ELTR 130 (Operational Amplifiers 1), section 2

Recommended schedule

Day 1

Topics: *Using the operational amplifier as a noninverting voltage amplifier*
Questions: *1 through 15*
Lab Exercise: *Opamp as noninverting amplifier (question 61)*
MIT 6.002 video clip: Disk 4, Lecture 21; Noninverting opamp 41:30 to 43:10

Day 2

Topics: *Using the operational amplifier as an inverting voltage amplifier*
Questions: *16 through 30*
Lab Exercise: *Opamp as inverting amplifier (question 62)*

Day 3

Topics: *Voltage/current converter and summer circuits*
Questions: *31 through 40*
Lab Exercise: *Troubleshooting practice on prototyped project*

Day 4

Topics: *Differential and instrumentation amplifier circuits*
Questions: *41 through 50*
Lab Exercise: *Op-amp as difference amplifier (question 63)*

Day 5

Topics: *Precision rectifier circuits*
Questions: *51 through 60*
Lab Exercise: *Precision half-wave rectifier (question 64)*

Day 6

Topics: *Review*
Lab Exercise: *Troubleshooting practice on prototyped project*

Day 7

Exam 2: *includes Inverting or Noninverting amplifier circuit performance assessment*
Troubleshooting Assessment due: *Opamp project prototype*
Question 65: Troubleshooting log
Question 66: Sample troubleshooting assessment grading criteria

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Troubleshooting practice problems

Questions: *67 through 76*

General concept practice and challenge problems

Questions: *77 through the end of the worksheet*

Skill standards addressed by this course section

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

E Technical Skills – Analog Circuits
E.10 Understand principles and operations of operational amplifier circuits.
E.11 Fabricate and demonstrate operational amplifier circuits.
E.12 Troubleshoot and repair operational amplifier circuits.

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

Common areas of confusion for students

Difficult concept: *Negative feedback.*

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

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

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

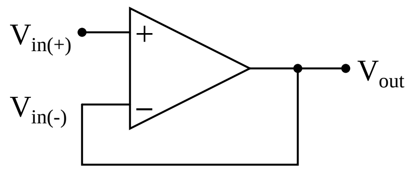
I think the reason for this misconception is the fact that power terminals are often omitted from opamp symbols for brevity, and after a while of seeing this it is easy to forget they are really still there performing a useful function!

Difficult concept: *Applying KVL and KCL to operational amplifier circuits.*

Many students have the unfortunate tendency to memorize rather than think. When approaching all the different types of operational amplifier circuits, this tendency is a recipe for failure. Instead of learning how to effectively apply Kirchhoff's Laws to the analysis of different opamp circuits, many students simply try to rote-memorize what all the different circuits do. Not only will these students experience difficulty remembering all the variations in circuit behavior, but they will also be helpless in troubleshooting opamp circuits, as a faulted circuit will not behave as it should! There is only one correct approach here, and that is to master the application of Kirchhoff's Voltage Law and Kirchhoff's Current Law. Difficult? Perhaps, but necessary. Remember: *there are no shortcuts to learning!*

Question 1

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 1

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

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

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

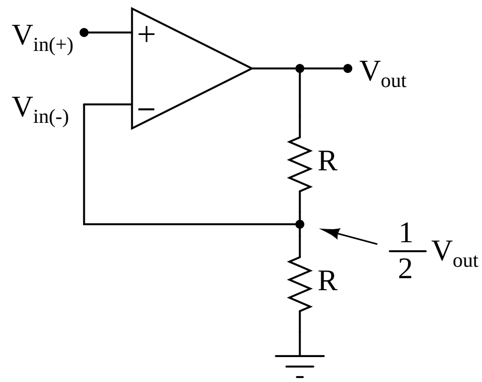
For an input voltage of +6 volts, the output voltage will be +5.99994 volts.

Notes 1

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 2

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 2

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

(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.

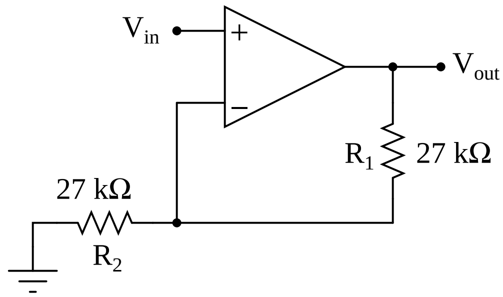
Follow-up question: what do you notice about the output voltage in this circuit? What value is it very close to being, in relation to the input voltage? Does this pattern hold true for other input voltages as well?

Notes 2

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 3

Calculate the overall voltage gain of this amplifier circuit (A_V), both as a ratio and as a figure in units of decibels (dB). Also, write a general equation for calculating the voltage gain of such an amplifier, given the resistor values of R_1 and R_2:



file 02457

Answer 3

$A_V = 2 = 6.02$ dB

$$A_V = \frac{R_1}{R_2} + 1 \qquad \text{(expressed as a ratio, not dB)}$$

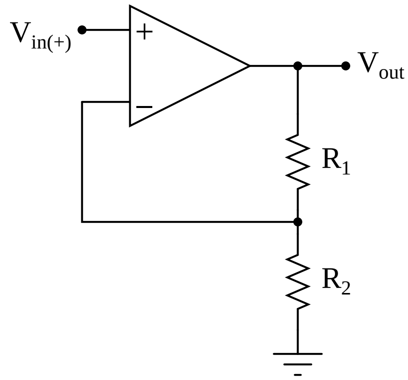
Follow-up question: explain how you could modify this particular circuit to have a voltage gain (ratio) of 3 instead of 2.

Notes 3

Nothing special here – just some practice with voltage gain calculations.

Question 4

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



file 00931

Answer 4

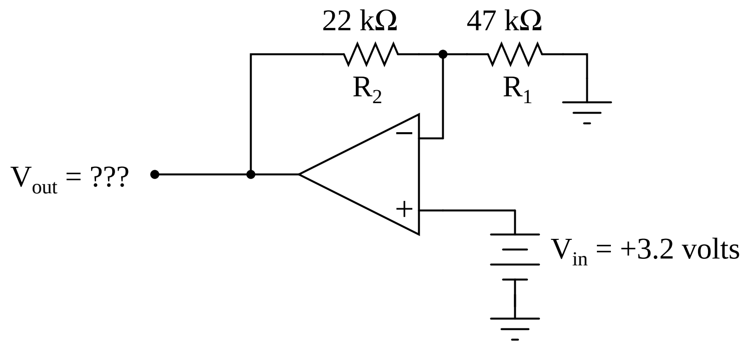
The voltage divider would have to altered so as to send a smaller proportion of the output voltage to the inverting input.

Notes 4

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 5

Calculate all voltage drops and currents in this circuit, complete with arrows for current direction and polarity markings for voltage polarity. Then, calculate the overall voltage gain of this amplifier circuit (A_V), both as a ratio and as a figure in units of decibels (dB):



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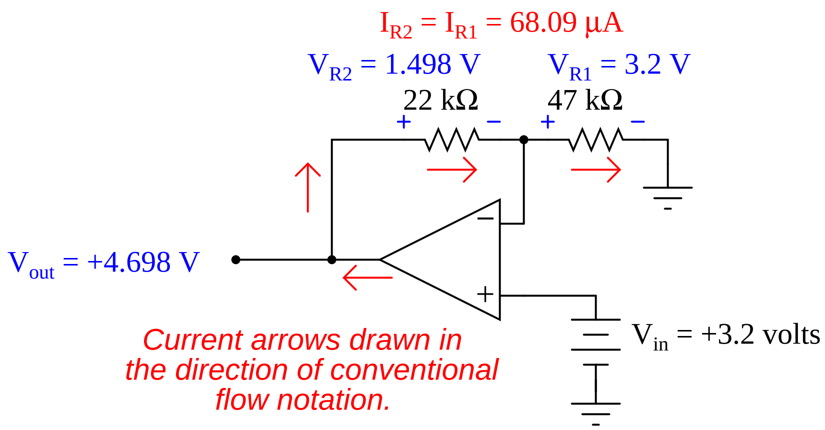
Answer 5



$A_V = 1.468 = 3.335$ dB

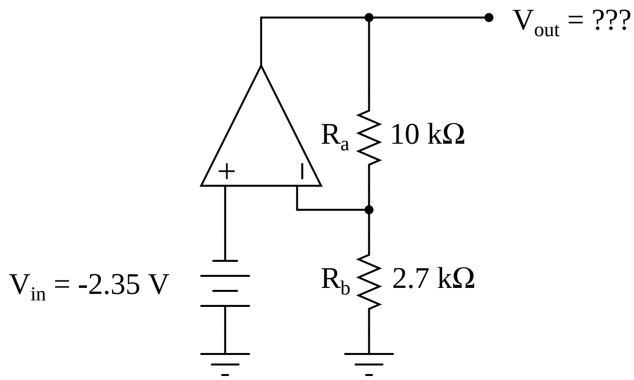
Notes 5

Operational amplifier circuits provide a great opportunity to review basic concepts of DC circuits: voltage drops, polarity, current directions, Ohm's Law, Kirchhoff's Voltage Law, Kirchhoff's Current Law, etc. This circuit is no exception. Emphasize the fact that a great many opamp circuits may be comprehensively analyzed merely with knowledge of these fundamental principles and the characteristics of an ideal opamp (zero input current, infinite open-loop gain, unlimited output voltage swing, zero voltage between input terminals when negative feedback is in effect).

Some students may arrive at the wrong gain figure because they blindly followed a formula with R_1 and R_2 shown as variables, plugging in this circuit's values for R_1 and R_2 without considering which resistor is which (is R_1 the feedback resistor or is R_2?). This is by design, as I want students to learn to *think* about what they are doing rather than thoughtlessly follow instructions.

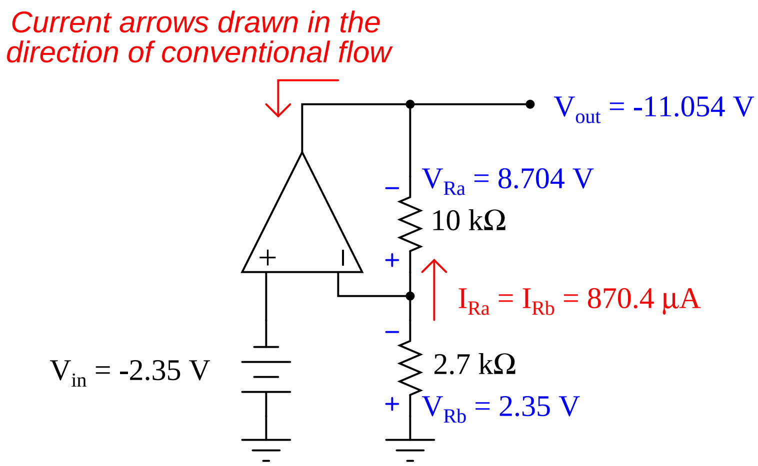
Question 6

Calculate all voltage drops and currents in this circuit, complete with arrows for current direction and polarity markings for voltage polarity. Then, calculate the overall voltage gain of this amplifier circuit (A_V), both as a ratio and as a figure in units of decibels (dB):



file 02460

Answer 6



$A_V = 4.704 = 13.449$ dB

Follow-up question: how much input impedance does the -2.35 volt source "see" as it drives this amplifier circuit?

Notes 6

Operational amplifier circuits provide a great opportunity to review basic concepts of DC circuits: voltage drops, polarity, current directions, Ohm's Law, Kirchhoff's Voltage Law, Kirchhoff's Current Law, etc. This circuit is no exception. Emphasize the fact that a great many opamp circuits may be comprehensively analyzed merely with knowledge of these fundamental principles and the characteristics of an ideal opamp (zero input current, infinite open-loop gain, unlimited output voltage swing, zero voltage between input terminals when negative feedback is in effect).

The follow-up question is important because it showcases one of the great advantages of using noninverting opamp amplifier circuits as voltage signal amplifiers: extremely high input impedance. This would be a good opportunity to review typical input impedance values for operational amplifiers, by showing datasheets for some typical opamps and for some non-typical (i.e. MOSFET input) opamps.

