 volts for any positive input voltage, the output will be equal to the (positive) input voltage, assuming it remains unloaded as shown.

Challenge question: what mathematical function does this circuit perform, with diode D1 failed open?

Notes 36

Note that the given failure does not render the circuit useless, but transforms its function into something different! This is an important lesson for students to understand: that component failures may not always results in complete circuit non-function. The circuit may continue to function, just differently. And, in some cases such as this, the new function may even appear to be intentional!

Question 37

Determine the output voltage of this circuit for the following input voltage conditions:

- $V_1 = +2$ volts
- $V_3 = -1.5$ volts
- $V_1 = +2.2$ volts
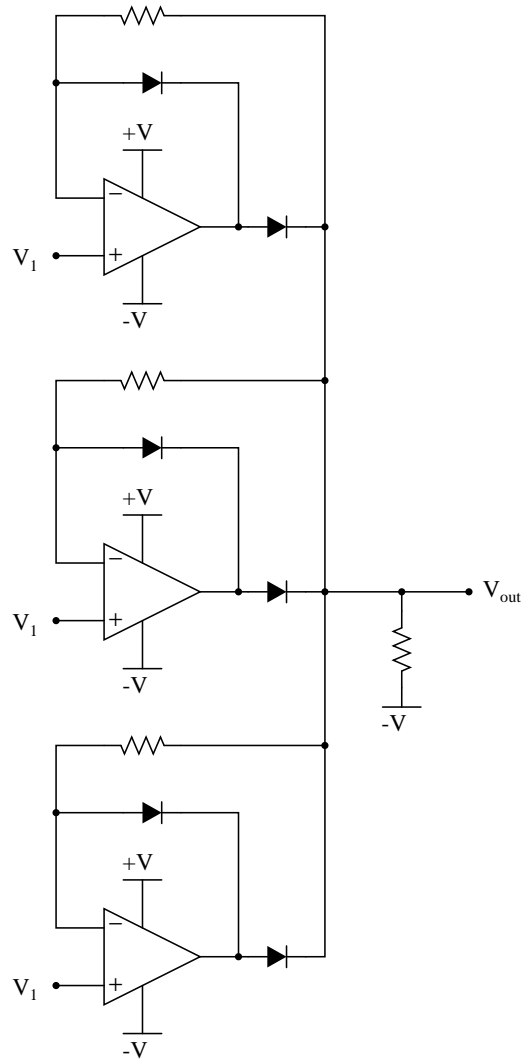
Hint: if you find this circuit too complex to analyze all at once, think of a way to simplify it so that you may analyze it one "piece" at a time.

file 01175

Answer 37

The output voltage will be +2.2 volts, precisely.

Follow-up question: what function does this circuit perform? Can you think of any practical applications for it?

Another facet of this question to ponder with your students is the simplification process, especially for those students who experience difficulty analyzing the whole circuit. What simplification methods did your students think of when they approached this problem? What conclusions may be drawn about the general concept of problem simplification (as a problem-solving technique)?

Question 38

A student connects a model CA3130 operational amplifier as a voltage follower (or voltage buffer), which is the simplest type of negative feedback op-amp circuit possible:
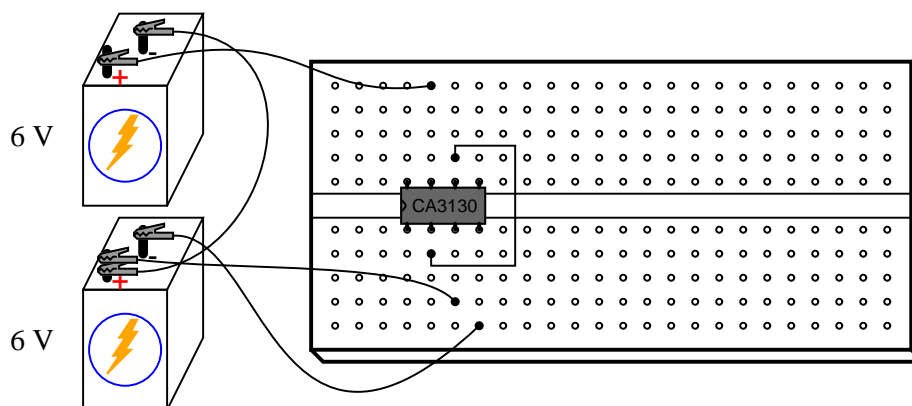
With the noninverting input connected to ground (the midpoint in the split +6/-6 volt power supply), the student expects to measure 0 volts DC at the output of the op-amp. This is what the DC voltmeter registers, but when set to AC, it registers substantial AC voltage!

Now this is strange. How can a simple voltage buffer output *alternating current* when its input is grounded and the power supply is pure DC? Perplexed, the student asks the instructor for help. "Oh," the instructor says, "you need a compensation capacitor between pins 1 and 8." What does the instructor mean by this cryptic suggestion?

file 00942

Answer 38

Some op-amps are inherently unstable when operated in negative-feedback mode, and will oscillate on their own unless "phase-compensated" by an external capacitor.

Follow-up question: Are there any applications of an op-amp such as the CA3130 where a compensation capacitor is not needed, or worse yet would be an impediment to successful circuit operation? Hint: some models of op-amp (such as the model 741) have built-in compensation capacitors!

Notes 38

Your students should have researched datasheets for the CA3130 op-amp in search of an answer to this question. Ask them what they found! Which terminals on the CA3130 op-amp do you connect the capacitor between? What size of capacitor is appropriate for this purpose?

Given the fact that some op-amp models come equipped with their own built-in compensation capacitor, what does this tell us about the CA3130's need for an external capacitor? Why didn't the manufacturer simply integrate a compensation capacitor into the CA3130's circuitry as they did with the 741? Or, to phrase the question more directly, ask your students to explain what *disadvantage* there is in connecting a compensation capacitor to an op-amp.

Question 39

Explain the effect that compensation capacitance has on an operational amplifier's gain-bandwidth product (GBW). Does a larger compensation capacitance yield a greater GBW or a lesser GBW, and why?

file 00980

Answer 39

The greater the amount of compensation capacitance in an op-amp (either internal, or externally connected), the less the GBW product.

Notes 39

In this question, the really important aspect is not the answer given. What is important here is that students understand what GBW product is, and how it is affected by this thing we call "compensation capacitance" (another topic of research). The goal here is to get students to research these concepts and relate them together, so please do not be satisfied with any student answers that merely restate the answer given here! Ask students to explain what these terms and concepts mean, and to explain *why* the GBW product decreases with increased C_{comp}.

Question 40

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:
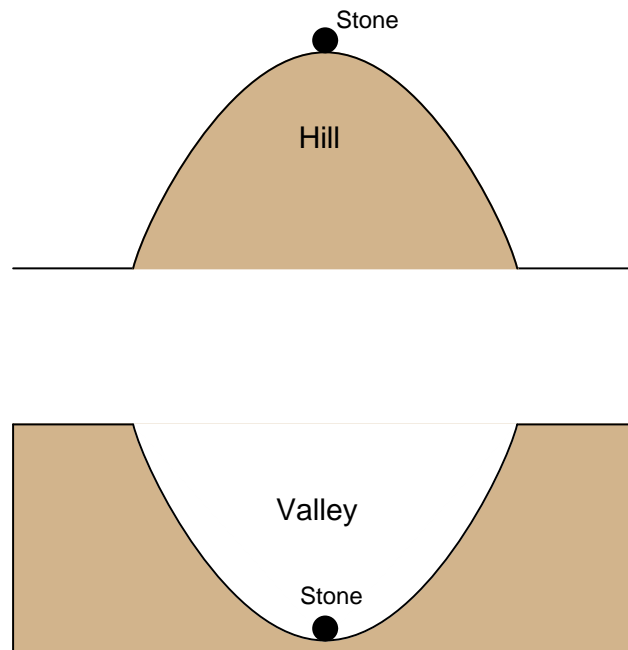
The stability of the stone in each of these scenarios represents the stability of a specific type of electrical feedback system. Which of these scenarios represents negative feedback, which represents positive feedback, and why?
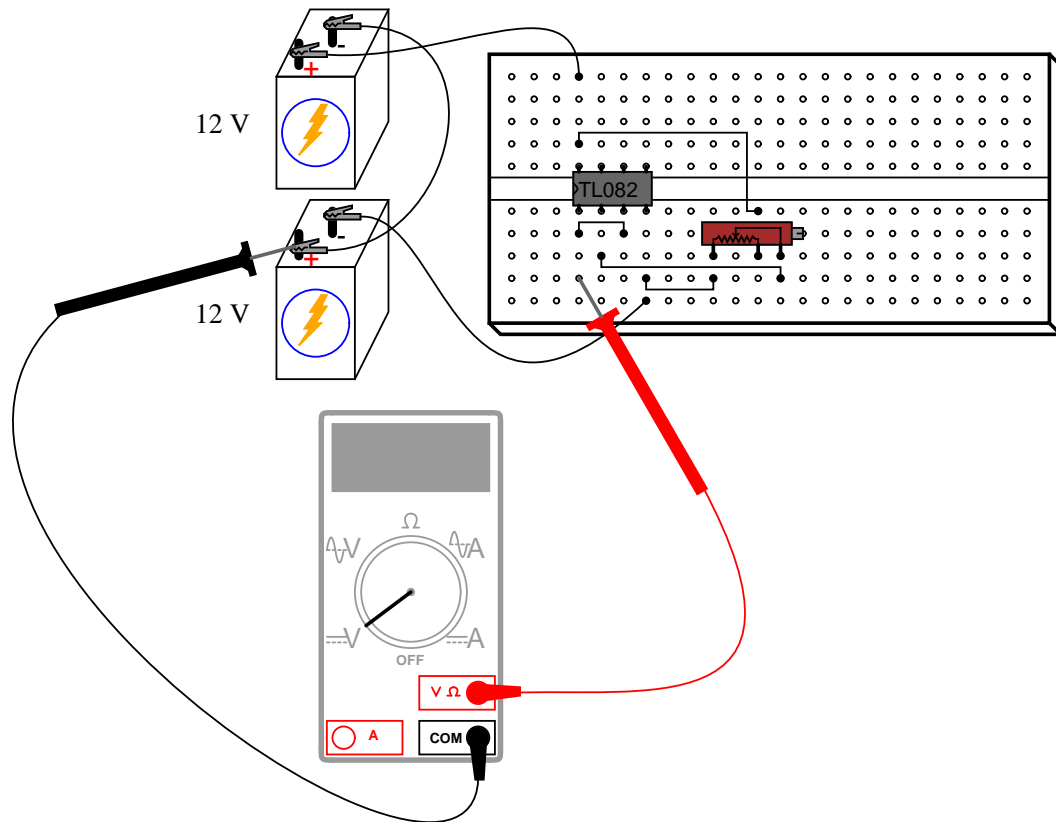
file 01149

Answer 40

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

Notes 40

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

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:
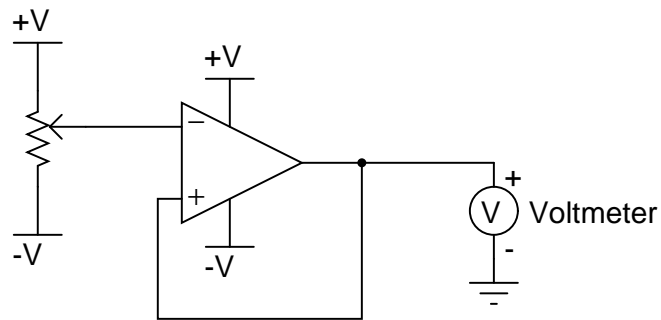

Draw a schematic diagram of this faulty circuit, and determine what the voltmeter's indication will be, explaining why it is such.

file 01148

Answer 41

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 41

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?