Question 7

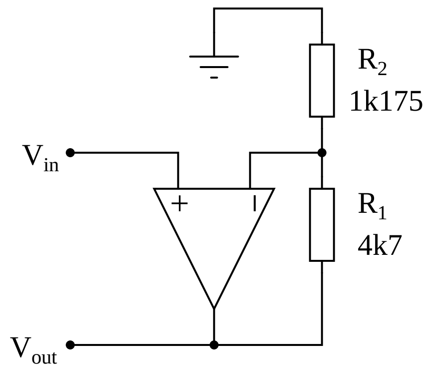
The equation for voltage gain (A_V) in a typical noninverting, single-ended opamp circuit is as follows:

$$A_V = \frac{R_1}{R_2} + 1$$

Where,

R_1 is the feedback resistor (connecting the output to the inverting input)
R_2 is the other resistor (connecting the inverting input to ground)

Suppose we wished to change the voltage gain in the following circuit from 5 to 6.8, but only had the freedom to alter the resistance of R_2:



Algebraically manipulate the gain equation to solve for R_2, then determine the necessary value of R_2 in this circuit to give it a voltage gain of 6.8.

file 02707

Answer 7

$$R_2 = \frac{R_1}{A_V - 1}$$

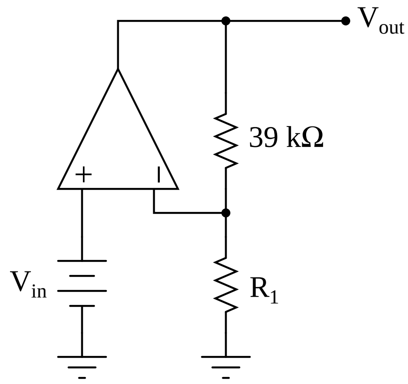
For the circuit shown, R_2 would have to be set equal to 810.3 Ω.

Notes 7

Nothing more than a little algebra to obtain the answers for this question!

Question 8

Calculate the necessary resistor value (R_1) in this circuit to give it a voltage gain of 30:



file 02725

Answer 8

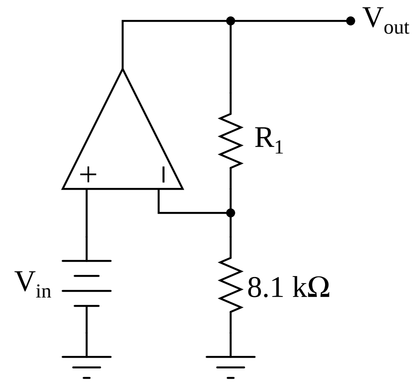
$R_1 = 1.345 \text{ k}\Omega$

Notes 8

Ask your students how they solved this problem, especially since it is fairly safe to say that they didn't find the equation directly solving for R_1 in any book. Algebraic manipulation is necessary to take the standard voltage gain equation and put it into a form suitable for use answering this question.

Question 9

Calculate the necessary resistor value (R_1) in this circuit to give it a voltage gain of 10.5:



file 02724

Answer 9

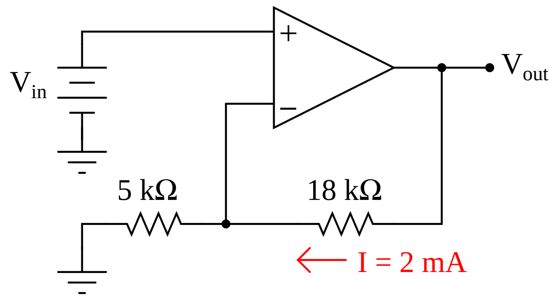
R_1 = 76.95 kΩ

Notes 9

Ask your students how they solved this problem, especially since it is fairly safe to say that they didn't find the equation directly solving for R_1 in any book. Algebraic manipulation is necessary to take the standard voltage gain equation and put it into a form suitable for use answering this question.

Question 10

Determine both the input and output voltage in this circuit:



file 02726

Answer 10

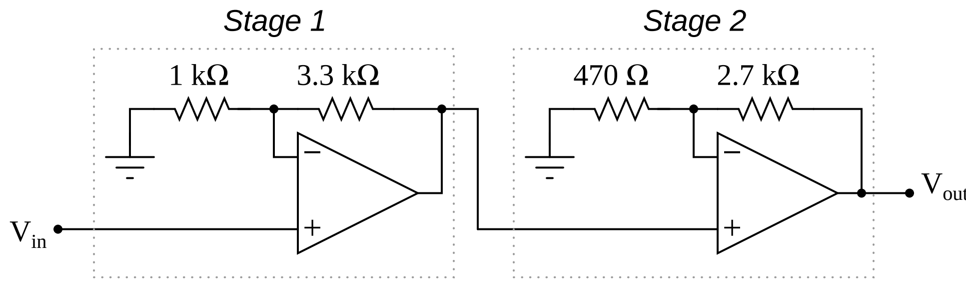
$V_{in} = 10$ V $\qquad$ $V_{out} = 46$ V

Notes 10

Ask your students how they solved this problem, sharing techniques and strategies to help other students know where to begin and where to proceed from there.

Question 11

Calculate the voltage gain for each stage of this amplifier circuit (both as a ratio and in units of decibels), then calculate the overall voltage gain:



file 02727

Answer 11

Stage 1:
- $A_V = 4.3 = 12.669$ dB

Stage 2:
- $A_V = 6.745 = 16.579$ dB

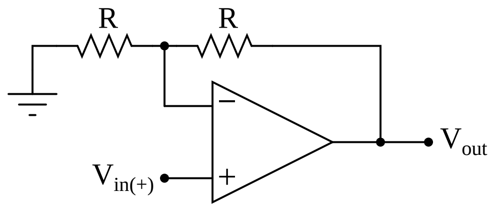
Overall:
- $A_V = 29.002 = 29.249$ dB

Notes 11

Not only does this question review calculation of voltage gain for inverting amplifier circuits, but it also reviews decibel calculations (for both single and multi-stage amplifiers). Discuss how the decibel figures for each stage add to equal the total decibel gain, whereas the ratios multiply.

Question 12

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 12

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 12

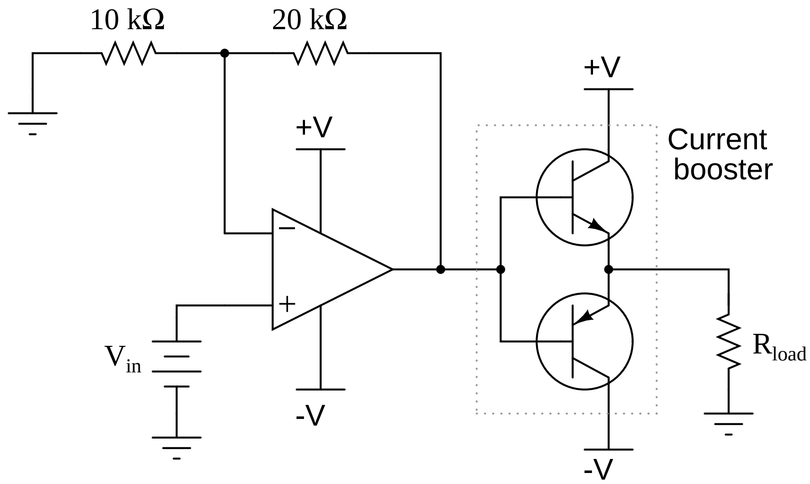
Work with your students to calculate a few example scenarios, with the old open-loop gain versus the new open-loop gain. Have the students validate their conclusions with numbers!

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.

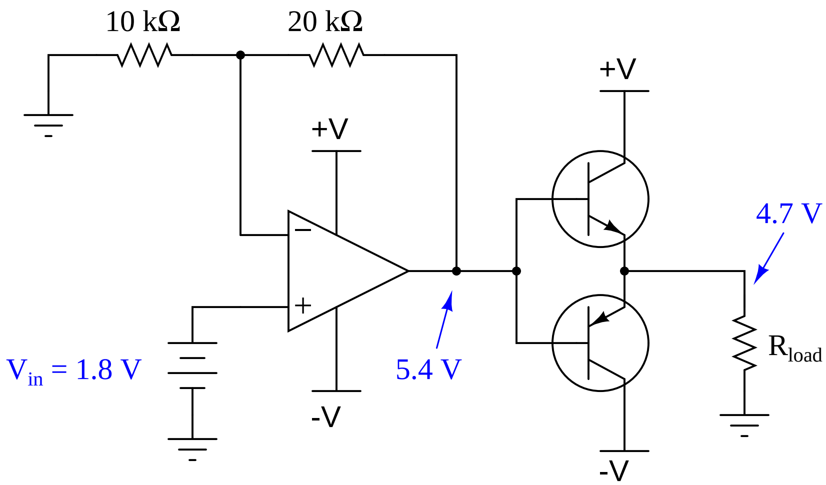
An interesting historical side-note is that Black's 1928 patent application was initially rejected on the grounds that he was trying to submit a perpetual motion device! The concept of negative feedback in an amplifier circuit was so contrary to established engineering thought at the time, that Black 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 13

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:



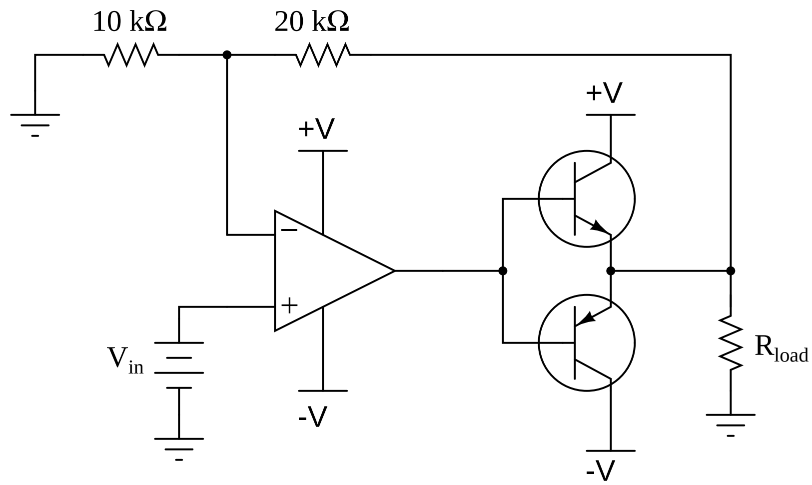
However, if connected exactly as shown, there will be a significant voltage error introduced to the opamp's output. No longer will the final output voltage (measured across the load) be an exact 3:1 multiple of the input voltage, due to the 0.7 volts dropped by the transistor in active mode:



There is a very simple way to completely eliminate this error, without adding any additional components. Modify the circuit accordingly.

file 00935

Answer 13



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!

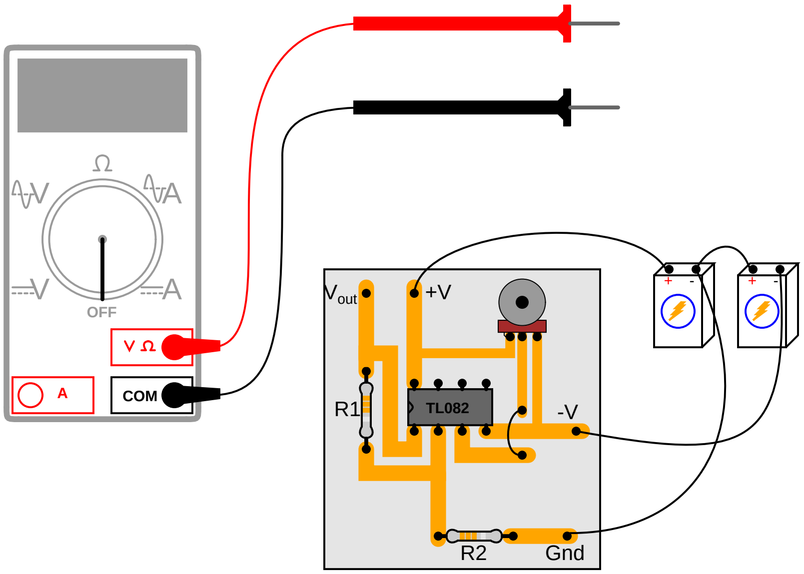
Notes 13

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.