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:
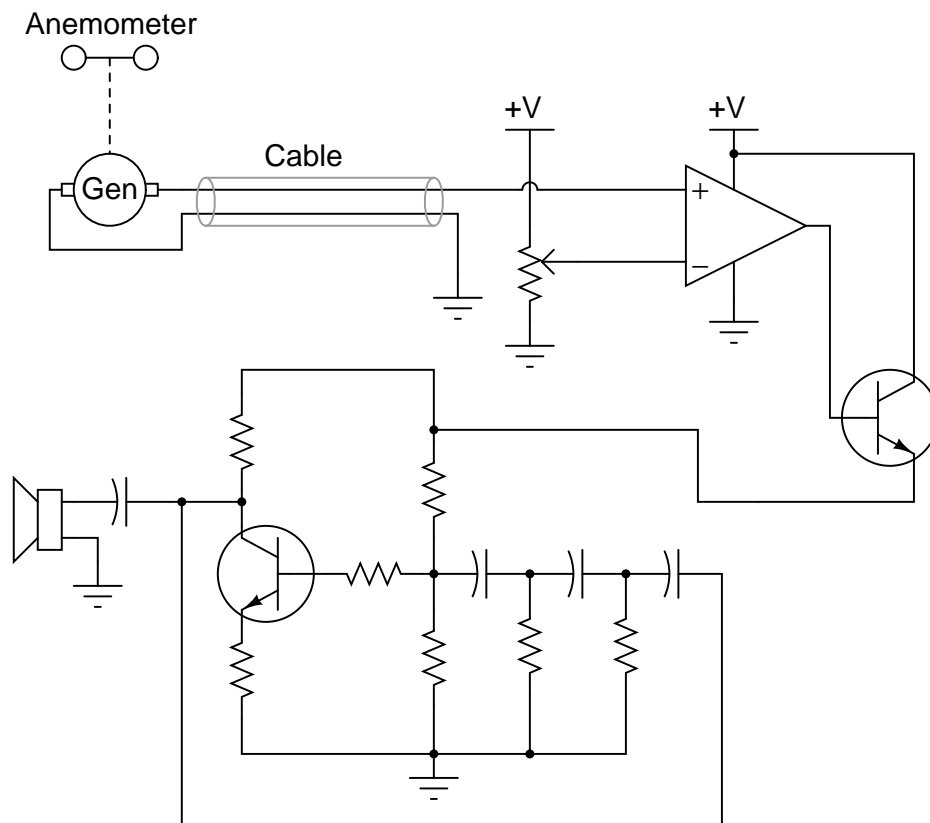
The circuit works well to warn of high wind speed, but when the wind speed is just near the threshold level, every little gust causes the alarm to briefly sound, then turn off again. What would be better is for the alarm to sound at a set wind speed, then *stay on* until the wind speed falls below a 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:
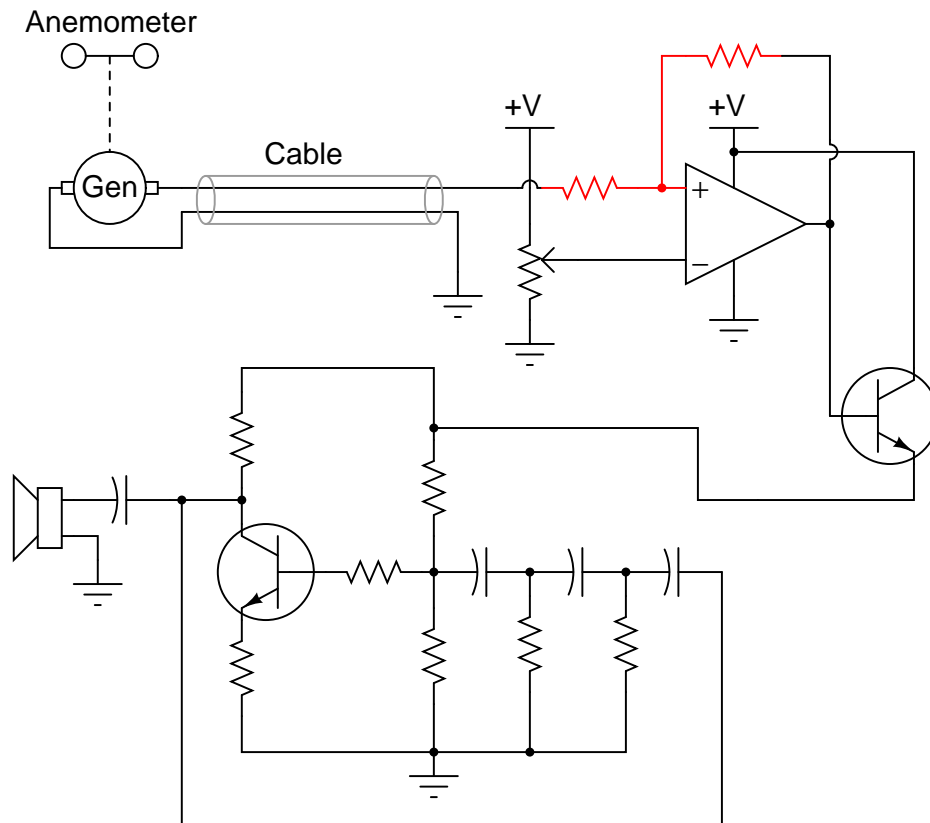
Explain why this circuit alteration works to solve the problem.

<u>file 01168</u>

Answer 42

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 42

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 43

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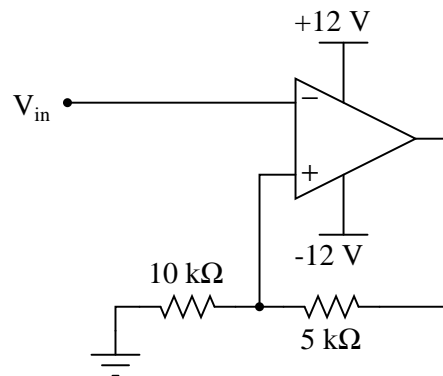
$$V_{UT} = \qquad\qquad V_{LT} =$$

file 01169
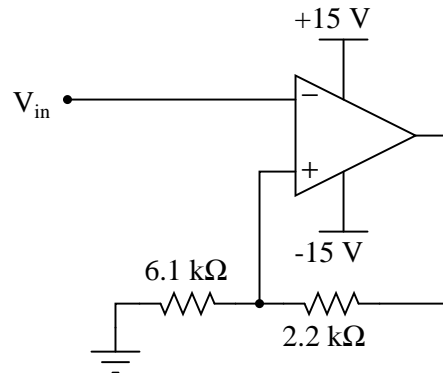
Answer 43

$V_{UT} = +8$ volts

$V_{LT} = -8$ volts

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

Notes 43

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 44

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:

$V_{UT} =$ $V_{LT} =$

file 01170

Answer 44

$V_{UT} = +10.29$ volts

$V_{LT} = -10.29$ 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 44

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

Question 45

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?
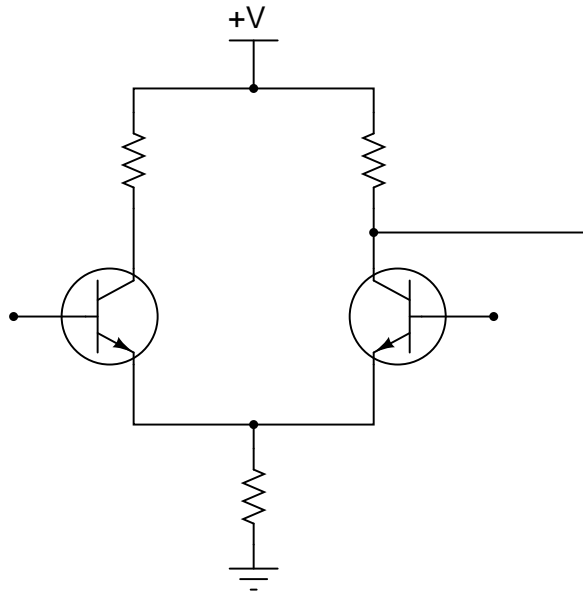
file 01243

Answer 45
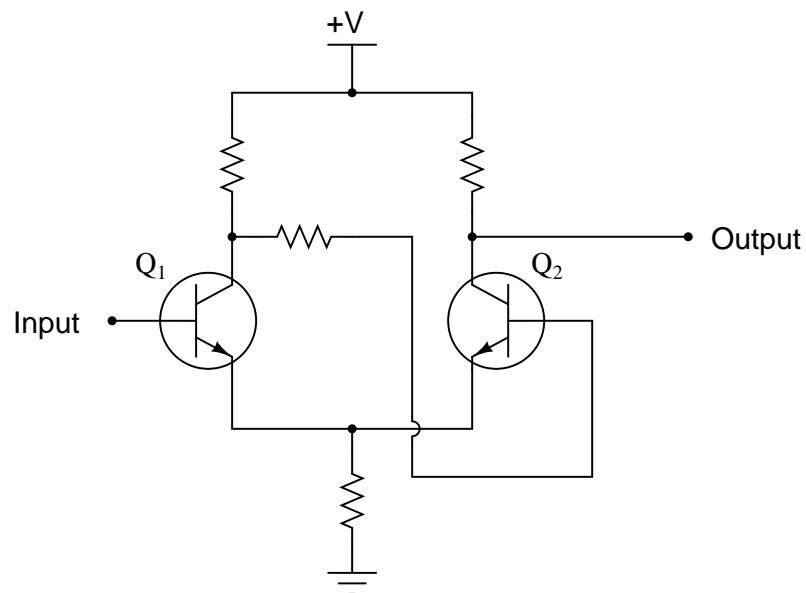
Ask your students to determine whether this Schmitt trigger circuit is inverting or non-inverting. Have them explain their reasoning step-by-step.

Authors Paul Horowitz and Winfield Hill, in their book <u>The Art of Electronics</u>, 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 46

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.
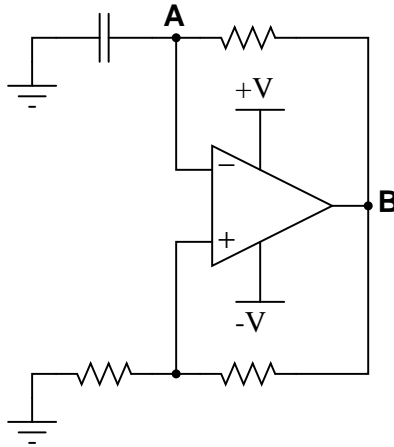
file 01172

Answer 46

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 46

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.

Question 47

This is a very common opamp oscillator circuit, technically of the *relaxation* type:

Explain how this circuit works, and what waveforms will be measured at points A and B. Be sure to make reference to *RC time constants* in your explanation.

file 01171

Answer 47

You will measure a sawtooth-like waveform at point A, and a square wave at point B.

Challenge question: explain how you might go about calculating the frequency of such a circuit, based on what you know about RC time constant circuits. Assume that the opamp can swing its output rail-to-rail, for simplicity.

Notes 47

This circuit is best understood by building and testing. If you use large capacitor values and/or a large-value resistor in the capacitor's current path, the oscillation will be slow enough to analyze with a voltmeter rather than an oscilloscope.

Question 48

What historical significance does the name "*operational amplifier*" have? Of course, it should be obvious that these devices are *amplifiers*, but what is meant by the word *operational*?

file 01000

Answer 48

Operational amplifier circuits were designed with the intent of electronically performing mathematical operations.

Notes 48

Your students should be able to find plenty of references to the historical development and use of op-amps as computational devices. Ask them where they found their information!

Question 49

Write a mathematical expression in the form of $y = \ldots x$ describing the function of this circuit:
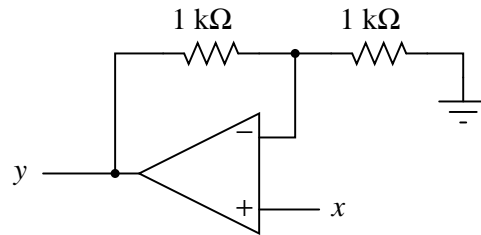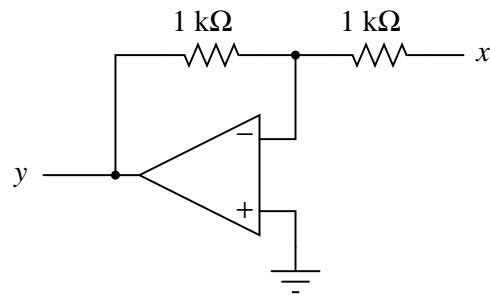
Answer 49

$y = 2x$

Notes 49

Your students should be able to recognize that this amplifier circuit has a voltage gain of 2, but expressing it in the form of an equation using variables such as x and y may be something very new to them. Discuss with your students the significance of this notation: that a *circuit* may embody an *equation*. Analog computers may be "obsolete" technology, but they still have many practical applications.

Question 50

Write a mathematical expression in the form of $y = \ldots x$ describing the function of this circuit:
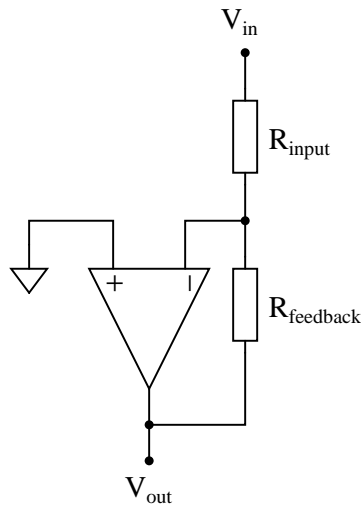

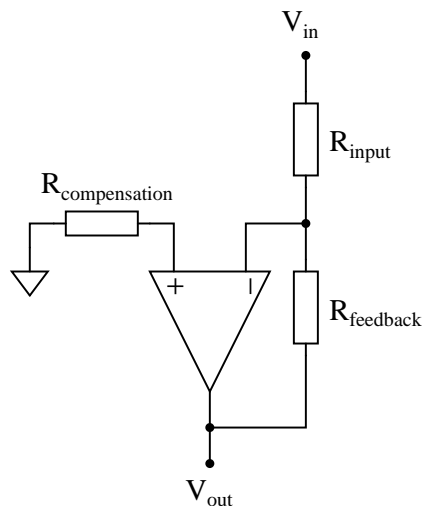file 01004

Answer 50

$y = -x$

Notes 50

Your students should be able to recognize that this amplifier circuit has a voltage gain of 1, and that it is *inverting* in nature, but expressing it in the form of an equation using variables such as x and y may be something very new to them. Discuss with your students the significance of this notation: that a *circuit* may embody an *equation*.

Question 51

Ideally, an inverting amplifier circuit may be comprised of just one op-amp and two resistors, as such:

However, if high accuracy is desired, a third resistor must be added to the circuit, in series with the other op-amp input:

Explain what this "compensation" resistor is compensating for, and also what its value should be.
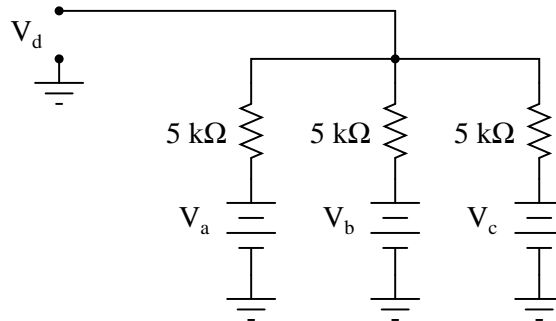
file 01007

Answer 51

The compensation resistor compensates for errors introduced into the voltage divider network due to input bias current. Its value should be equal to the parallel equivalent of R_{input} and $R_{feedback}$.

Notes 51

First, your students will have to know what "bias currents" are in op-amp circuits, so begin your discussion of this question with a call for this definition. Why the compensation resistor value must be equal to the *parallel* equivalent of the two resistors in the voltage divider is something that confuses most students. The key to understanding it is network analysis, in particular Thévenin's and Norton's theorems.

Question 52

The simple resistor network shown here is known as a *passive averager*. Describe what the word "passive" means in this context, and write an equation describing the output voltage (V_d) in terms of the input voltages (V_a, V_b, and V_c):

Hint: there is a network theorem that directly applies to this form of circuit, and it is known as *Millman's Theorem*. Research this theorem and use it to generate your equation!

file 01001

Answer 52

"Passive" means that the circuit contains no amplifying components.

$$V_d = \frac{V_a + V_b + V_c}{3}$$

Notes 52

Students need to realize that even passive circuits are able to model (some) mathematical functions! Ask your students if they can think of any network analysis methods to easily calculate the output voltage (V_d) of this circuit, given the input voltages. There is one theorem in particular that works very well for this particular circuit.
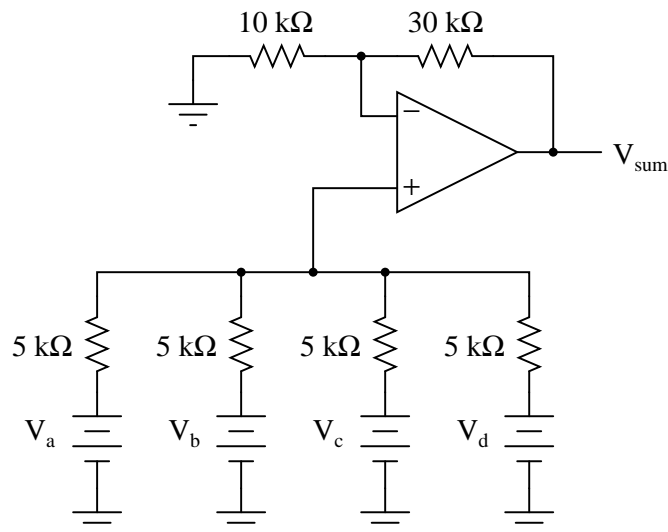
Question 53

Add an op-amp circuit to the output of this passive averager network to produce a *summer* circuit: an operational circuit generating an output voltage equal to the *sum* of the four input voltages. Then, write an equation describing the whole circuit's function.
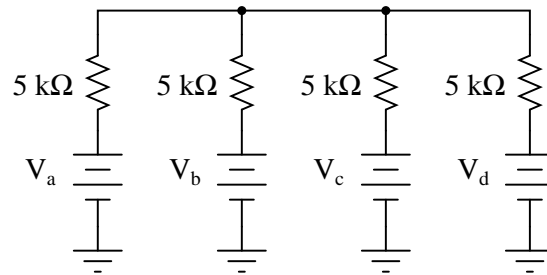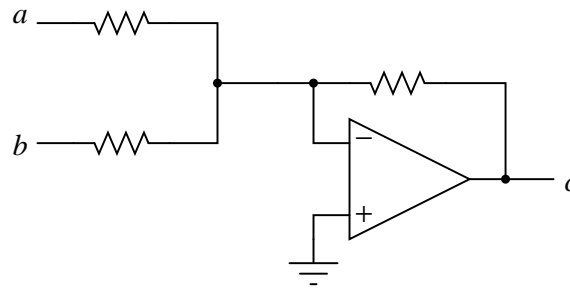

file 01002

Answer 53

$$V_{sum} = V_a + V_b + V_c + V_d$$

Notes 53

The equation for this circuit is simple enough as to require no explanation. How your students derived this equation, from the base equation of a passive averager network, on the other hand, is worth discussion. Discuss with them the necessary gain of the op-amp circuit, and how this gain figure converts an averaging function into a summing function.

Question 54

Write a mathematical equation for this op-amp circuit, assuming all resistor values are equal:

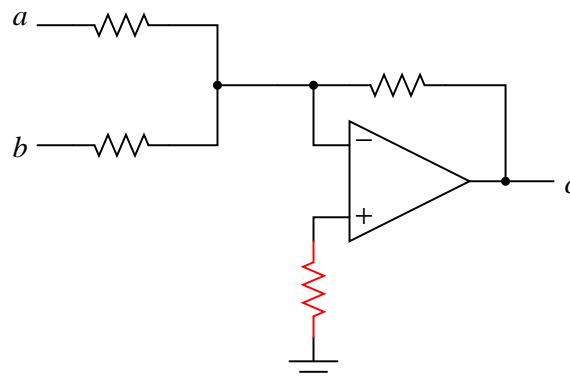What is this circuit typically called?
file 01003

Answer 54

$c = -(a + b)$

This type of circuit is typically called an *inverting summer*.

Follow-up question: explain why the addition of another resistor in this circuit is recommended for optimum accuracy, as shown in the following schematic.


Challenge question: write an equation describing the proper value of this extra resistor.

Notes 54

Ask your students about the proper resistor values for an inverting summer circuit. The choices of resistor values are definitely not the same for inverting summer and noninverting summer circuits alike! Discuss why the values are what they are in an inverting summer circuit (using Ohm's Law to analyze the circuit's function), emphasizing comprehension over rote memorization.

Question 55

This opamp circuit is known as a *difference amplifier*, sometimes called a *subtractor*. Assuming that all resistor values are equal in the circuit, write an equation expressing the output (y) as a function of the two input voltages (a and b):
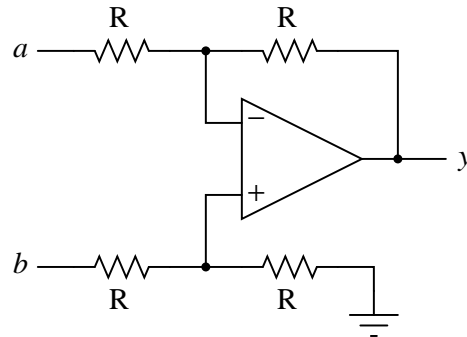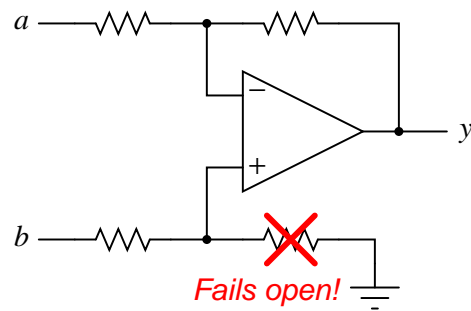

<u>file 01010</u>

Answer 55

$y = b - a$

Notes 55

Work through some example conditions of input voltages and resistor values to calculate the output voltage using Ohm's Law and the general principle of negative feedback in an opamp circuit (namely, an assumption of zero voltage differential at the opamp inputs). The goal here is to have students comprehend *why* this circuit subtracts one voltage from another, rather than just encourage rote memorization.

Question 56

Re-write the equation for this differential amplifier circuit, assuming that the marked resistor fails open:
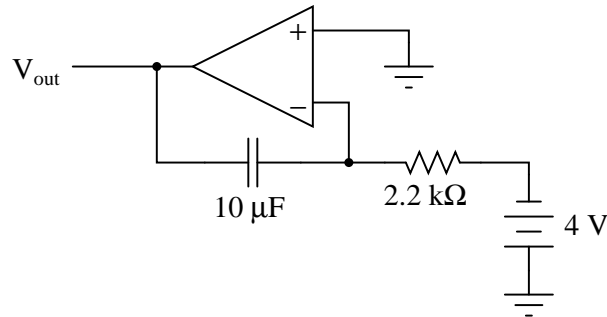

file 01011

Answer 56

$y = 2b - a$

Notes 56

Ask your students to explain how they would verify the failure of the marked resistor, using a voltmeter (not an ohmmeter!).

Question 57

$\int f(x)\,dx$ *Calculus alert!*

How much current will go "through" the capacitor in this op-amp circuit, and what effect does this have on the output voltage?

file 01008

Answer 57

$I_C = 1.818$ mA

This circuit is an *integrator*: its output voltage changes over time at a rate proportional to the input voltage magnitude.

Follow-up question: what is the output voltage rate-of-change over time ($\frac{dv}{dt}$) for the circuit shown in the question?


Notes 57

This question is a good review of capacitor theory (relating voltage and current with regard to a capacitor), as well as an introduction to how op-amp circuits can perform calculus functions.

Challenge your students to calculate the output $\frac{dv}{dt}$ without using a calculator!

Question 58

Practical integrator circuits must have a *compensating resistor* connected in parallel with the capacitor, in the feedback loop. Typically, this resistor value is very large: about 100 times as large as R_{in}.
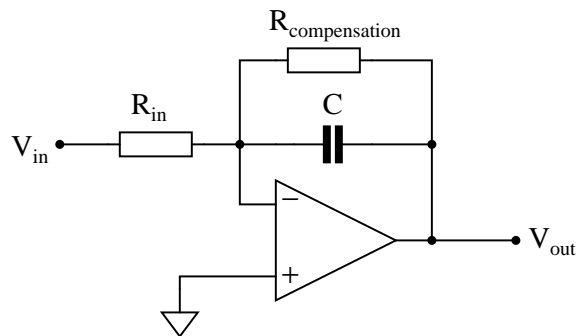
Describe why this is a necessity for accurate integration. Hint: an ideal opamp would not need this resistor!

file 01012

Answer 58

This compensation resistor helps offset errors otherwise incurred by the opamp's *bias current* on the inverting input.

Notes 58

Discuss where bias currents originate from in the opamp's internal circuitry, and ask your students if they have any recommendations on specific opamp types that minimize bias current.

Question 59

A *Rogowski Coil* is essentially an air-core current transformer that may be used to measure DC currents as well as AC currents. Like all current transformers, it measures the current going through whatever conductor(s) it encircles.

Normally transformers are considered AC-only devices, because electromagnetic induction requires a *changing* magnetic field ($\frac{d\phi}{dt}$) to induce voltage in a conductor. The same is true for a Rogowski coil: it produces a voltage only when there is a change in the measured current. However, we may measure any current (DC or AC) using a Rogowski coil if its output signal feeds into an integrator circuit as shown:
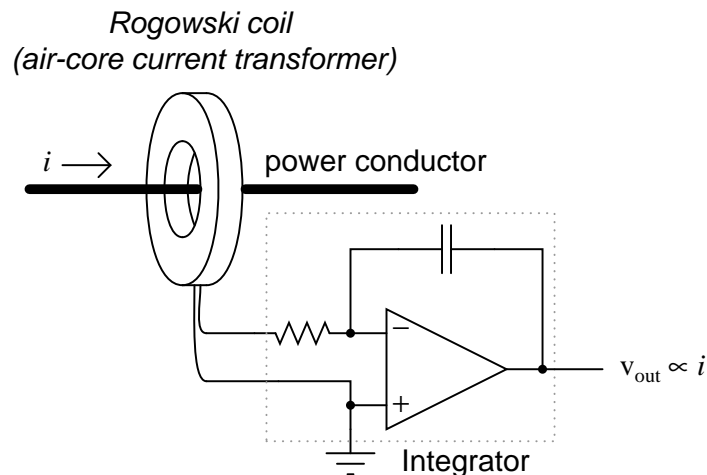
Connected as such, the output of the integrator circuit will be a direct representation of the amount of current going through the wire.

Explain why an integrator circuit is necessary to condition the Rogowski coil's output so that output voltage truly represents conductor current.

file 01009

Answer 59

The coil produces a voltage proportional to the conductor current's rate of change over time ($v_{coil} = M\frac{di}{dt}$). The integrator circuit produces an output voltage changing at a rate proportional to the input voltage magnitude ($\frac{dv_{out}}{dt} \propto v_{in}$). Substituting algebraically:

$$\frac{dv_{out}}{dt} = M\frac{di}{dt}$$

Review question: Rogowski coils are rated in terms of their *mutual inductance* (M). Define what "mutual inductance" is, and why this is an appropriate parameter to specify for a Rogowski coil.

Follow-up question: the operation of a Rogowski coil (and the integrator circuit) is probably easiest to comprehend if one imagines the measured current starting at 0 amps and linearly increasing over time. Qualitatively explain what the coil's output would be in this scenario and then what the integrator's output would be.

Challenge question: the integrator circuit shown here is an "active" integrator rather than a "passive" integrator. That is, it contains an amplifier (an "active" device). We could use a passive integrator circuit instead to condition the output signal of the Rogowski coil, but only if the measured current is purely AC. A passive integrator circuit would be insufficient for the task if we tried to measure a DC current – only an active integrator would be adequate to measure DC. Explain why.

Notes 59

This question provides a great opportunity to review Faraday's Law of electromagnetic induction, and also to apply simple calculus concepts to a practical problem. The coil's natural function is to *differentiate* the current going through the conductor, producing an output voltage proportional to the current's rate of change over time ($v_{out} \propto \frac{di_{in}}{dt}$). The integrator's function is just the opposite. Discuss with your students how the integrator circuit "undoes" the natural calculus operation inherent to the coil (differentiation).

The subject of Rogowski coils also provides a great opportunity to review what mutual inductance is. Usually introduced at the beginning of lectures on transformers and quickly forgotten, the principle of mutual inductance is at the heart of every Rogowski coil: the coefficient relating instantaneous current change through one conductor to the voltage induced in an *adjacent* conductor (magnetically linked).

$$v_2 = M\frac{di_1}{dt}$$

Unlike the iron-core current transformers (CT's) widely used for AC power system current measurement, Rogowski coils are inherently linear. Being air-core devices, they lack the potential for saturation, hysteresis, and other nonlinearities which may corrupt the measured current signal. This makes Rogowski coils well-suited for high frequency (even RF!) current measurements, as well as measurements of current where there is a strong DC bias current in the conductor. By the way, this DC bias current may be "nulled" simply by re-setting the integrator after the initial DC power-up!