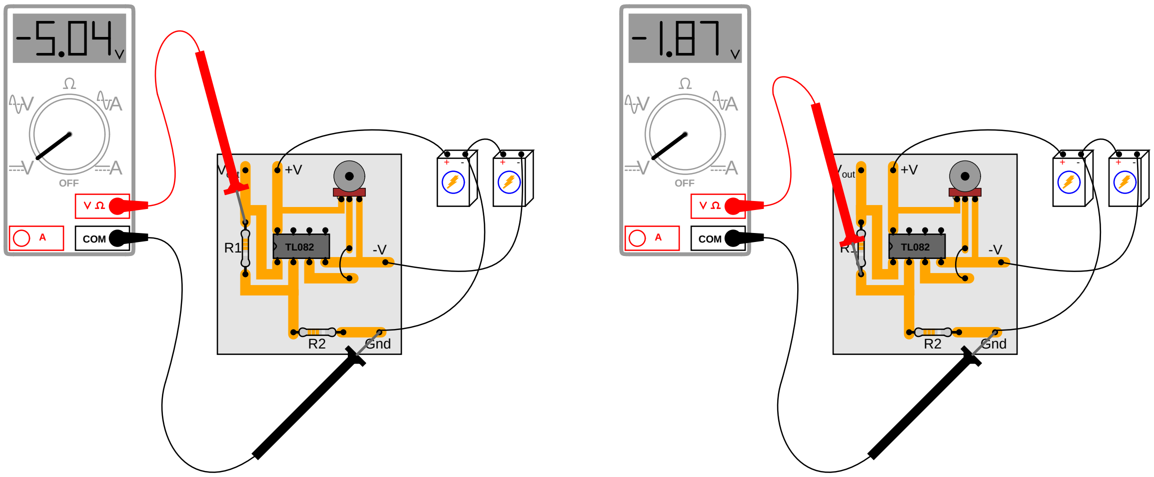
It might help your students understand if you label the new wire with the word *sense*, to indicate its purpose of providing feedback from the very output of the circuit, back to the opamp so it can sense how much voltage the load is receiving.

Question 14

Suppose a technician is checking the operation of the following electronic circuit:



She decides to measure the voltage on either side of resistor R1 with reference to ground, and obtains these readings:



On the top side of R1, the voltage with reference to ground is -5.04 volts. On the bottom side of R1, the voltage with reference to ground is -1.87 volts. The color code of resistor R1 is Yellow, Violet, Orange, Gold. From this information, determine the following:

- Voltage across R1 (between top to bottom):
- Polarity (+ and -) of voltage across R1:
- Current (magnitude) through R1:
- Direction of current through R1:

Additionally, explain how this technician would make each one of these determinations. What rules or laws of electric circuits would she apply?

file 02733

Answer 14

- Voltage across R1 (between top to bottom): **3.17 volts**
- Polarity (+ and -) of voltage across R1: **(-) on top, (+) on bottom**
- Current (magnitude) through R1: **67.45 μA**
- Direction of current through R1: **upward, following conventional flow**

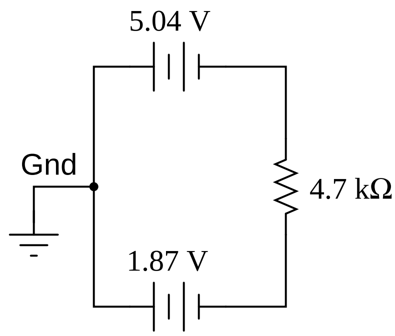
Follow-up question: calculate the range of possible currents, given the specified tolerance of resistor R1 (67.45 μA assumes 0% error).

Challenge question: if you recognize the type of circuit this is (by the part number of the IC "chip": TL082), identify the voltage between pin 3 and ground.

Notes 14

This is a good example of how Kirchhoff's Voltage Law is more than just an abstract tool for mathematical analysis – it is also a powerful technique for practical circuit diagnosis. Students must apply KVL to determine the voltage drop across R1, and then use Ohm's Law to calculate its current.

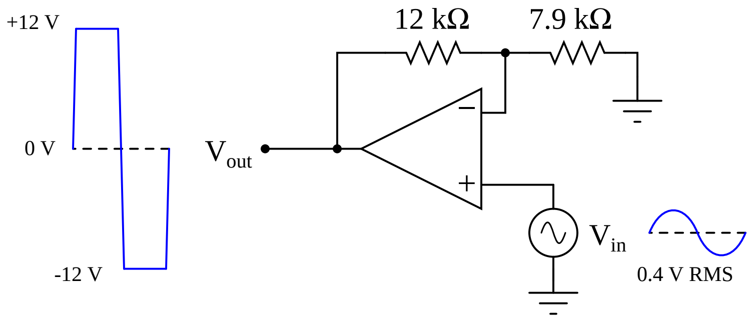
If students experience difficulty visualizing how KVL plays a part in the solution of this problem, show them this illustration:



By the way, the answer to the challenge question may only be realized if students recognize this circuit as a noninverting opamp voltage amplifier. The voltage at pin 3 (noninverting input) will be the same as the voltage at pin 2 (inverting input): -1.87 volts.

Question 15

There is something wrong with this amplifier circuit. Note the relative amplitudes of the input and output signals as measured by an oscilloscope:



This circuit used to function perfectly, but then began to malfunction in this manner: producing a "clipped" output waveform of excessive amplitude. Determine the approximate amplitude that the output voltage waveform *should* be for the component values given in this circuit, and then identify possible causes of the problem and also elements of the circuit that you know cannot be at fault.

file 02465

Answer 15

V_{out} (ideal) = 1.01 volts RMS

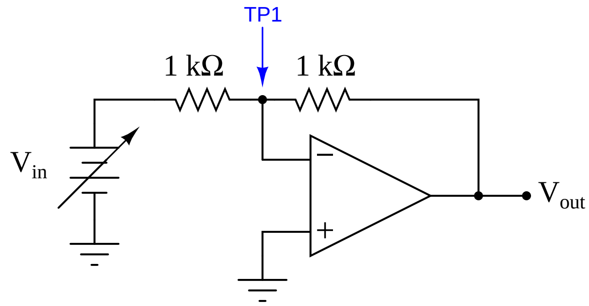
I'll let you determine possible faults in the circuit! From what we see here, we know the power supply is functioning (both +V and -V rails) and that there is good signal getting to the noninverting input of the opamp.

Notes 15

There is definitely more than one possible cause for the observed problem. Discuss alternatives with your students, involving them in the diagnosis process. Ask them why we know that certain elements of the circuit are functioning as they should? Of the possible causes, which are more likely, and why?

Question 16

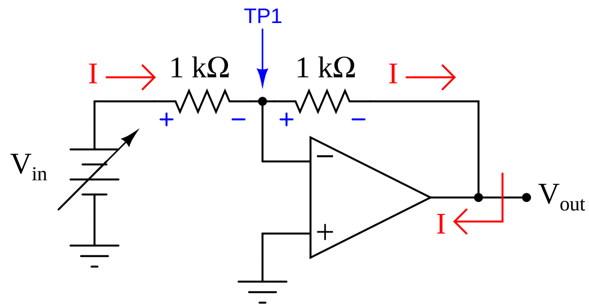
Trace the directions for all currents in this circuit, and calculate the values for voltage at the output (V_{out}) and at test point 1 (V_{TP1}) for several values of input voltage (V_{in}):



V_{in}	V_{TP1}	V_{out}
0.0 V		
0.4 V		
1.2 V		
3.4 V		
7.1 V		
10.8 V		

Then, from the table of calculated values, determine the voltage gain (A_V) for this amplifier circuit.
file 02467

Answer 16



V_{in}	V_{TP1}	V_{out}
0.0 V	0.0 V	0.0 V
0.4 V	0.0 V	-0.4 V
1.2 V	0.0 V	-1.2 V
3.4 V	0.0 V	-3.4 V
7.1 V	0.0 V	-7.1 V
10.8 V	0.0 V	-10.8 V

$$A_V = 1 \text{ (ratio)} = 0 \text{ dB}$$

Follow-up question: the point marked "TP1" in this circuit is often referred to as a *virtual ground*. Explain why this is, based on the voltage figures shown in the above table.

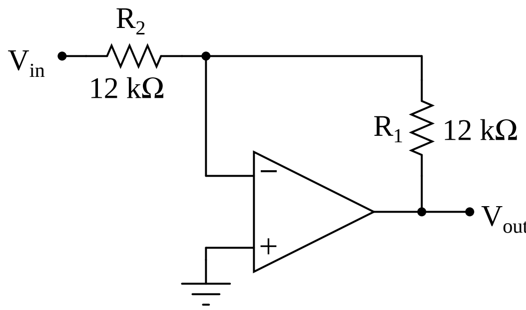
Notes 16

Some texts describe the voltage gain of an inverting voltage amplifier as being a negative quantity. I tend not to look at things that way, treating all gains as positive quantities and relying on my knowledge of circuit behavior to tell whether the signal is inverted or not. In my teaching experience, I have found that students have a tendency to blindly follow equations rather than think about what it is they are calculating, and that strict adherence to the mathematical signs of gain values only encourages this undesirable behavior ("If the sign of the gain tells me whether the circuit is inverting or not, I can just multiply input voltage by gain and the answer will always be right!").

This strategy is analogous to problem-solving in electromagnetics, where a common approach is to use math to solve for the absolute values of quantities (potential, induced voltage, magnetic flux), and then to use knowledge of physical principles (Lenz' Law, right-hand rule) to solve for polarities and directions. The alternative – to try to maintain proper sign convention throughout all calculations – not only complicates the math but it also encourages students to over-focus on calculations and neglect fundamental principles.

Question 17

Calculate the overall voltage gain of this amplifier circuit (A_V), both as a ratio and as a figure in units of decibels (dB). Also, write a general equation for calculating the voltage gain of such an amplifier, given the resistor values of R_1 and R_2:



file 02458

Answer 17

$A_V = 1 = 0$ dB

$$A_V = \frac{R_1}{R_2} \qquad \text{(expressed as a ratio, not dB)}$$

Follow-up question #1: sometimes the voltage gain equation for an amplifier of this type is given in the following form:

$$A_V = -\frac{R_1}{R_2}$$

What is the significance of the negative sign in this equation? Is it really necessary, or does it communicate an important concept?

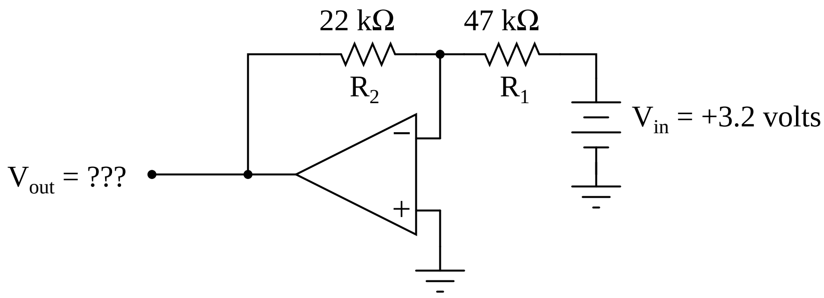
Follow-up question #2: manipulate the gain equation for this amplifier circuit to solve for the value of resistor R_1.

Notes 17

Whether inverting amplifier gains are expressed as negative or positive quantities seems to be a matter of taste, from surveying introductory textbooks on the subject. I prefer to stick with absolute (positive) gain values and consider signal inversion separately.