If time permits, this would be an excellent point of departure to other realms of physics, where op-amp signal conditioning circuits can be used to "undo" the calculus functions inherent to certain physical measurements (acceleration vs. velocity vs. position, for example).

Question 60

$\boxed{\int f(x)\,dx \quad \textit{Calculus alert!}}$

The *chain rule* of calculus states that:

$$\frac{dx}{dy}\frac{dy}{dz} = \frac{dx}{dz}$$

Similarly, the following mathematical principle is also true:

$$\frac{dx}{dy} = \frac{\frac{dx}{dz}}{\frac{dy}{dz}}$$

It is very easy to build an opamp circuit that differentiates a voltage signal with respect to *time*, such that an input of x produces an output of $\frac{dx}{dt}$, but there is no simple circuit that will output the differential of one input signal with respect to a second input signal.

However, this does not mean that the task is impossible. Draw a block diagram for a circuit that calculates $\frac{dy}{dx}$, given the input voltages x and y. Hint: this circuit will make use of differentiators.

Challenge question: draw a full opamp circuit to perform this function!
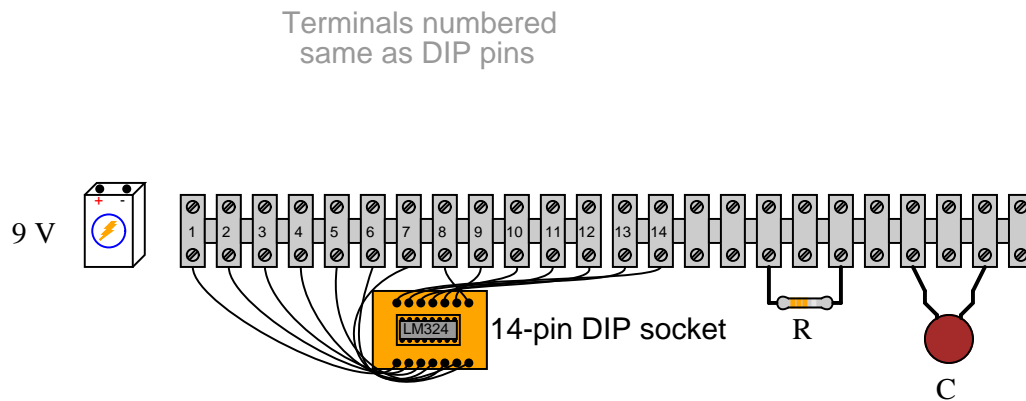file 01073

Answer 60
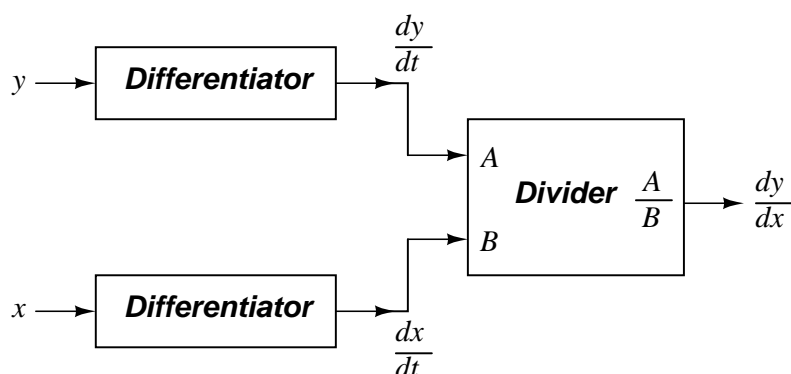
Notes 60

Differentiator circuits are very useful devices for making "live" calculations of time-derivatives for variables represented in voltage form. Explain to your students, for example, that the physical measurement of velocity, when differentiated with respect to time, is *acceleration*. Thus, a differentiator circuit connected to a tachogenerator measuring the speed of something provides a voltage output representing *acceleration*.

Being able to differentiate one signal in terms of another, although equally useful in physics, is not so easy to accomplish with opamps. A question such as this one highlights a practical use of calculus (the "chain rule"), where the differentiator circuit's natural function is exploited to achieve a more advanced function.
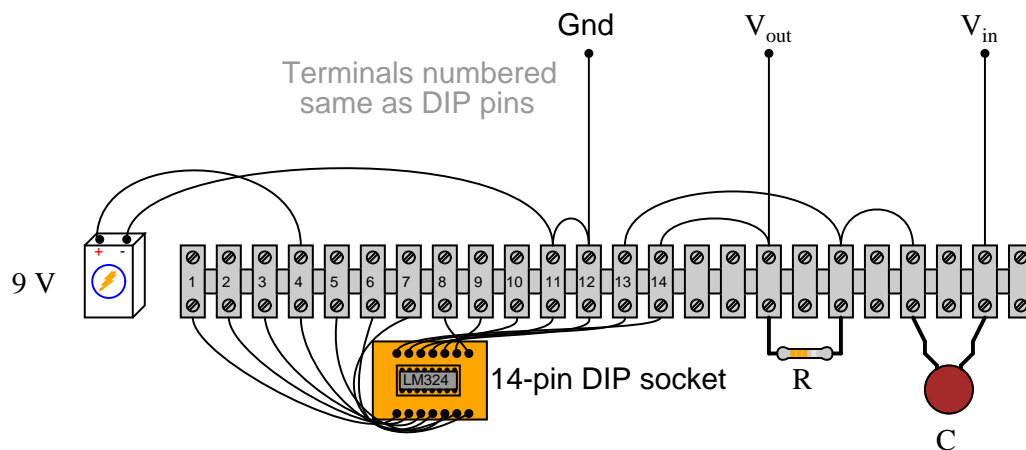
Question 61

Draw the appropriate wires in this diagram to complete the circuit for a *differentiator* circuit (the opposite function of an *integrator* circuit):

Terminals numbered same as DIP pins

9 V

LM324 14-pin DIP socket

R

C

The particular opamp used in this circuit is an LM324 (quad) operational amplifier. Of course, you need only show how one of the four opamps within the IC may be connected to form a differentiator.

file 01013

Answer 61

Gnd V_{out} V_{in}

Terminals numbered same as DIP pins

9 V

LM324 14-pin DIP socket

R

C

Challenge question: given the single-supply configuration (+9 volts only), this differentiator circuit can only respond to one direction of input voltage change ($\frac{dv_{in}}{dt}$). Which direction is this: positive or negative?
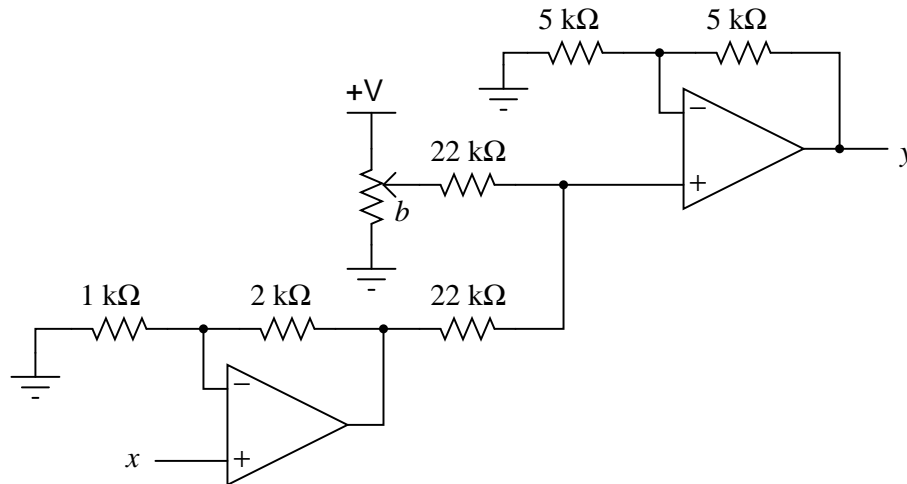
Notes 61

As always with problems centered around a pictorial diagram, the solution is more apparent if a schematic diagram is drawn as a "map" first. Ask your students to explain how they transitioned from the original diagram, to their own schematic, back to a completed diagram.

Also discuss the similarities between differentiator circuits and integrator circuits. The two mathematical functions are inverse operations of each other. How is this symmetry reflected in the respective circuit configurations?

Question 62

Write a mathematical expression in the form of $y = \ldots x$ describing the function of this circuit:

file 01006

Answer 62

$y = 3x + b$

Notes 62

In this circuit, we combine two different op-amp functions into one system, embodying a linear equation. Discuss with your students what circuit alterations would be required to change the coefficients of this equation.

If it helps some of your students understand the overall function of this circuit better, you might want to ask other students to outline which groups of components in this circuit perform which portion of the equation (while the circuit schematic is displayed on the whiteboard for all to see).

Question 63

Analog computers have been all but replaced by digital computers in modern electronic systems. Yet, analog computational circuits still enjoy certain advantages over digital circuits. Describe what some of the limitations of analog computers are, and why these limitations have led to their obsolescence. Also, discuss some of the advantages of analog computers, and why a designer might still choose to use an analog computational circuit in a modern system.

file 01005

Answer 63

Analog computational circuits are much less precise than their digital counterparts. On the other hand, analog circuits tend to be much simpler than digital circuits (for the same functions), and they are generally faster.

Notes 63

I like to introduce analog computational circuits to beginning electronics students because of their elegant simplicity, and for the fact that they greatly help to "link" the abstract world of mathematics to real mechanisms. Students are generally excited to realize they can build an actual *computer* with just a handful of inexpensive electronic components.
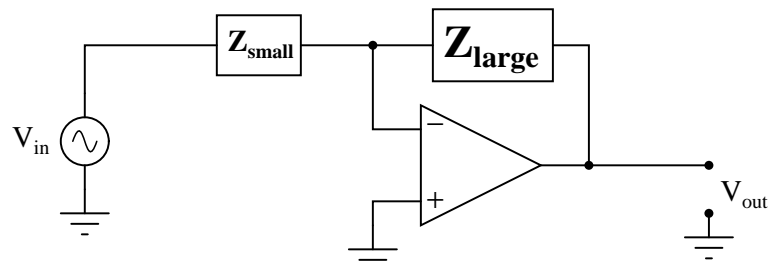
Question 64

Compare the voltage gains of these two opamp circuits:
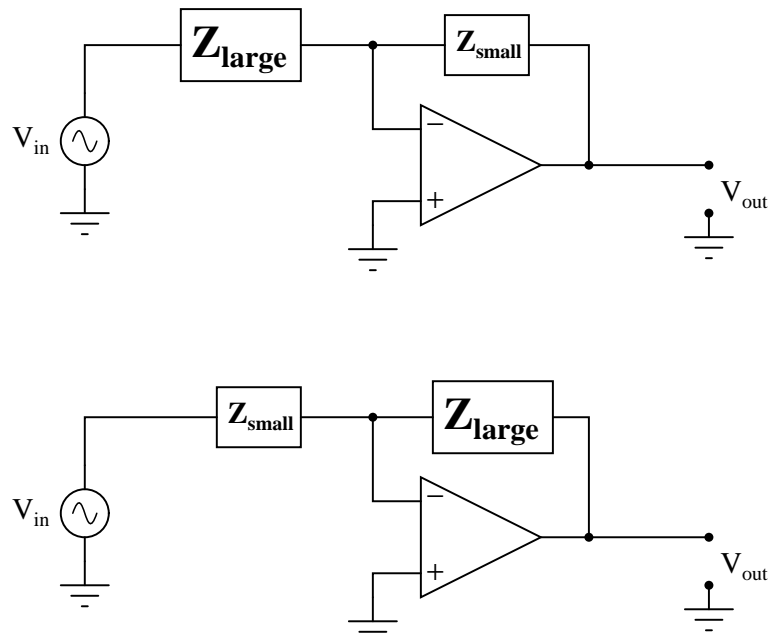
Which one has the greater A_V, and why?
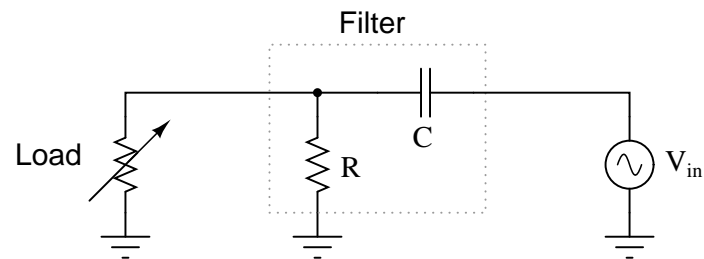<u>file 00700</u>

Answer 64

This opamp circuit has the greater voltage gain, because its $\frac{Z_{feedback}}{Z_{input}}$ ratio is greater.

Notes 64

It is common to see impedances represented as boxes, if their constituent components are not germane to the operation of the circuit.

Question 65

In this passive filter circuit, how will the filter's cutoff frequency be affected by changes in the load resistance? Be as specific as you can in your answer.

file 00701

Answer 65

f_{cutoff} will increase as the load resistance decreases.

Notes 65

Ask your students to define what "cutoff frequency" means. There is more than one definition: one based on output voltage, and one based on output power. When defined in terms of power, the cutoff frequency is sometimes described as f_{-3dB}.

Question 66

In this active filter circuit, how will the filter's cutoff frequency be affected by changes in the load resistance? Be as specific as you can in your answer.
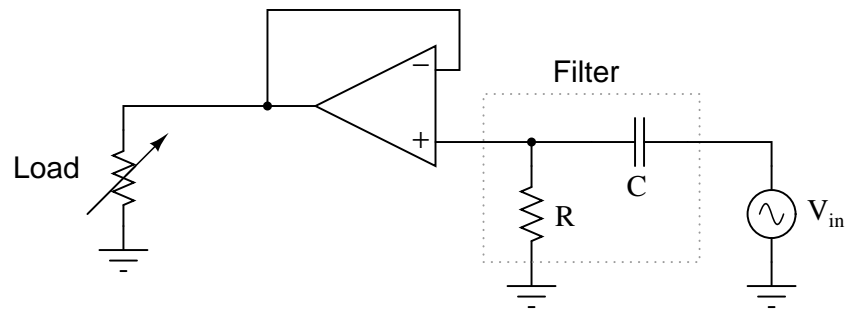
Answer 66

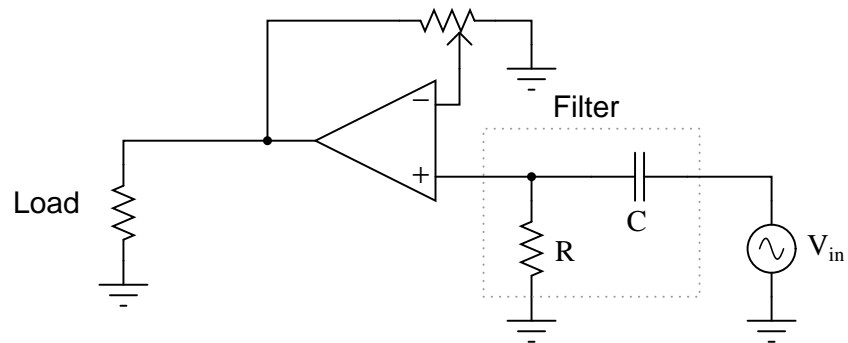f_{cutoff} is unaffected by changes in load resistance.

Follow-up question: explain the opamp's role in providing immunity to the filter circuit from load resistance changes. *How* does it accomplish this feat?

Notes 66

Ask your students what the function of the opamp is, taken by itself. What do we call an opamp that has its output directly connected to its inverting input? How does this function and name relate to the granting of load-impedance immunity in the filter circuit shown in the question?

Question 67

In this filter circuit, how will the filter's cutoff frequency be affected by changes in the potentiometer position? Be as specific as you can in your answer.

file 00703

Answer 67

This is a "trick" question: f_{cutoff} is unaffected by changes in the potentiometer's position.

Follow-up question: what *does* change as the potentiometer wiper is moved back and forth along its adjustment range?

Notes 67

Ask your students what the function of the op-amp is (with potentiometer feedback), taken by itself. If there were no filter circuit in place at all, but V_{in} connected straight to the op-amp's noninverting input, what function would the potentiometer adjustment serve?

Question 68

Describe what will happen to the impedance of both the capacitor and the resistor as the input signal frequency increases:
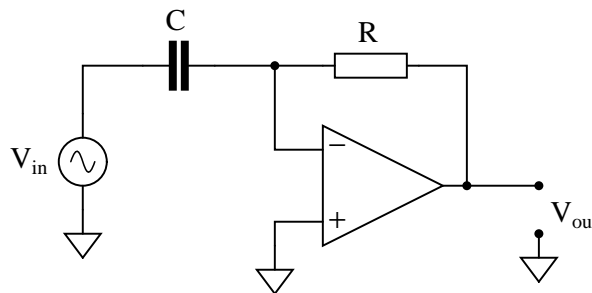
Also, describe what result the change in impedances will have on the op-amp circuit's voltage gain. If the input signal amplitude remains constant as frequency increases, what will happen to the amplitude of the output voltage? What type of filtering function does this behavior represent?

file 00704

Answer 68

As the frequency of V_{in} increases, Z_C decreases and Z_R remains unchanged. This will result in an increased A_V for the amplifier circuit.

Follow-up question: normally we calculate the cutoff frequency of a simple RC filter circuit by determining the frequency at which $R = X_C$. Here, things are a little different. Determine the voltage gain (A_V) when $R = X_C$, and also determine the phase shift from input to output.

Challenge question #1: explain why the phase shift from input to output for this circuit is always constant, regardless of signal frequency.

Challenge question #2: explain why this type of circuit is usually equipped with a low-value resistor (R_1) in series with the input capacitor:
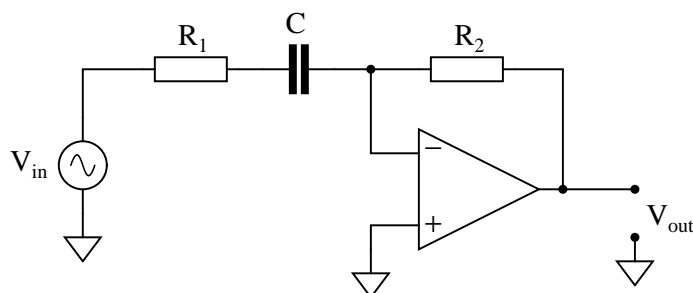

Notes 68

The answer I've given is technically correct, but there is a practical limit here. As we know, the intrinsic gain of an op-amp does not remain constant as signal frequency rises. Ask your students to describe the impact of this phenomenon on the circuit's performance at very high frequencies.

On another note, this same op-amp circuit is known by a particular name when used with DC input signals. Ask your students what this design of circuit is called.

Question 69

Describe what will happen to the impedance of both the capacitor and the resistor as the input signal frequency increases:
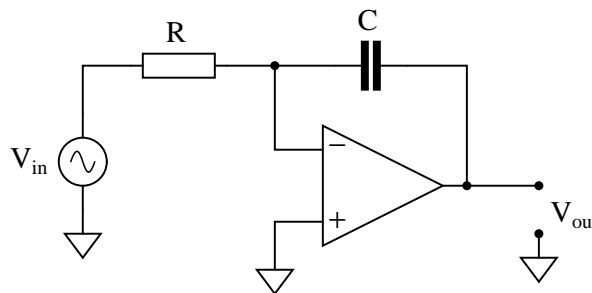

Also, describe what result the change in impedances will have on the op-amp circuit's voltage gain. If the input signal amplitude remains constant as frequency increases, what will happen to the amplitude of the output voltage? What type of filtering function does this behavior represent?

file 00710

Answer 69

As the frequency of V_{in} increases, Z_C decreases and Z_R remains unchanged. This will result in a decreased A_V for the amplifier circuit.

Challenge question: explain why this type of circuit is usually equipped with a high-value resistor (R_2) in parallel with the feedback capacitor:
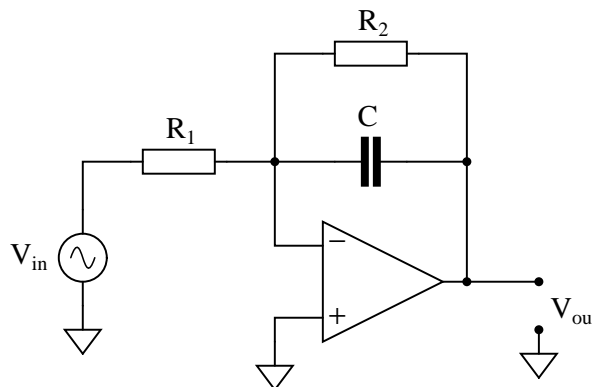

Notes 69

This same op-amp circuit is known by a particular name when used with DC input signals. Ask your students what this design of circuit is called. When receiving a DC input signal, what function does it serve? The answer to this is key to answering the "challenge" question.

Question 70

Approximate the voltage gains of this *active filter* circuit at $f = 0$ and $f = \infty$ (assume ideal op-amp behavior):
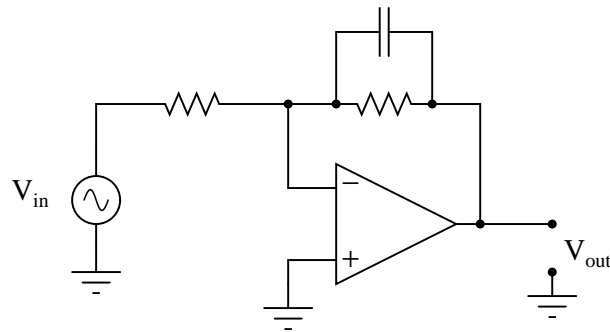
Approximate the voltage gains of this other "active filter" circuit at $f = 0$ and $f = \infty$ (assume ideal op-amp behavior):
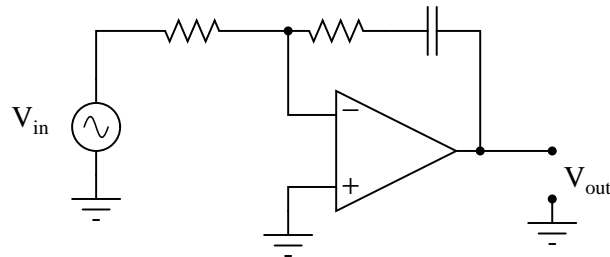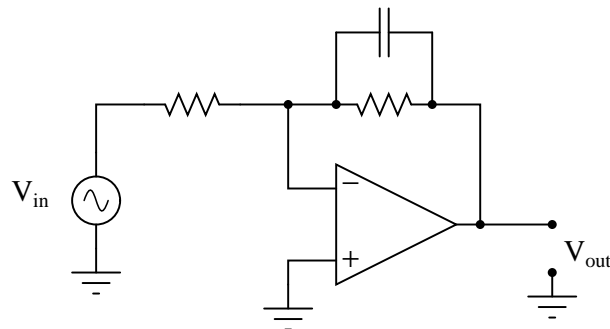

What type of filtering function (low pass, high pass, band pass, band stop) is provided by both these filter circuits? Comparing these two circuit designs, which one do you think is more practical? Explain your answer.

file 00706

Answer 70

These are both low pass filters. The circuit with the shunt capacitor is the more practical one, because its voltage gain remains finite for all possible input signal frequencies:
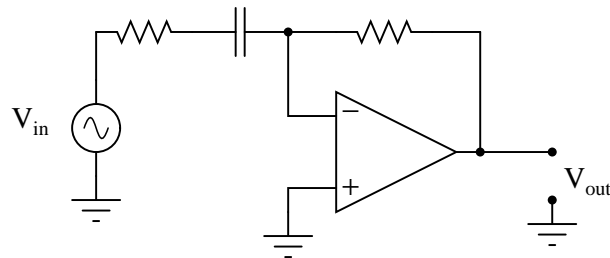
Discuss with your students their methods of determining filter type. How did they approach this problem, to see what type of filter both these circuits were?
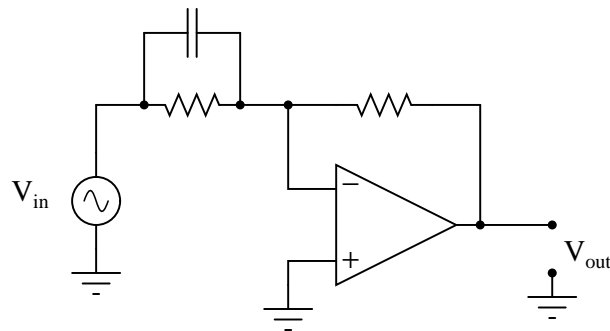
Also, discuss with your students the problem of having an amplifier circuit with an unchecked gain (approaching infinity). Ask them what is wrong with obtaining such high voltage gains from any amplifier. Have them describe to you the effect of a huge voltage gain on the integrity of the amplified signal.

Question 71

Approximate the voltage gains of this *active filter* circuit at $f = 0$ and $f = \infty$ (assume ideal op-amp behavior):

Approximate the voltage gains of this other "active filter" circuit at $f = 0$ and $f = \infty$ (assume ideal op-amp behavior):
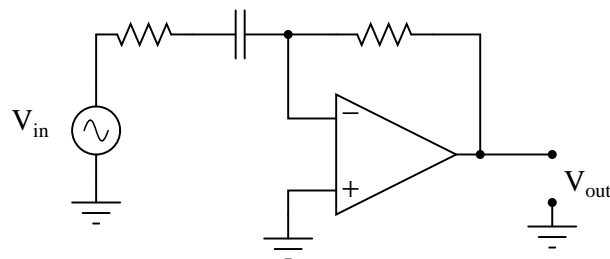

What type of filtering function (low pass, high pass, band pass, band stop) is provided by both these filter circuits? Comparing these two circuit designs, which one do you think is more practical? Explain your answer.

file 00707

Answer 71

These are both high pass filters. The circuit with the series capacitor is the more practical one, because its voltage gain remains finite for all possible input signal frequencies:
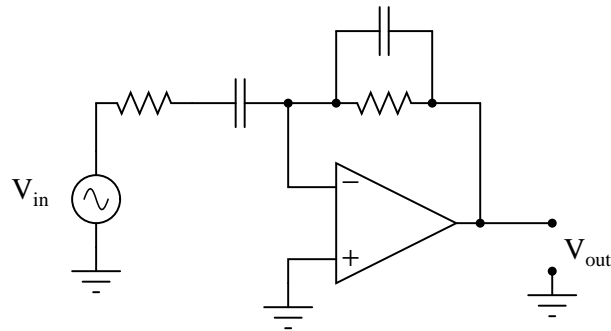
Discuss with your students their methods of determining filter type. How did they approach this problem, to see what type of filter both these circuits were?

Also, discuss with your students the problem of having an amplifier circuit with an unchecked gain (approaching infinity). Ask them what is wrong with obtaining such high voltage gains from any amplifier. Have them describe to you the effect of a huge voltage gain on the integrity of the amplified signal.

Question 72

Identify the function of this active filter:

It is low pass, high pass, band pass, or band stop? Explain your answer.
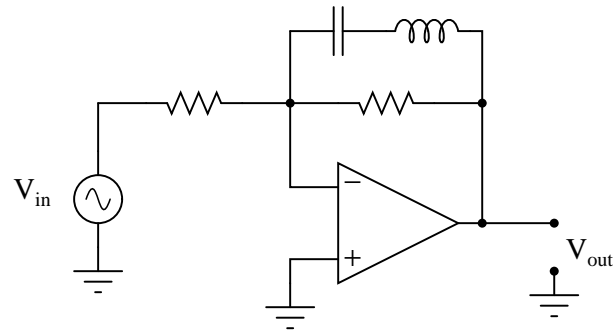
<u>file 00708</u>

Answer 72

This is a band pass filter circuit.