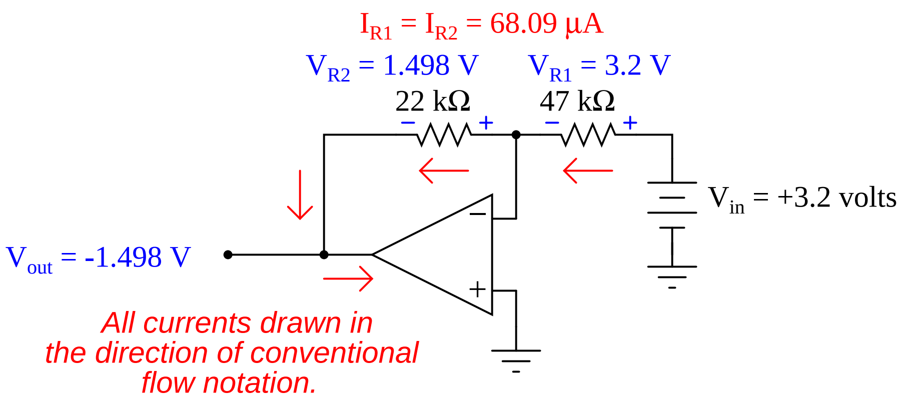
Question 18

Calculate all voltage drops and currents in this circuit, complete with arrows for current direction and polarity markings for voltage polarity. Then, calculate the overall voltage gain of this amplifier circuit (A_V), both as a ratio and as a figure in units of decibels (dB):



file 02468

Answer 18



A_V = 0.468 = -6.594 dB

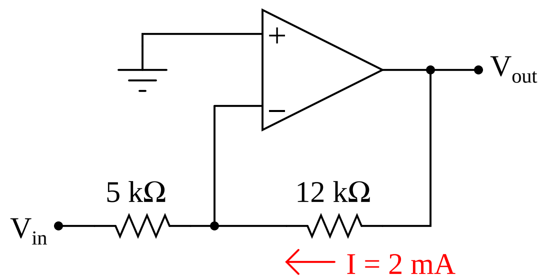
Notes 18

Operational amplifier circuits provide a great opportunity to review basic concepts of DC circuits: voltage drops, polarity, current directions, Ohm's Law, Kirchhoff's Voltage Law, Kirchhoff's Current Law, etc. This circuit is no exception. Emphasize the fact that a great many opamp circuits may be comprehensively analyzed merely with knowledge of these fundamental principles and the characteristics of an ideal opamp (zero input current, infinite open-loop gain, unlimited output voltage swing, zero voltage between input terminals when negative feedback is in effect).

Some students may arrive at the wrong gain figure because they blindly followed a formula with R_1 and R_2 shown as variables, plugging in this circuit's values for R_1 and R_2 without considering which resistor is which (is R_1 the feedback resistor or is R_2?). This is by design, as I want students to learn to *think* about what they are doing rather than thoughtlessly follow instructions.

Question 19

Determine both the input and output voltage in this circuit:



file 02732

Answer 19

V_{in} = -10 V $\qquad$ V_{out} = 24 V

Follow-up question: how do we know that the input voltage in this circuit is negative and the output voltage is positive?

Notes 19

Ask your students how they solved this problem, sharing techniques and strategies to help other students know where to begin and where to proceed from there.

Question 20

The equation for voltage gain (A_V) in a typical inverting, single-ended opamp circuit is as follows:

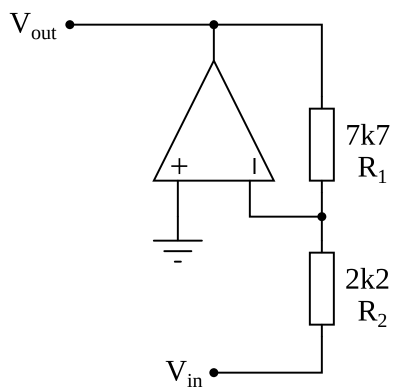
$$A_V = \frac{R_1}{R_2}$$

Where,

R_1 is the feedback resistor (connecting the output to the inverting input)

R_2 is the other resistor (connecting the inverting input to voltage signal input terminal)

Suppose we wished to change the voltage gain in the following circuit from 3.5 to 4.9, but only had the freedom to alter the resistance of R_2:



Algebraically manipulate the gain equation to solve for R_2, then determine the necessary value of R_2 in this circuit to give it a voltage gain of 4.9.

file 02708

Answer 20

$$R_2 = \frac{R_1}{A_V}$$

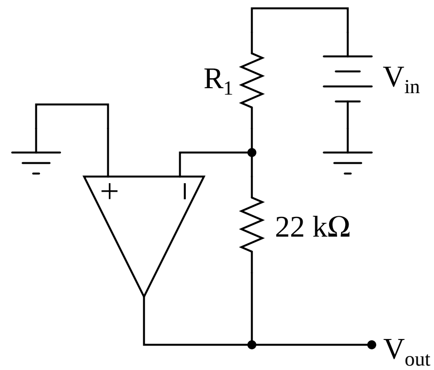
For the circuit shown, R_2 would have to be set equal to 1.571 kΩ.

Notes 20

Nothing more than a little algebra to obtain the answers for this question!

Question 21

Calculate the necessary resistor value (R_1) in this circuit to give it a voltage gain of 15:



file 02729

Answer 21

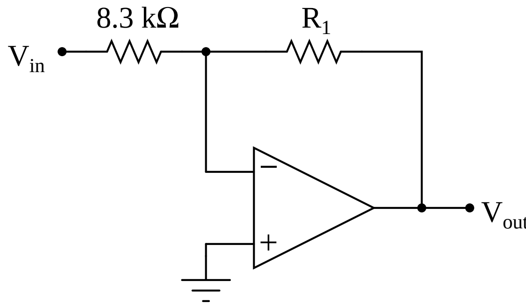
$R_1 = 1.467 \text{ k}\Omega$

Notes 21

Ask your students how they solved this problem, especially since it is fairly safe to say that they didn't find the equation directly solving for R_1 in any book. Algebraic manipulation is necessary to take the standard voltage gain equation and put it into a form suitable for use answering this question.

Question 22

Calculate the necessary resistor value (R_1) in this circuit to give it a voltage gain of 7.5:



file 02730

Answer 22

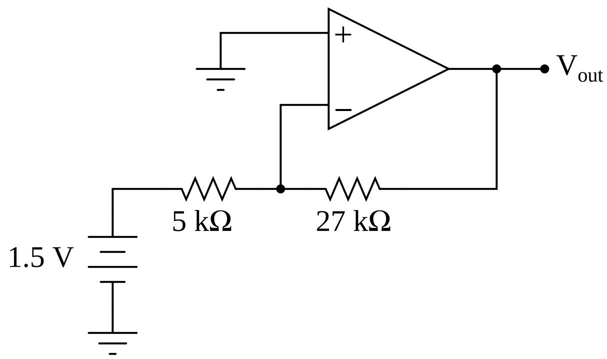
R_1 = 62.25 kΩ

Notes 22

Ask your students how they solved this problem, especially since it is fairly safe to say that they didn't find the equation directly solving for R_1 in any book. Algebraic manipulation is necessary to take the standard voltage gain equation and put it into a form suitable for use answering this question.

Question 23

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



Also, calculate the DC voltage gain of this circuit.

file 00932

Answer 23

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.

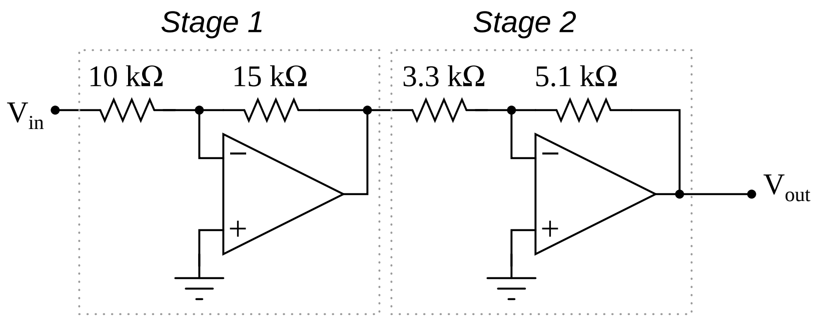
Notes 23

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 24

Calculate the voltage gain for each stage of this amplifier circuit (both as a ratio and in units of decibels), then calculate the overall voltage gain:



file 02470

Answer 24

Stage 1:

- $A_V = 1.5 = 3.522$ dB

Stage 2:

- $A_V = 1.545 = 3.781$ dB

Overall:

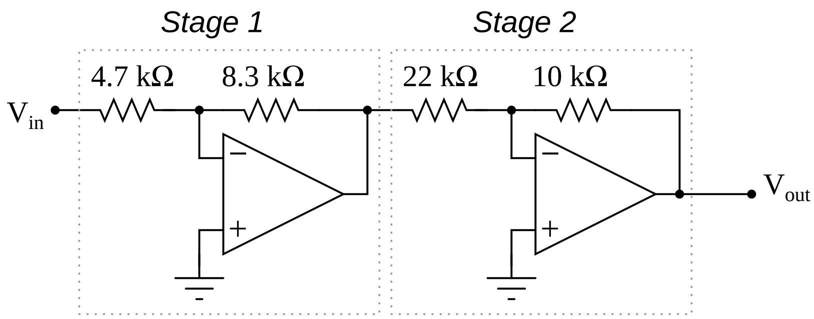
- $A_V = 2.318 = 7.303$ dB

Notes 24

Not only does this question review calculation of voltage gain for inverting amplifier circuits, but it also reviews decibel calculations (for both single and multi-stage amplifiers). Discuss how the decibel figures for each stage add to equal the total decibel gain, whereas the ratios multiply.

Question 25

Calculate the voltage gain for each stage of this amplifier circuit (both as a ratio and in units of decibels), then calculate the overall voltage gain:



file 02471

Answer 25

Stage 1:
- $A_V = 1.766 = 4.940$ dB

Stage 2:
- $A_V = 0.455 = -6.848$ dB

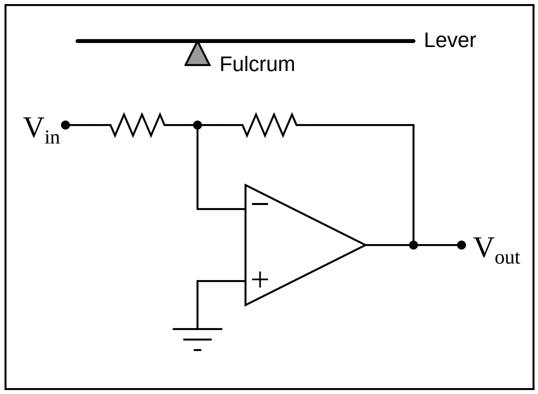
Overall:
- $A_V = 0.803 = -1.909$ dB

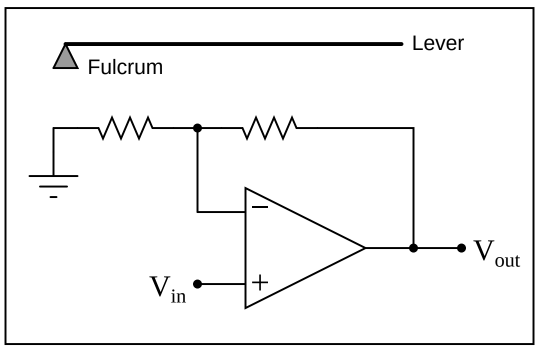
Notes 25

Not only does this question review calculation of voltage gain for inverting amplifier circuits, but it also reviews decibel calculations (for both single and multi-stage amplifiers). Discuss how the decibel figures for each stage add to equal the total decibel gain, whereas the ratios multiply.

Question 26

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 26

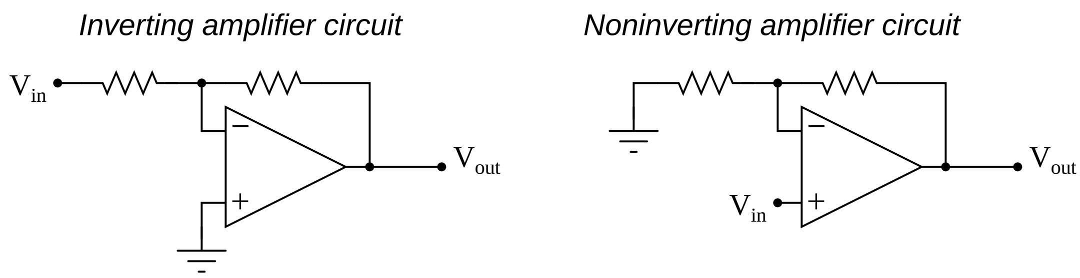
The analogy of a lever works well to explain how the output voltage of an op-amp circuit relates to the input voltage, in terms of both magnitude and polarity. Resistor values correspond to *moment arm* lengths, while direction of lever motion (up versus down) corresponds to polarity. The position of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

Notes 26

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

Question 27

Compare and contrast inverting versus noninverting amplifier circuits constructed using operational amplifiers:



How do these two general forms of opamp circuit compare, especially in regard to input impedance and the range of voltage gain adjustment?

file 02469

Answer 27

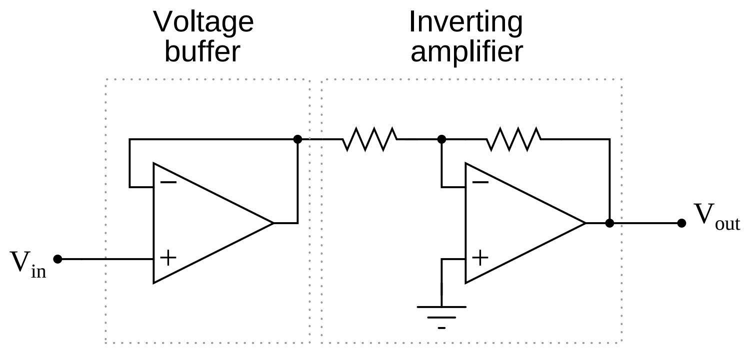
The noninverting configuration exhibits a far greater input impedance than the inverting amplifier, but has a more limited range of voltage gain: always greater than or equal to unity.

Notes 27

Just a simple comparison between amplifier configurations, nothing more. Ask your students to elaborate on the inverting amplifier's range of gain adjustment: how does it differ from the noninverting configuration?

Question 28

What possible benefit is there to adding a voltage buffer to the front end of an inverting amplifier, as shown in the following schematic?



file 02472

Answer 28

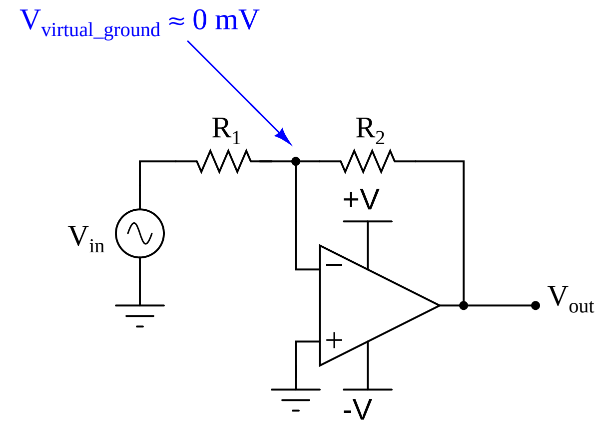
The voltage buffer raises the amplifier's input impedance without altering voltage gain.

Notes 28

Discuss with your students how this is very common: using a voltage buffer as an impedance transformation (or *isolation*) device so that a weak (high-impedance) source is able to drive an amplifier.

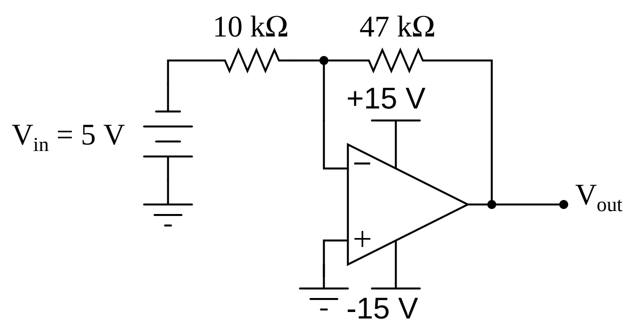
Question 29

The junction between the two resistors and the inverting input of the operational amplifier is often referred to as a *virtual ground*, the voltage between it and ground being (almost) zero over a wide range of circuit conditions:



If the operational amplifier is driven into saturation, though, the "virtual ground" will no longer be at ground potential. Explain why this is, and what condition(s) may cause this to happen.

Hint: analyze all currents and voltage drops in the following circuit, assuming an opamp with the ability to swing its output voltage rail-to-rail.



file 02473

Answer 29

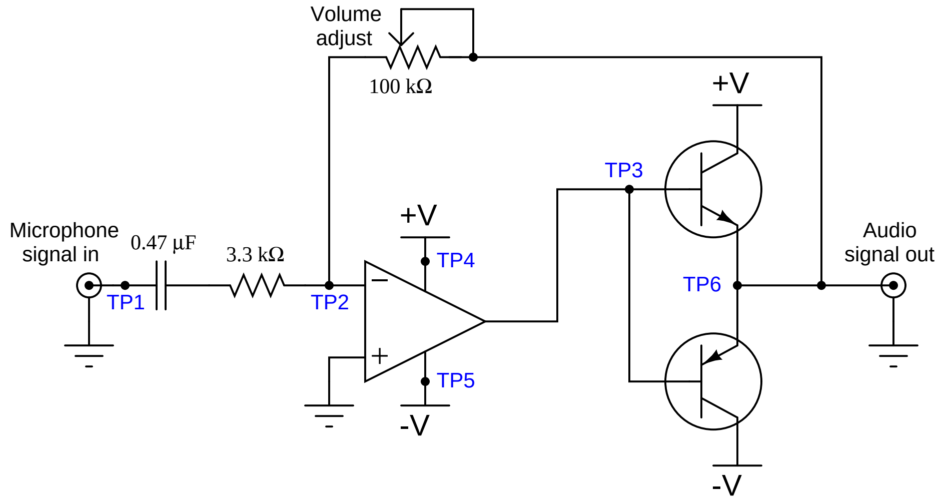
Any input signal causing the operational amplifier to try to output a voltage beyond either of its supply rails will cause the "virtual ground" node to deviate substantially from ground potential.

Notes 29

Before students can answer this question, they must understand what saturation means with regard to an operational amplifier. This is where the "hint" scenario comes into play. Students failing to grasp this concept will calculate the voltage drops and currents in the "hint" circuit according to standard procedures and assumptions, and arrive at an output voltage well in excess of +15 volts. Resolving this paradox will lead to insight, and hopefully to a more realistic set of calculations.

Question 30

There is something wrong with this amplifier circuit. Despite an audio signal of normal amplitude detected at test point 1 (TP1), there is no output measured at the "Audio signal out" jack:



Next, you decide to check for the presence of a good signal at test point 3 (TP3). There, you find 0 volts AC and DC no matter where the volume control is set.

From this information, formulate a plan for troubleshooting this circuit, answering the following questions:

- What type of signal would you expect to measure at TP3?
- What would be your next step in troubleshooting this circuit?
- Are there any elements of this circuit you know to be working properly?
- What do you suppose would be the most *likely* failure, assuming this circuit once worked just fine and suddenly stopped working all on it's own?

file 02474

Answer 30

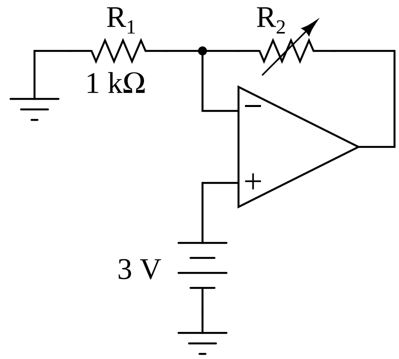
The correct voltage signal at TP3 should be an audio waveform with significant crossover distortion (specifically, a vertical "jump" at each point where the waveform crosses zero volts, about 1.4 volts peak to peak). I'll let you figure out answers to the other questions on your own, or with classmates.

Notes 30

I have found that troubleshooting scenarios are always good for stimulating class discussions, with students posing strategies for isolating the fault(s) and correcting one another on logical errors. There is not enough information given in this question to ensure a single, correct answer. Discuss this with your students, helping them to use their knowledge of circuit theory and opamps to formulate good diagnostic strategies.

Question 31

Calculate the current through resistor R_2 in this opamp circuit for several different values of R_2:



R_2	I_{R_2}
1 kΩ	
2 kΩ	
3 kΩ	
4 kΩ	
5 kΩ	
6 kΩ	

For each value of R_2, what is it that establishes the amount of current through it? Do you see any practical value for a circuit such as this?

file 02511

Answer 31

R_2	I_{R_2}
1 kΩ	3 mA
2 kΩ	3 mA
3 kΩ	3 mA
4 kΩ	3 mA
5 kΩ	3 mA
6 kΩ	3 mA

This circuit acts like a *current mirror*, except much more precise.

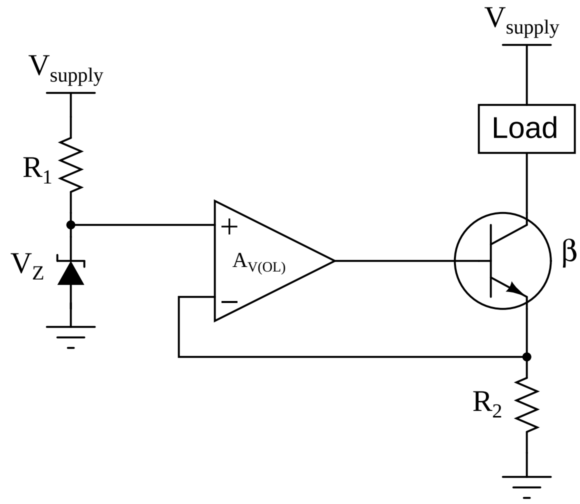
Follow-up question: what factor(s) limit the greatest resistance value of R_2 that the operational amplifier may sustain 3 milliamps of current through?

Notes 31

Besides reviewing the purpose of a current mirror circuit, this question draws students' attention to the current-regulating capabilities of an operational amplifier by having them analyze it as though it were simply a noninverting voltage amplifier circuit.

Question 32

Explain how the operational amplifier maintains a constant current through the load:



Write an equation solving for the regulated load current, given any relevant variables shown in the schematic diagram (R_1, V_Z, V_{supply}, $A_{V(OL)}$, etc.).

file 02512

Answer 32

$$I_{load} = \frac{V_Z}{R_2}$$

Follow-up question: is the transistor *sourcing* current to the load, or *sinking* current from it?

Challenge question #1: modify the given equation to more precisely predict load current, taking the β of the transistor into account.

Challenge question #2: modify the location of the load in this circuit so that the given equation does precisely predict load current, rather than closely approximate load current.

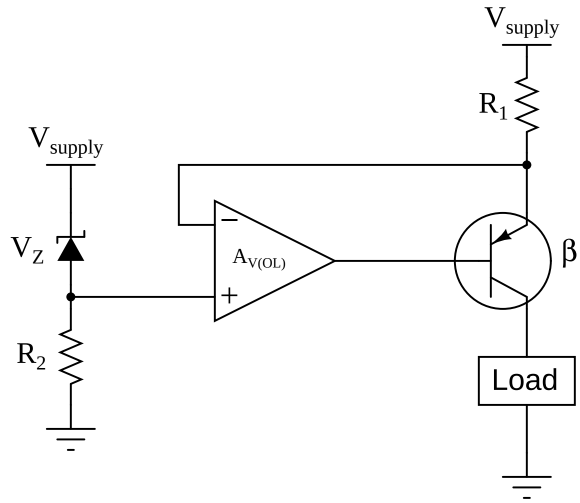
Notes 32

This is a good example of how operational amplifiers may greatly improve the functions of discrete-component circuits. In this case, the opamp performs the function of a *current mirror* circuit, and does so with greater precision and reliability than a simple current mirror ever could.