Notes 72

Discuss with your students their methods of determining filter type. How did they approach this problem, to see what type of filter this circuit was? Determining the identify of a "band-" filter is more difficult than with a low- or a high- pass filter circuit, because the behavior is roughly the same at both extremes of the frequency range.

Question 73

Identify the function of this active filter:

It is low pass, high pass, band pass, or band stop? Explain your answer.

<u>file 00709</u>

Answer 73

This is a band stop filter circuit.

Challenge question: how much voltage gain does this amplifier have at resonance? How much voltage gain does it have at $f = 0$ and $f = \infty$, if the two resistor values are equal?

Notes 73

If some students have difficulty analyzing the function of this circuit, ask them to identify the total impedance of a series-connected inductor and capacitor at resonance, then transfer that amount of impedance to the circuit to see what the effects will be at the resonant frequency.

Question 74

A very popular active filter topology is called the *Sallen-Key*. Two examples of Sallen-Key active filter circuits are shown here:
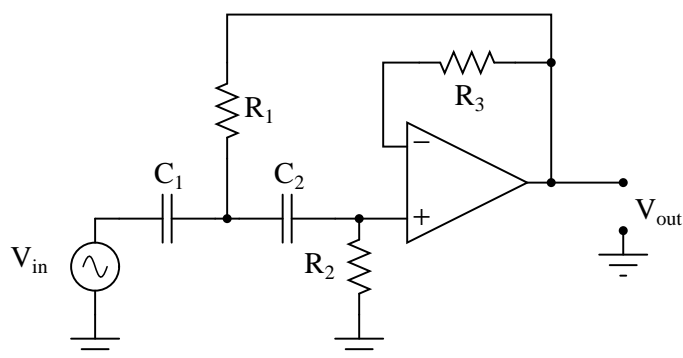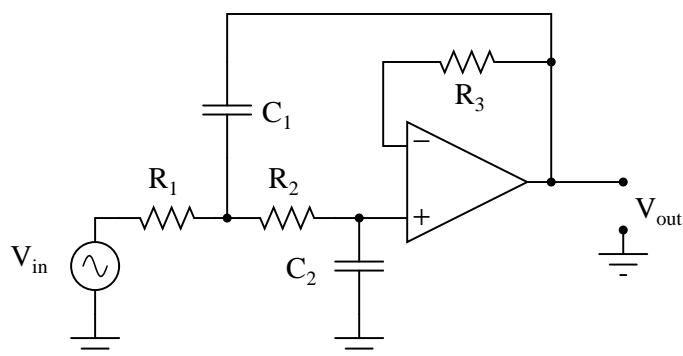
Determine which of these Sallen-Key filters is low pass, and which is high pass. Explain your answers.
<u>file 00765</u>

Answer 74

The first filter shown is low pass, while the second filter shown is high pass.

Challenge question: what is the purpose of resistor R_3 in each circuit?

Notes 74

The word "topology" may be strange to your students. If any of them ask you what it means, ask them if they own a dictionary!

Like all the other active filter circuits, the fundamental characteristic of each filter may be determined by qualitative analysis at $f = 0$ and $f = \infty$. This is a form of *thought experiment*: determining the characteristics of a circuit by imagining the effects of certain given conditions, following through by analysis based on "first principles" of circuits, rather than by researching what the circuit's intended function is.

Resistor R_3 is actually not essential to the circuit's operation, but is normally found in Sallen-Key filters anyway. If it makes the analysis of the circuit any simpler, tell your students they may replace that resistor with a straight wire in their schematic diagrams.

Question 75

In active and passive filter design literature, you often come across filter circuits classified as one of three different names:

- Chebyshev
- Butterworth
- Bessel

Describe what each of these names means. What, exactly, distinguishes a "Chebyshev" filter circuit from a "Butterworth" filter circuit?

file 00766

Answer 75

Each of these terms describes a class of filter *responses*, rather than a particular circuit configuration (topology). The shape of the Bode plot for a filter circuit is the determining factor for whether it will be a "Chebyshev," "Butterworth," or "Bessel" filter.

Notes 75

I purposely omitted Bode plot examples for these three filter classifications. Presentation and examination of Bode plots is an appropriate activity for discussion time. Draw a set of Bode plot axes on the whiteboard, and then have students draw approximate Bode plots for each filter response, as determined from their research.

In the early 1970's, the Fluke company invented a revolutionary new "RMS sensor" integrated circuit, used to convert an arbitrary waveform into its DC-equivalent (RMS) voltage. The device uses two precision resistors to heat a pair of matched transistors connected as a differential pair:
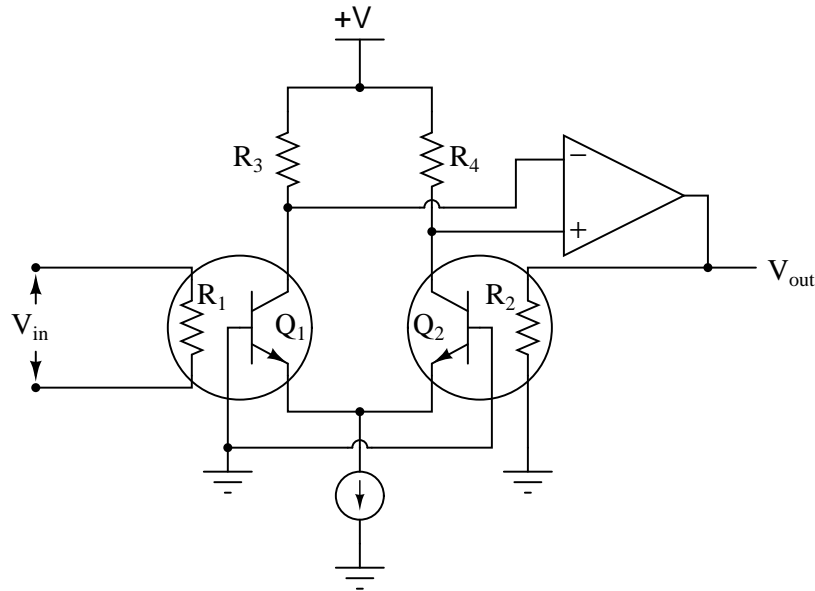
Describe how this circuit functions. What physical principle(s) does it use to derive an RMS value for V_{in}? Why is it important that all identical components (transistors, resistors) be precisely matched?
file 01014

Answer 76

This circuit exploits the temperature sensitivity of transistors to sense thermal balance between the two resistors R1 and R2. By definition, whatever DC voltage produces the same heat dissipation in a given resistance as an AC voltage is the RMS value of that AC voltage.

Notes 76

This question provides a good opportunity to review the function of differential pair circuits, and also the concept of RMS AC measurement. Ask your students how temperature influences the conductivity of bipolar junction transistors, and how the opamp's connection to resistor R2 forms a negative feedback loop.

Question 77

The relationship between voltage and current for a PN junction is described by this equation, sometimes referred to as the "diode equation," or "Shockley's diode equation" after its discoverer:

$$I_D = I_S(e^{\frac{qV_D}{NkT}} - 1)$$

Where,

I_D = Current through the PN junction, in amps

I_S = PN junction saturation current, in amps (typically 1 picoamp)

e = Euler's number ≈ 2.718281828

q = Electron unit charge, 1.6×10^{-19} coulombs

V_D = Voltage across the PN junction, in volts

N = Nonideality coefficient, or emission coefficient (typically between 1 and 2)

k = Boltzmann's constant, 1.38×10^{-23}

T = Junction temperature, degrees Kelvin

At first this equation may seem very daunting, until you realize that there are really only three variables in it: I_D, V_D, and T. All the other terms are constants. Since in most cases we assume temperature is fairly constant as well, we are really only dealing with two variables: diode current and diode voltage. Based on this realization, re-write the equation as a proportionality rather than an equality, showing how the two variables of diode current and voltage relate:

$$I_D \propto \ . \ . \ .$$

Based on this simplified equation, what would an I/V graph for a PN junction look like? How does this graph compare against the I/V graph for a resistor?
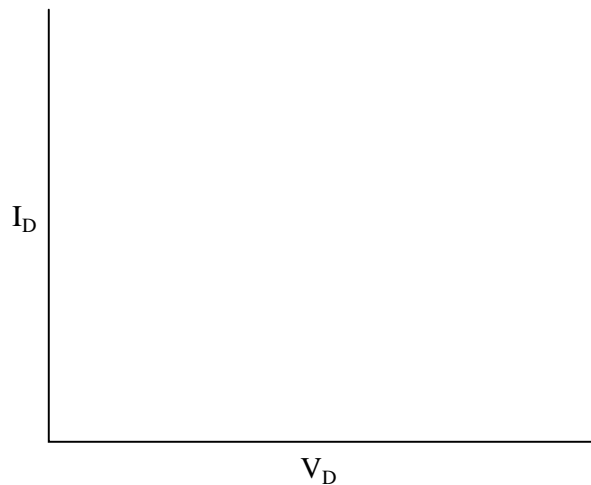
file 00712

Answer 77

Simplified proportionality:

$$I_D \propto e^{V_D}$$

The graph described by the "diode formula" is a standard exponential curve, rising sharply as the independent variable (V_D, in this case) increases. The corresponding graph for a resistor, of course, is linear.

95

Ask your students to sketch their own renditions of an exponential curve on the whiteboard for all to see. Don't just let them get away with parroting the answer: "It's an exponential curve."
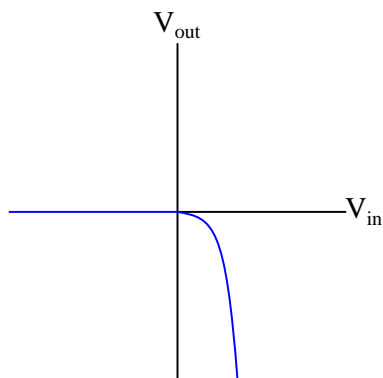
Question 78

Plot the transfer function (V_{out} versus V_{in}) for this opamp circuit, and explain how the circuit works:
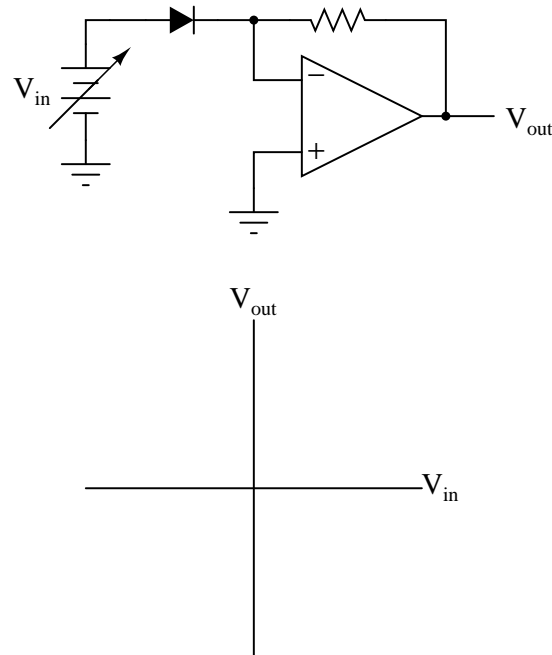
What type of mathematical function is represented by this circuit?
file 01015

Answer 78

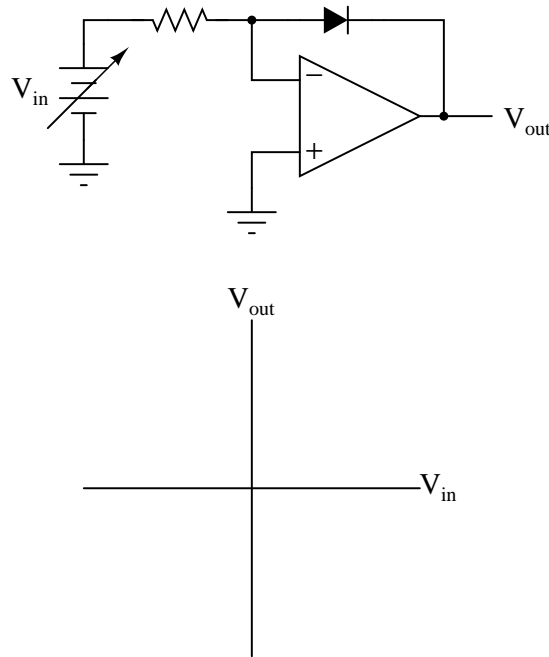This circuit represents an *exponential* function ($y \propto e^x$):

Notes 78

The direction of the transfer function curve may surprise some students. Ask them why the curve goes down (negative) for increasingly positive input voltages.

Plot the transfer function (V_{out} versus V_{in}) for this opamp circuit, and explain how the circuit works:
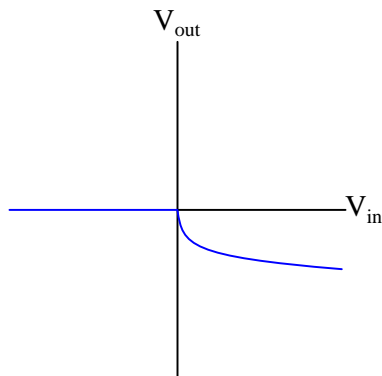

What type of mathematical function is represented by this circuit?
file 01016

Answer 79

This circuit represents a *logarithmic* function ($y \propto \ln x$):

Notes 79

The direction of the transfer function curve may surprise some students. Ask them why the curve goes down (negative) for increasingly positive input voltages.