It should be noted that the equation provided in the answer does not directly predict the current through the load, rather it predicts current through resistor R_2. This is equal to load current only if the transistor's base current is zero, which of course it cannot be. The *real* equation for predicting load current will be a bit more complex than what is given in the answer, and I leave it for your students to derive.

Question 33

Explain how the operational amplifier maintains a constant current through the load:



Write an equation solving for the regulated load current, given any relevant variables shown in the schematic diagram (R_1, V_Z, V_{supply}, $A_{V(OL)}$, etc.). Also, describe what would have to be changed in this circuit in order to set the regulated current at a different value.

file 02513

Answer 33

$$I_{load} = \frac{V_Z}{R_1}$$

Follow-up question: is the transistor *sourcing* current to the load, or *sinking* current from it?

Challenge question #1: modify the given equation to more precisely predict load current, taking the β of the transistor into account.

Challenge question #2: modify the location of the load in this circuit so that the given equation does precisely predict load current, rather than closely approximate load current.

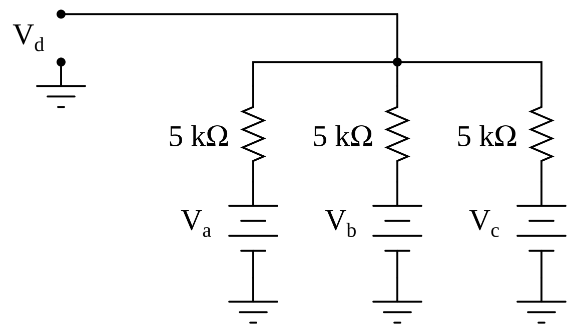
Notes 33

This is a good example of how operational amplifiers may greatly improve the functions of discrete-component circuits. In this case, the opamp performs the function of a *current mirror* circuit, and does so with greater precision and reliability than a simple current mirror ever could.

It should be noted that the equation provided in the answer does not directly predict the current through the load, rather it predicts current through resistor R_2. This is equal to load current only if the transistor's base current is zero, which of course it cannot be. The *real* equation for predicting load current will be a bit more complex than what is given in the answer, and I leave it for your students to derive.

Question 34

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 34

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

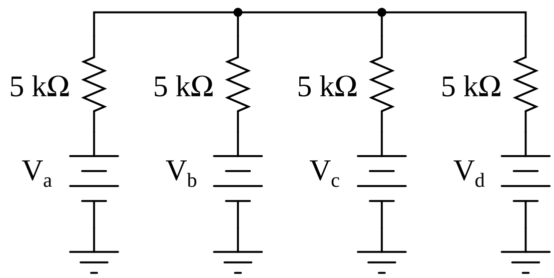
$$V_d = \frac{V_a + V_b + V_c}{3}$$

Notes 34

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.

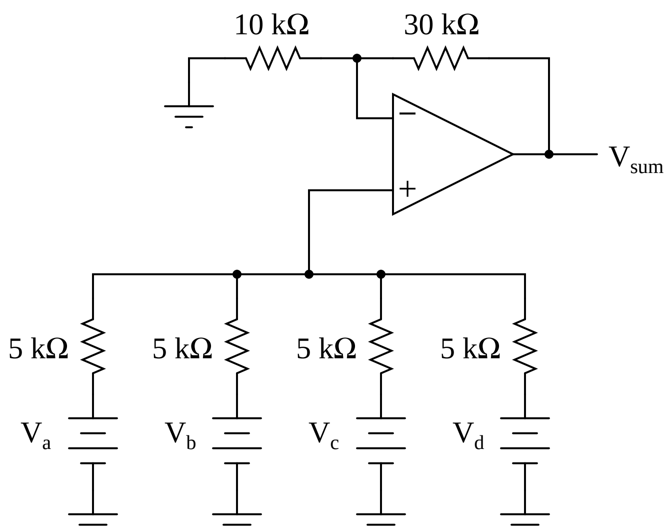
Question 35

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 35



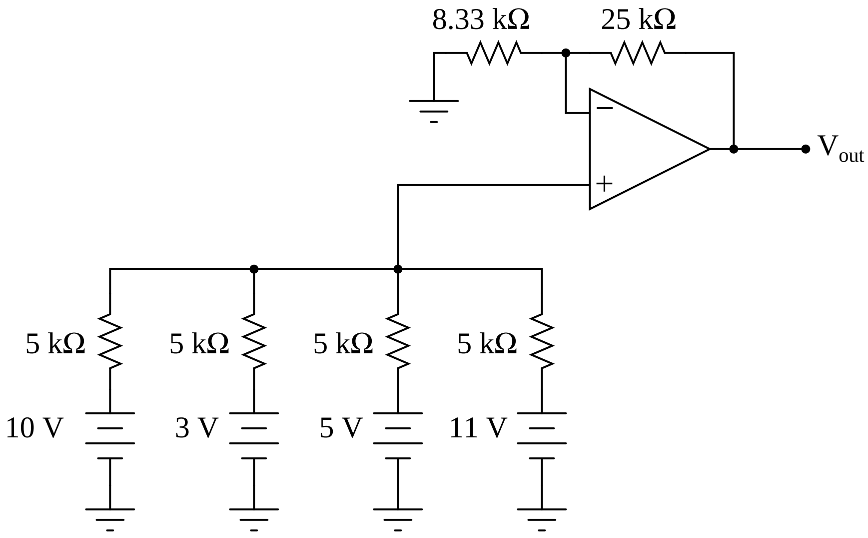
$$V_{sum} = V_a + V_b + V_c + V_d$$

Notes 35

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.

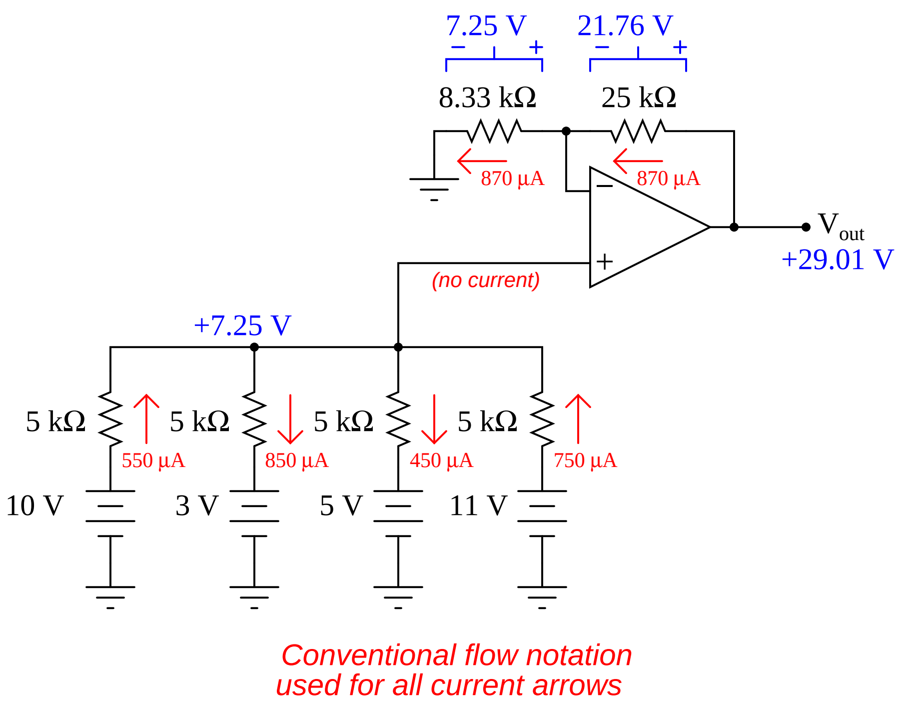
Question 36

Determine all current magnitudes and directions, as well as voltage drops, in this circuit:



file 02515

Answer 36



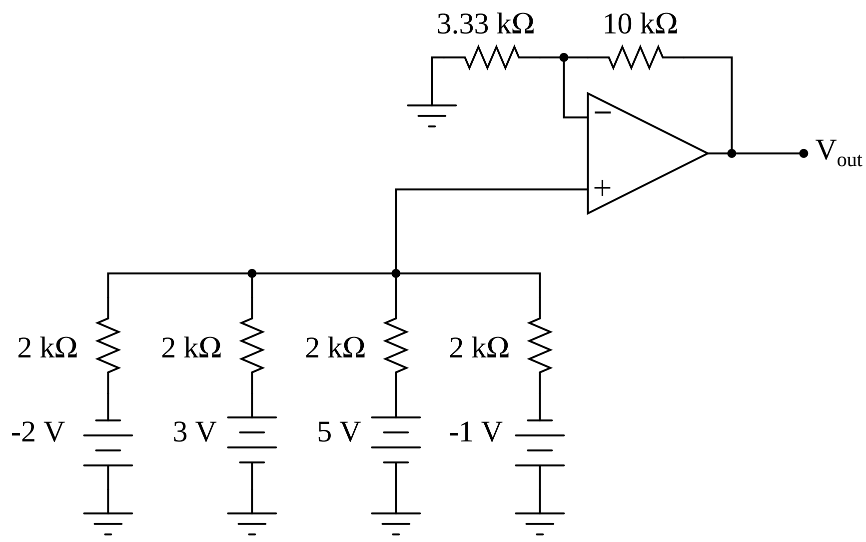
Follow-up question: what would be required to get this circuit to output the *exact* sum of the four input voltages?

Notes 36

This question not only provides practice analyzing the behavior of a summer circuit, but also analyzing the behavior of a passive averager circuit. If your students need some refreshing on how to analyze the passive averager, you might want to review Millman's Theorem with them.

Question 37

Determine all current magnitudes and directions, as well as voltage drops, in this circuit:



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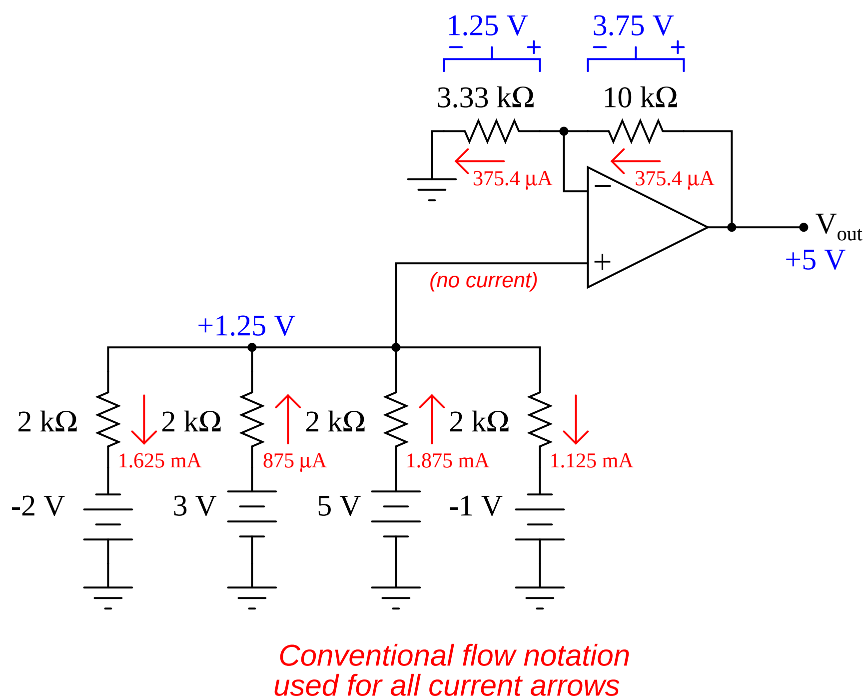
Answer 37



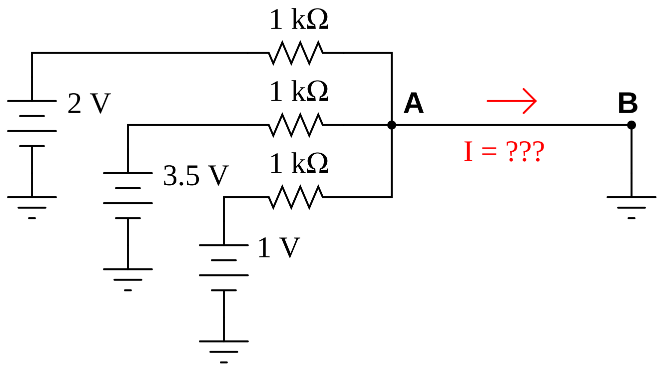
Follow-up question: what would be required to get this circuit to output the *exact* sum of the four input voltages?