Ask your students how they obtained this transfer function curve. There are conceptual methods for obtaining it, as well as algebraic methods. It would be interesting to compare more than one of these methods in a class discussion, and have students gain insight from each others' methods.
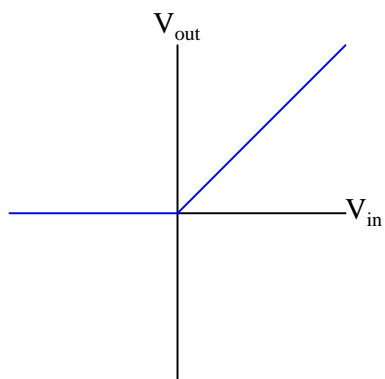
Question 80

Plot the transfer function (V_{out} versus V_{in}) for this opamp circuit:
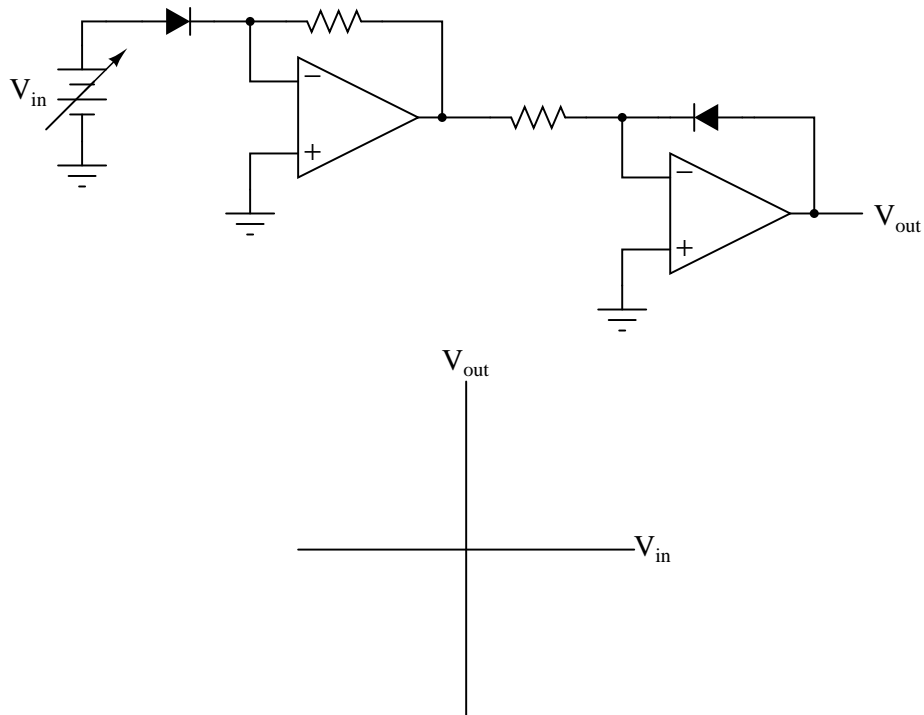
What type of mathematical function is represented by this circuit?
file 01017

Answer 80

This circuit (ideally) represents a *linear* function ($y \propto x$):

99

It should be obvious from inspection that the two opamp circuits represent inverse mathematical functions. Ask your students why the final transfer function is linear rather than nonlinear. After all, they should realize that each of the opamp circuits, taken individually, are very nonlinear. Why would their combined effect be linear?

An interesting exercise would be to have your students perform inverse functions like this on their hand calculators, first calculating an exponential function ($f(x) = e^x$), then a logarithmic ($g(x) = \ln x$), and verifying the combined functions' output ($f[g(x)] = x$).

Question 81

Logarithms have interesting properties, which we may exploit in electronic circuits to perform certain complex operations. In this question, I recommend you use a hand calculator to explore these properties.

Calculate the following:

- $10^{\log 3} =$
- $\log(10^8) =$

- $e^{\ln 3} =$
- $\ln(e^8) =$

- $10^{(\log 3 + \log 5)} =$
- $e^{(\ln 3 + \ln 5)} =$

- $10^{(\log 2.2 + \log 4)} =$
- $e^{(\ln 2.2 + \ln 4)} =$

- $10^{(\log 12 - \log 4)} =$
- $e^{(\ln 12 - \ln 4)} =$

- $10^{(2 \log 3)} =$
- $e^{(2 \ln 3)} =$

- $10^{(\frac{\log 25}{2})} =$
- $e^{(\frac{\ln 25}{2})} =$

file 01018

Answer 81

- $10^{\log 3} = 3$
- $\log(10^8) = 8$

- $e^{\ln 3} = 3$
- $\ln(e^8) = 8$

- $10^{(\log 3 + \log 5)} = 15$
- $e^{(\ln 3 + \ln 5)} = 15$

- $10^{(\log 2.2 + \log 4)} = 8.8$
- $e^{(\ln 2.2 + \ln 4)} = 8.8$

- $10^{(\log 12 - \log 4)} = 3$
- $e^{(\ln 12 - \ln 4)} = 3$

- $10^{(2 \log 3)} = 9$
- $e^{(2 \ln 3)} = 9$

- $10^{(\frac{\log 25}{2})} = 5$
- $e^{(\frac{\ln 25}{2})} = 5$

Discuss what mathematical operations are being done with the constants in these equations, by using logarithms. What patterns do your students notice? Also, discuss the terms "log" and "antilog," and relate them to opamp circuits they've seen.

Ask your students whether or not they think it matters what "base" of logarithm is used in these equations. Can they think of any other arithmetic operations to try using logarithms in this manner?

Question 82

Identify the mathematical function of this circuit (if you look closely, you'll notice that the transistors are connected in such a way that they act very similar to diodes):
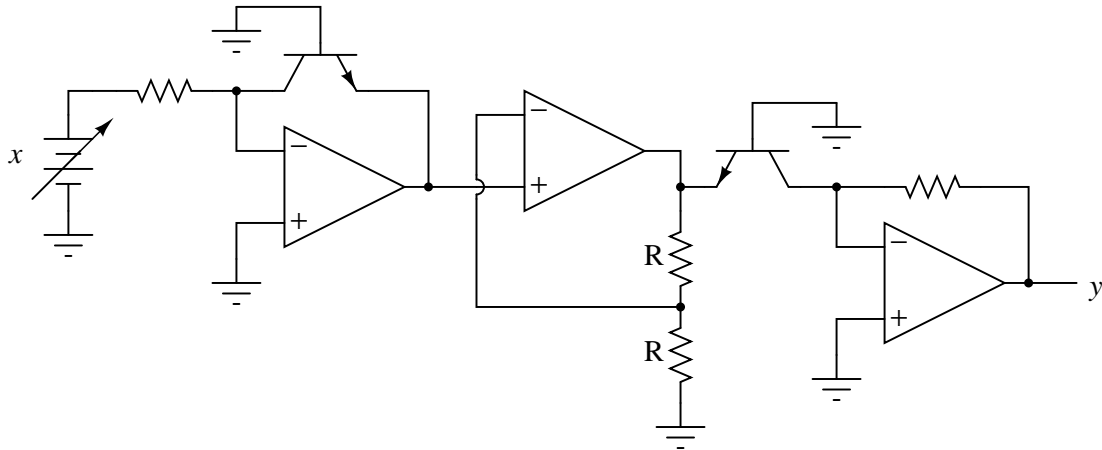
Note: the two resistors labeled "R" are equal in value.

<u>file 01019</u>

Answer 82

This circuit *squares* the input signal ($y = x^2$).

Challenge question: why are transistors used instead of diodes, since they have been effectively "disabled" to act as such?

Notes 82

This circuit is not nearly as complex as it may appear at first, if students take the time to isolate it section-by-section and identify the mathematical function each section performs.

Question 83

Suppose that in the course of building this exponential circuit you encounter severe inaccuracies: the circuit seems to work some of the time, but often its output deviates substantially (as much as +/- 10%) from what it ought to be:
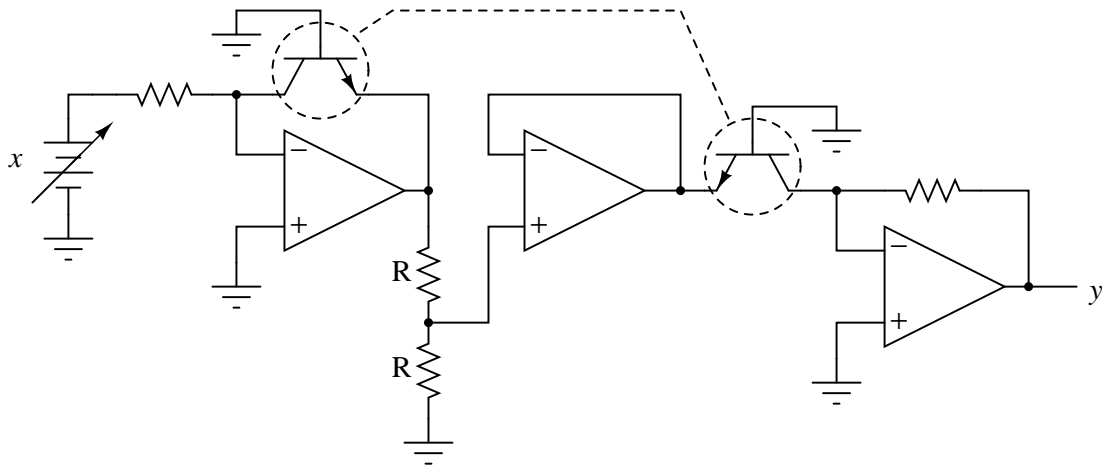
Intended transfer function:

$$y = x^{0.5}$$
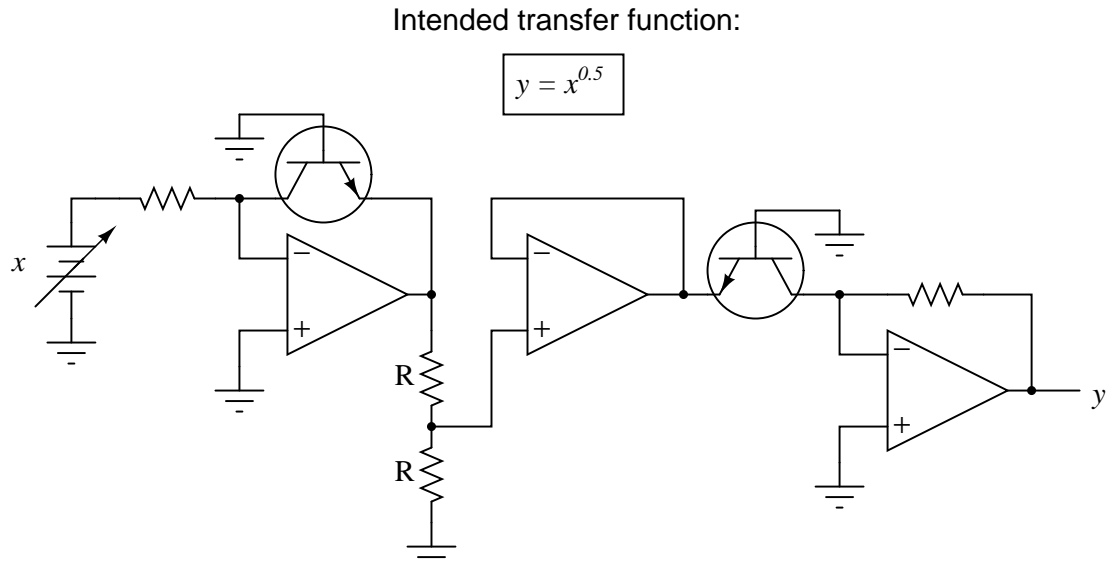
Based on what you know of the components in this circuit, what could be varying so much as to cause these errors? What do you recommend as a solution to the problem?

file 01020

Answer 83

The solution is to make sure both transistors are precisely matched, at held at the exact same temperature:

Challenge question: is there a part we could order that contains two matched, heat-stabilized transistors for an application such as this? Are there any other circuit applications you can think of that could benefit from using a precision-matched pair of transistors?
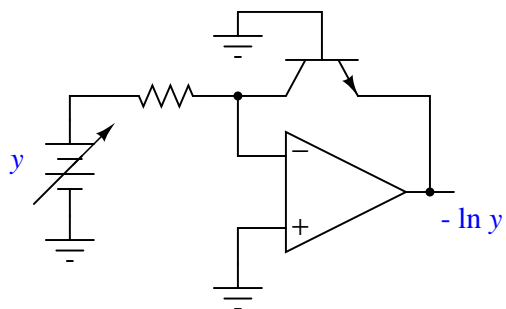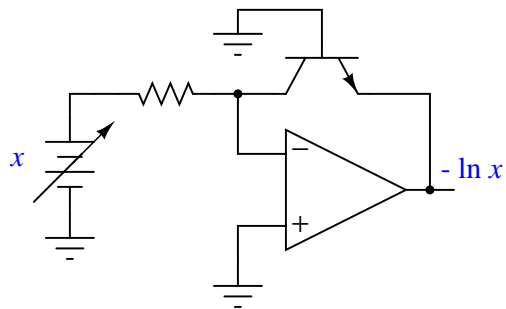
Notes 83

Ask your students to explain how they know temperature is an influencing factor in the accuracy of this circuit. Ask them to show any equations describing transistor behavior that demonstrate temperature dependence.

This question provides an opportunity to review the meaning of fractional exponents with your students. What, exactly, does $y = x^{0.5}$ mean? Ask your students to write this expression using more common symbols. Also, ask them what would have to be modified in this circuit to alter the exponent's value.

As for the challenge question, ask your students to produce a part number for the precision-matched transistor pair they find. Where did they obtain the information on this component?