Notes 37

This question not only provides practice analyzing the behavior of a summer circuit, but also analyzing the behavior of a passive averager circuit. If your students need some refreshing on how to analyze the passive averager, you might want to review Millman's Theorem with them.

Question 38

Determine the amount of current from point **A** to point **B** in this circuit:



file 02516

Answer 38

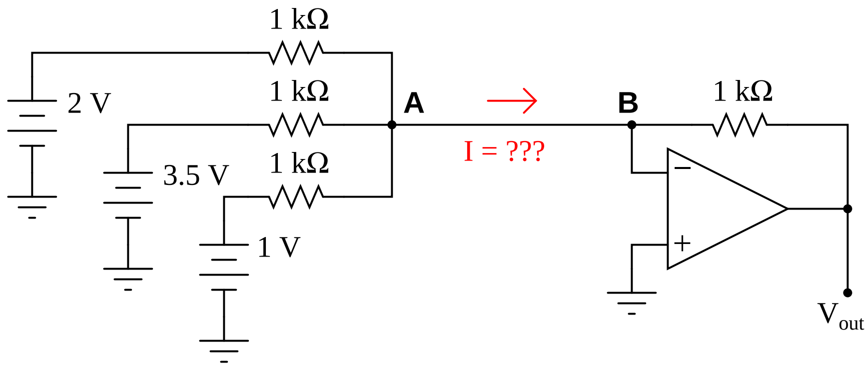
$I = 6.5$ mA

Notes 38

This question, while being an application of Kirchhoff's Current Law, is also a prelude to an inverting summer circuit, where an opamp takes that 6.5 mA (total) current and converts it into an output voltage.

Question 39

Determine the amount of current from point **A** to point **B** in this circuit, and also the output voltage of the operational amplifier:



file 02517

Answer 39

$I = 6.5$ mA $\qquad V_{out} = $ -6.5 V

Notes 39

This question is best preceded by #02516, which asks for students to solve for the current between **A** and **B** with no opamp in the circuit (simply grounded at point **B**). When students realize that point **B** is now a *virtual* ground instead of a real ground, they see that the same conclusion derived by Kirchhoff's Current Law in the passive circuit is still valid in this active circuit, and that the result is an output *voltage* corresponding to that current.

Question 40

Identify some of the distinguishing characteristics of inverting and noninverting summer circuits. How may you identify which is which, and how may you determine the proper resistor values to make each one work as it should?

file 02520

Answer 40

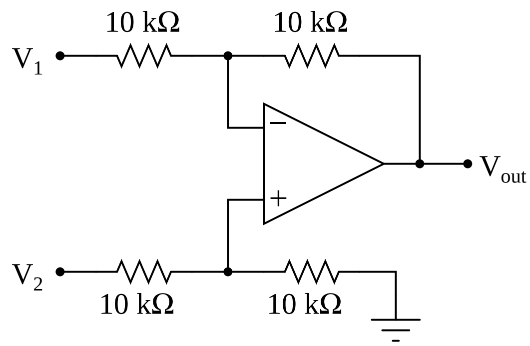
I won't directly answer the questions here, but I will give some hints. A noninverting summer circuit is composed of a *passive voltage averager* circuit coupled to a *noninverting voltage amplifier* with a voltage gain equal to the number of inputs on the averager. An inverting summer circuit is composed of a *passive current summer* node coupled to a *current-to-voltage converter*.

Notes 40

This question is designed to spur discussion amongst your students, exchanging ideas about each circuit's defining characteristics. Having students explore each circuit type on their own, reaching their own conclusions about how to differentiate the two, is a far more effective way of making them understand the differences than simply telling them outright.

Question 41

Complete the table of values for this opamp circuit, calculating the output voltage for each combination of input voltages shown:



V_1	V_2	V_{out}
0 V	0 V	
+1 V	0 V	
0 V	+1 V	
+2 V	+1.5 V	
+3.4 V	+1.2 V	
-2 V	+4 V	
+5 V	+5 V	
-3 V	-3 V	

What pattern do you notice in the data? What mathematical relationship is there between the two input voltages and the output voltage?

file 02518

Answer 41

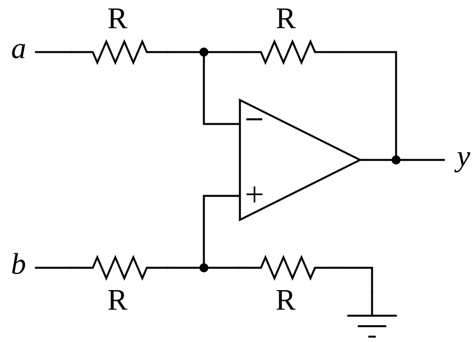
V_1	V_2	V_{out}
0 V	0 V	0 V
+1 V	0 V	-1 V
0 V	+1 V	+1 V
+2 V	+1.5 V	-0.5 V
+3.4 V	+1.2 V	-2.2 V
-2 V	+4 V	+6 V
+5 V	+5 V	0 V
-3 V	-3 V	0 V

Notes 41

Thought it may be tedious to calculate the output voltage for each set of input voltages, working through all the voltage drops and currents in the opamp circuit one at a time, it shows students how they may be able to discern the function of an opamp circuit merely by applying basic laws of electricity (Ohm's Law, KVL, and KCL) and the "golden assumptions" of negative feedback opamp circuits (no input currents, zero differential input voltage).

Question 42

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):



file 01010

Answer 42

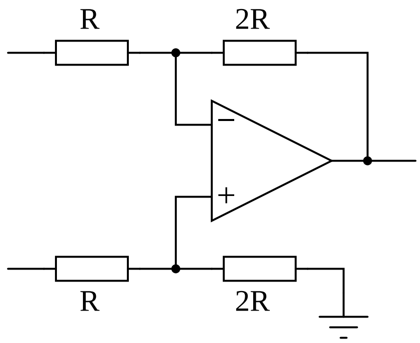
$y = b - a$

Notes 42

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 43

How does the operation of this difference amplifier circuit compare with the resistor values given ($2R$ = twice the resistance of R), versus its operation with all resistor values equal?



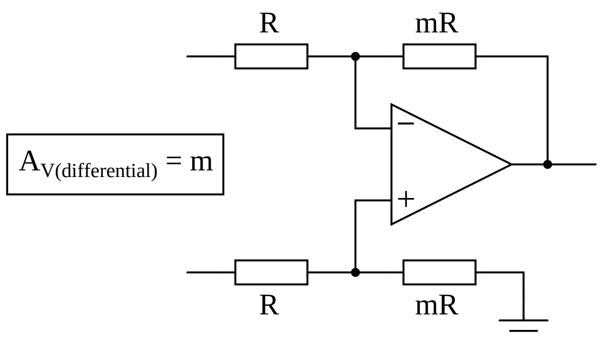
Describe what approach or technique you used to derive your answer, and also explain how your conclusion for this circuit might be generalized for all difference amplifier circuits.

file 02525

Answer 43

It is very important that you develop the skill of "exploring" a circuit configuration to see what it will do, rather than having to be told what it does (either by your instructor or by a book). All you need to have is a solid knowledge of basic electrical principles (Ohm's Law, Kirchhoff's Voltage and Current Laws) and know how opamps behave when configured for negative feedback.

As for a generalized conclusion:



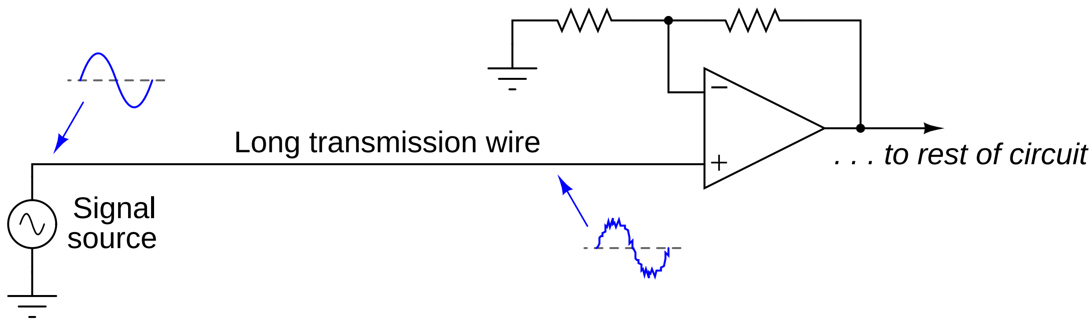
Notes 43

It is easy for you (the instructor) to show how and why this circuit acts as it does. The point of this question, however, is to get students to take the initiative to explore the circuit on their own. It is simple enough for any student to set up some hypothetical test conditions (a *thought experiment*) to analyze what this circuit will do, that the only thing holding them back from doing so is attitude, not aptitude.

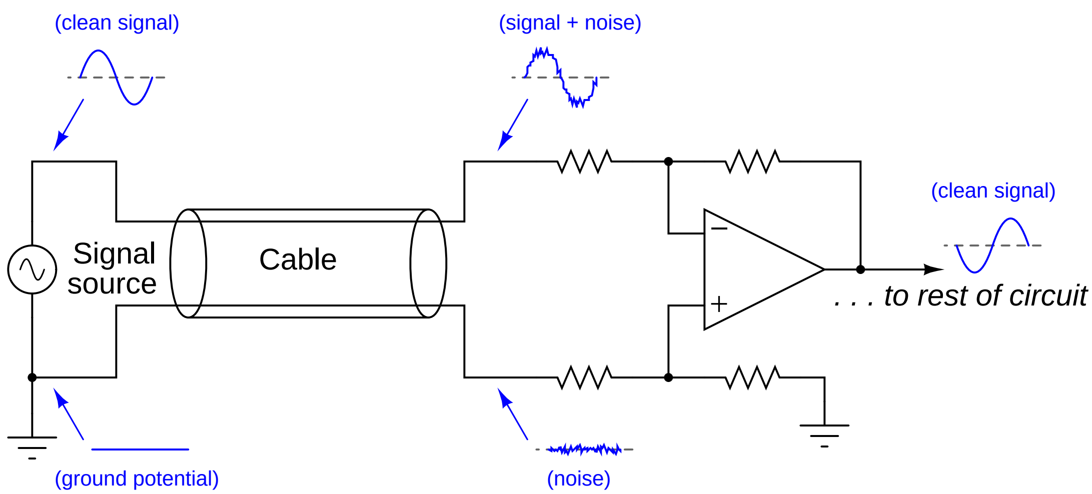
This is something I have noticed over years of teaching: so many students who are more than capable of doing the math and applying well-understood electrical rules refuse to do so *on their own*, because years of educational tradition has indoctrinated them to wait for the instructor's lead rather than explore a concept on their own.

Question 44

If a weak voltage signal is conveyed from a source to an amplifier, the amplifier may detect more than just the desired signal. Along with the desired signal, external electronic "noise" may be coupled to the transmission wire from AC sources such as power line conductors, radio waves, and other electromagnetic interference sources. Note the two waveshapes, representing voltages along the transmission wire measured with reference to earth ground:



Shielding of the transmission wire is always a good idea in electrically noisy environments, but there is a more elegant solution than simply trying to shield interference from getting to the wire. Instead of using a single-ended amplifier to receive the signal, we can transmit the signal along *two* wires and use a *difference* amplifier at the receiving end. Note the four waveforms shown, representing voltages at those points measured with reference to earth ground:



If the two wires are run parallel to each other the whole distance, so as to be exposed to the exact same noise sources along that distance, the noise voltage at the end of the bottom wire will be the same noise voltage as that superimposed on the signal at the end of the top wire.

Explain how the difference amplifier is able to restore the original (clean) signal voltage from the two noise-ridden voltages seen at its inputs with respect to ground, and also how the phrase *common-mode voltage* applies to this scenario.

file 02519

Answer 44

"Common-mode" voltage refers to that voltage which is common to two or more wires as measured with reference to a third point (in this case, ground). The amplifier in the second circuit only outputs the *difference* between the two signals, and as such does not reproduce the (common-mode) noise voltage at its output.

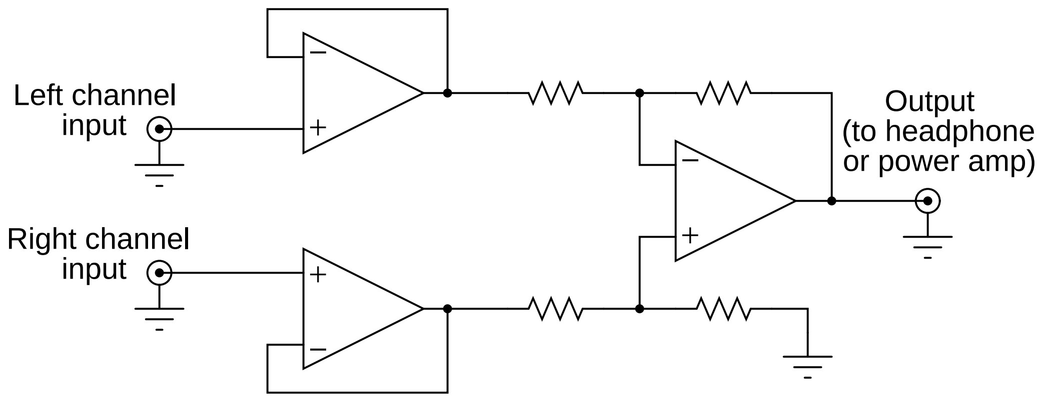
Challenge question: re-draw the original (one wire plus ground) schematic to model the sources of interference and the wire's impedance, to show exactly how the signal could become mixed with noise from source to amplifier.

Notes 44

Differential signal transmission is a very practical application of difference amplifiers, and forms the foundation of certain data transmission standard physical layers such as RS-422 and RS-485.

Question 45

Singers who wish to practice singing to popular music find that the following *vocal eliminator* circuit is useful:



The circuit works on the principle that vocal tracks are usually recorded through a single microphone at the recording studio, and thus are represented equally on each channel of a stereo sound system. This circuit effectively eliminates the vocal track from the song, leaving only the music to be heard through the headphone or speaker.

Explain how the operational amplifiers accomplish this task of vocal track elimination. What role does each opamp play in this circuit?

file 02524

Answer 45

The first two opamps merely "buffer" the audio signal inputs so they do not become unnecessarily loaded by the resistors. The third opamp *subtracts* the left channel signal from the right channel signal, eliminating any sounds common to both channels.

Challenge question: unfortunately, the circuit as shown tends to eliminate bass tones as well as vocals, since the acoustic properties of bass tones make them represented nearly equally on both channels. Determine how the circuit may be expanded to include opamps that re-introduce bass tones to the "vocal-eliminated" output.

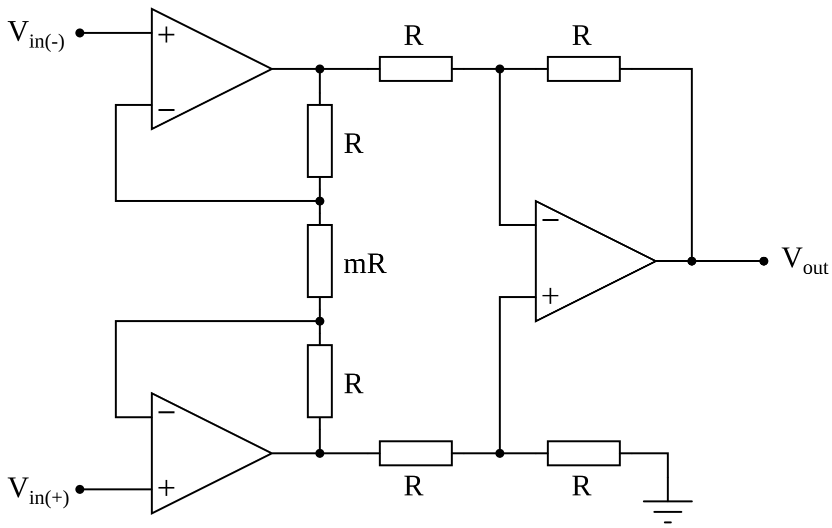
Notes 45

Circuits like this are great for illustration, because they show practical application of a principle while engaging student interest.

One of my students, when faced with the challenge question, suggested placing a high-pass filter before *one* of the subtractor's inputs, eliminating bass tones at one of the inputs and therefore reproducing bass tones at the subtractor output. This is a great idea, and shows what can happen when students are given a forum to think creatively and freely express ideas, but there are some practical reasons it would be difficult to implement. The concept works great if we assume the use of a perfect HP filter, with absolutely zero phase shift and zero attenuation through the entire pass-band. Unfortunately, real filter circuits always exhibit some degree of both, and so the process of subtraction would not be as effective as necessary to eliminate the vocals from a song.

Question 46

The following circuit is known as an *instrumentation amplifier*:



Suppose a DC voltage were to be applied to the noninverting input terminal, +1 volt at $V_{in(+)}$, and the inverting input terminal grounded. Complete the following table showing the output voltage of this circuit for different values of m:

m	V_{out}
1	
2	
3	
4	
5	
6	

file 02526

Answer 46

m	V_{out}
1	3 volts
2	2 volts
3	1.66 volts
4	1.5 volts
5	1.4 volts
6	1.33 volts

$$A_{V(diff)} = \frac{2+m}{m}$$

Follow-up question: why did I choose to set the noninverting input voltage at +1 volts and ground the inverting input? Should we not be able to calculate gain given *any* two input voltages and a value for m? Explain the purpose behind my choice of input voltage conditions for this "thought experiment."

Notes 46

While the relationship between instrumentation amplifier differential gain and m may be looked up in any good opamp circuit textbook, it is something that your students should learn to figure out on their own from the data in the table.

Question 47

Find the datasheet for a real instrumentation amplifier (packaged as a single integrated circuit) and bring it to class for discussion with your classmates. Analyze and discuss the inner workings of the circuit, and some of its performance parameters. If you do not know where to begin looking, try researching the Analog Devices model AD623, either in a reference book or on the internet.

file 02527

Answer 47

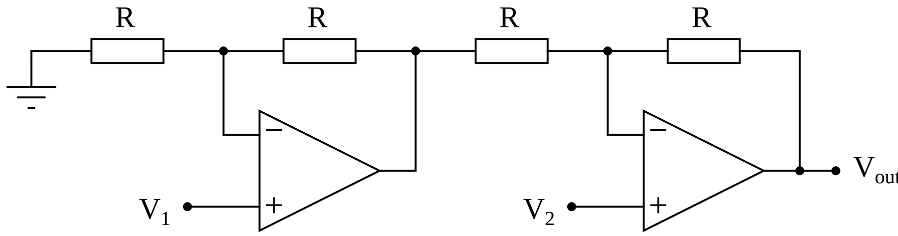
I'll leave the discussion up to you and your classmates. With any luck, you should have found some example circuits showing how the instrumentation amplifier may be used, or possibly some application notes to complement the datasheet.

Notes 47

The idea of this question is to get students researching real integrated circuit applications, to teach them how to do this research and also how to interpret what they find. Since there are so many high-quality instrumentation amplifiers already built and packaged as monolithic units, it is usually not worth the technician's time to fabricate one from individual opamps. However, when specifying a pre-built instrumentation amplifier, it is essential to know what you need and how to use it once it arrives!

Question 48

The following circuit is a type of difference amplifier, similar in behavior to the instrumentation amplifier, but only using two operational amplifiers instead of three:



Complete the table of values for this opamp circuit, calculating the output voltage for each combination of input voltages shown. From the calculated values of output voltage, determine which input of this circuit is inverting, and which is noninverting, and also how much differential voltage gain this circuit has. Express these conclusions in the form of an equation.

V_1	V_2	V_{out}
0 V	0 V	
+1 V	0 V	
0 V	+1 V	
+2 V	+1.5 V	
+3.4 V	+1.2 V	
-2 V	+4 V	
+5 V	+5 V	
-3 V	-3 V	

file 02539

Answer 48

V_1	V_2	V_{out}
0 V	0 V	0 V
+1 V	0 V	-2 V
0 V	+1 V	+2 V
+2 V	+1.5 V	-1 V
+3.4 V	+1.2 V	-4.4 V
-2 V	+4 V	+12 V
+5 V	+5 V	0 V
-3 V	-3 V	0 V

$$V_{out} = 2(V_2 - V_1)$$

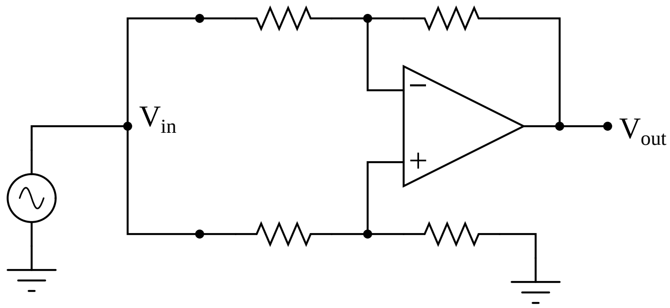
Follow-up question: explain how this circuit is at once similar and different from the popular "instrumentation amplifier" circuit.

Notes 48

Although it would be easy enough just to tell students which input is inverting and which input is noninverting, they will learn more (and practice their analysis skills more) if asked to work through the table of values to figure it out.

Question 49

An important parameter of any differential amplifier – bare opamps and difference amplifiers made from opamps alike – is *common-mode rejection*, or CMR. Explain what this parameter means, how the following circuit tests this parameter, and why it is important to us:



$$CMR = 20 \log (V_{out}/V_{in})$$

file 02521

Answer 49

CMR measures the degree to which a differential amplifier ignores common-mode signals.

Follow-up question: what range of CMR values would you expect from a good differential amplifier, if subjected to the test shown in the schematic and CMR calculated by the given formula?

Notes 49

In case some students do not recall (!), the logarithmic formula is nothing special. It simply provides an answer in units of decibels.

Question 50

Explain what *common-mode rejection ratio* means for a differential amplifier, and give a formula for calculating it.

file 02522

Answer 50

Common-mode rejection ratio compares an amplifier's differential voltage gain to its common-mode voltage gain. Ideally, CMRR is infinite.

$$\text{CMRR} = 20 \log \left(\frac{A_{diff(ratio)}}{A_{CM(ratio)}} \right)$$

The fundamental mechanism causing a common-mode signal to make it through to the output of a differential amplifier is a change in input offset voltage resulting from shifts in bias caused by that common-mode voltage. So, sometimes you may see CMRR defined as such:

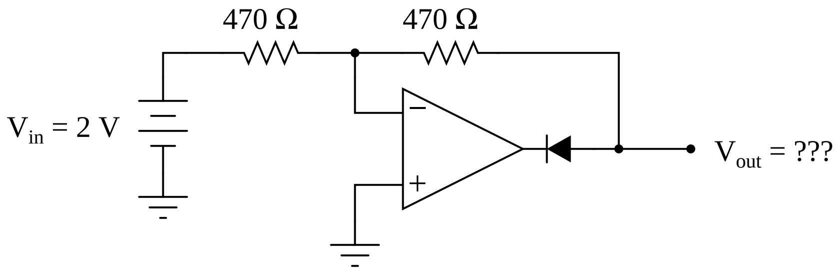
$$\text{CMRR} = 20 \log \left(\frac{\Delta V_{in(common)}}{\Delta V_{offset}} \right)$$

Notes 50