Question 84

Design an op-amp circuit that *divides* one quantity (x) by another quantity (y) using logarithms. To give you a start on this circuit, I'll provide the initial logarithmic op-amp modules in this diagram:

Note: it will be helpful for your analysis to write the mathematical expression at each op-amp output in your circuit, so you may readily see how the overall math function is constructed from individual steps.
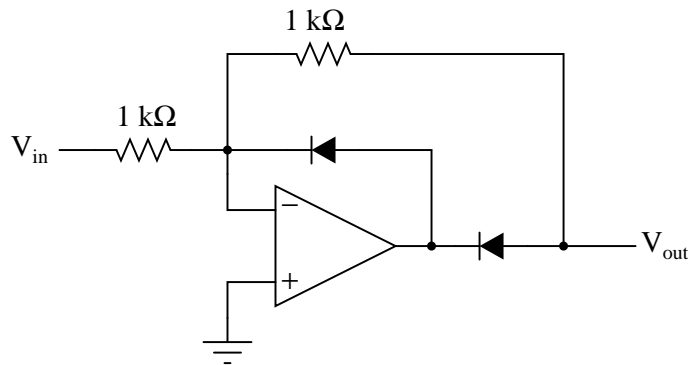
file 01023
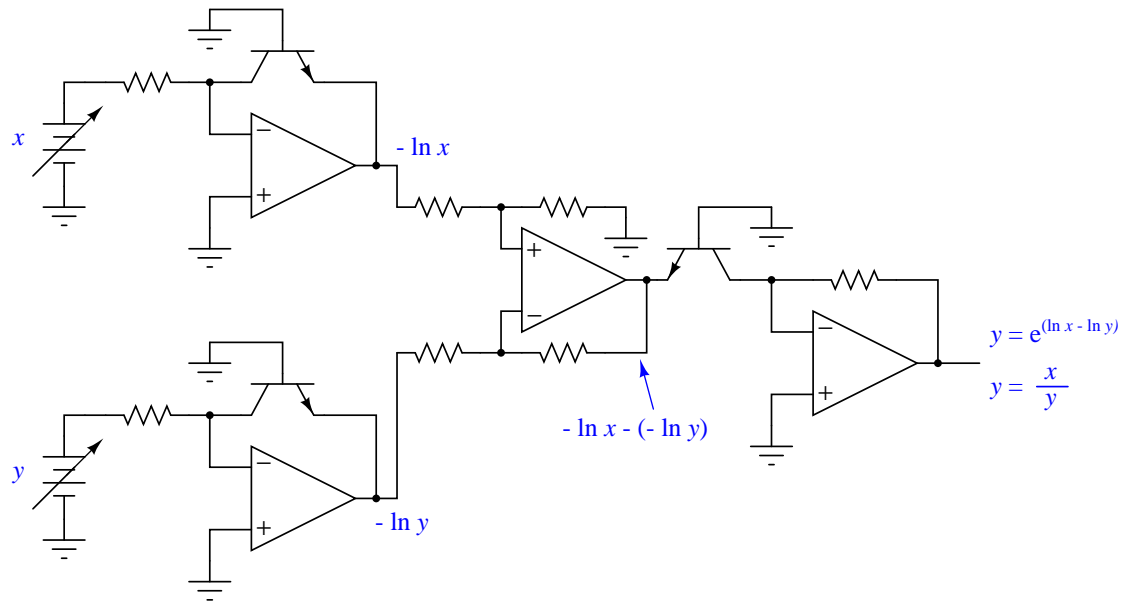
Answer 84

Notes 84

The circuit shown in the answer is a very common logarithmic construction: a *log-ratio* circuit, useful for many operations other than simple division. This question challenges students to put together the logarithm, antilogarithm, and differential op-amp circuits in a way that achieves the final design goal. Perhaps the most challenging aspect of this problem is managing the sign reversals.

Question 85

Determine the output voltage of this circuit for two different input voltage values: +5 volts, and -5 volts, assuming the use of ordinary silicon rectifying diodes:

Based on this data (and any other input conditions you wish to test this circuit under), describe what the function of this circuit is.

file 01024

Answer 85

When V_{in} = +5 volts, V_{out} = -5 volts

When V_{in} = -5 volts, V_{out} = 0 volts

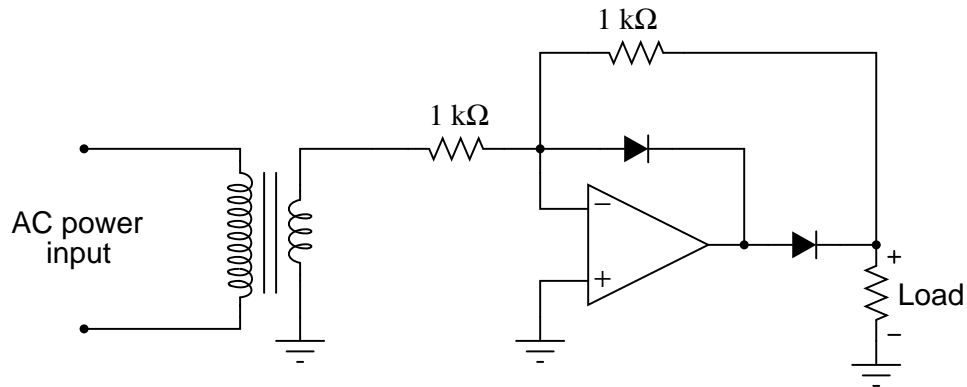This circuit is a precision rectifier.

Notes 85

Work with your students to analyze the behavior of this circuit, using Ohm's Law and the basic principle of negative feedback (zero differential input voltage). Ask your students whether or not it matters what types of diodes are used (silicon versus germanium versus light-emitting).

Question 86

Explain why the following opamp circuit cannot be used as a rectifier in an AC-DC power supply circuit:

A precision power supply rectifier?
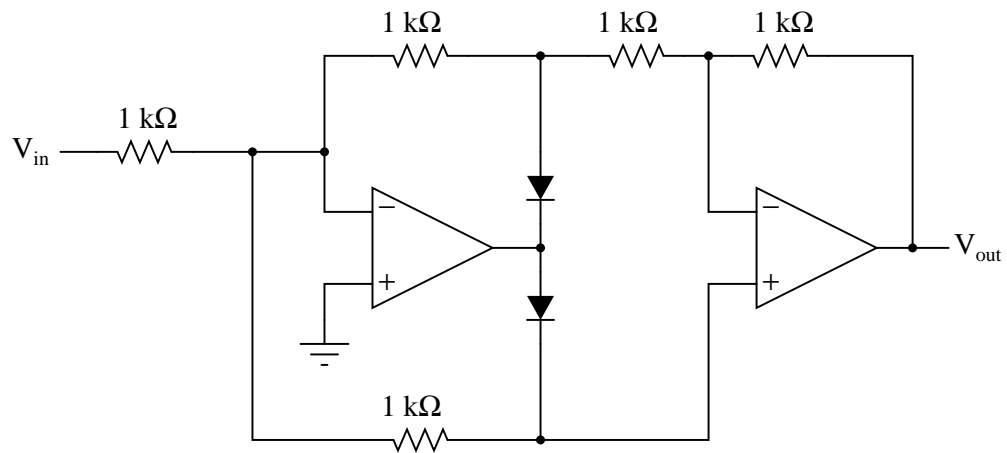

file 01025

Answer 86

Here's a hint: where does the opamp get its power from?

Notes 86

Believe it or not, I actually sat in an electronics class one time and listened to an instructor present the precision rectifier opamp circuit as a "precision rectifier for a power supply". He was serious, too, claiming that this type of circuitry was used to provide split (+V/-V) voltage outputs for benchtop power supplies. The saddest part of this ordeal is that none of his students recognized anything wrong with his statement (or at least did not feel comfortable in raising a question about it).
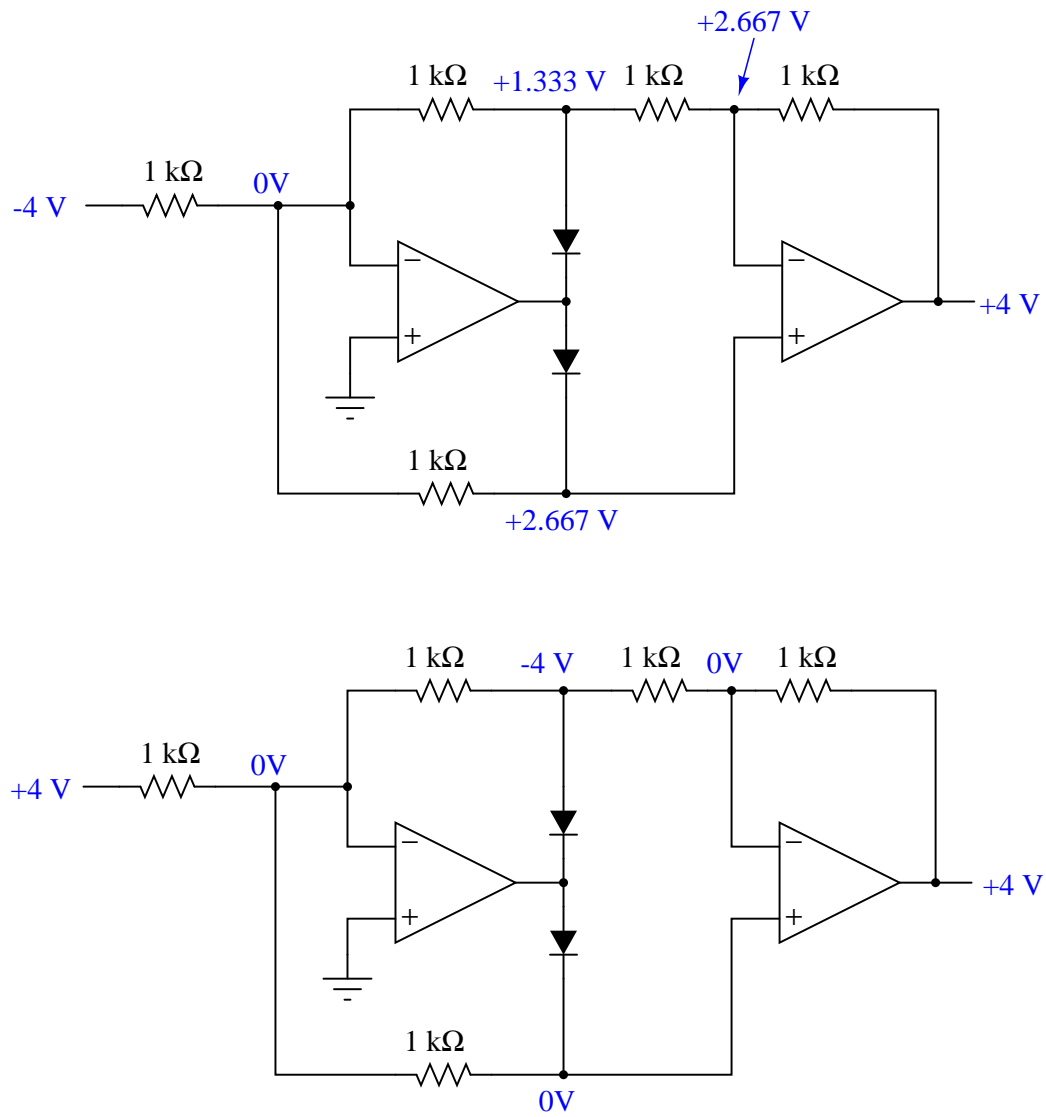
Question 87

Determine the output voltage of this circuit for two different input voltage values: +4 volts, and -4 volts. Determine the voltage at each and every node with respect to ground as part of your analysis:


Based on this data (and any other input conditions you wish to test this circuit under), describe what the function of this circuit is.

file 01026

110

This circuit is a precision full-wave rectifier.

It is much easier to analyze the behavior of this circuit with a positive input voltage than it is to analyze it with a negative input voltage! There is a tendency for students to reach this conclusion when analyzing the circuit's behavior with a negative input voltage:
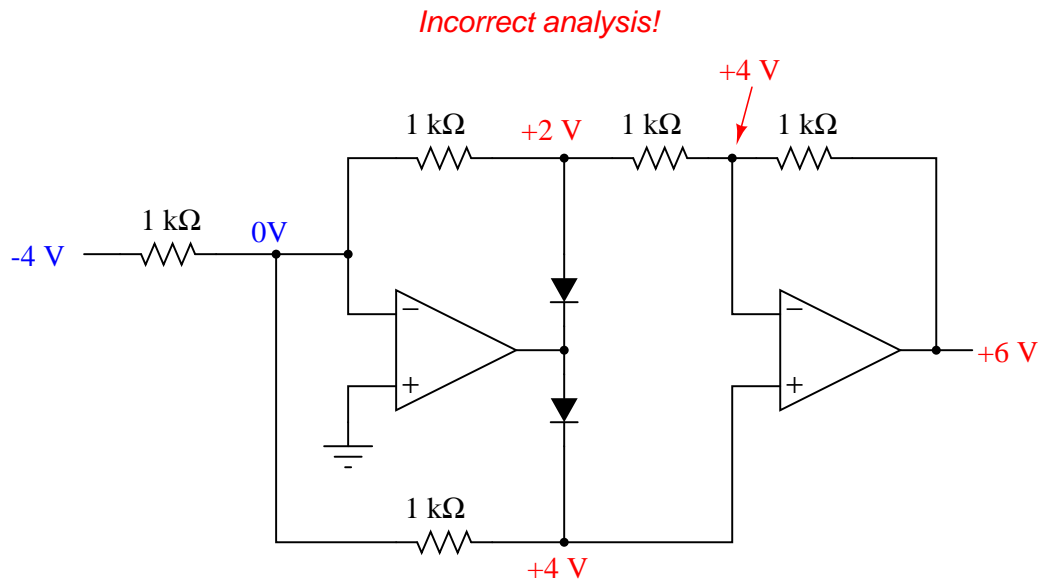
The error seems reasonable until an analysis of *current* is made. If these voltages were true, Kirchhoff's Current Law would be violated at the first opamp's virtual ground: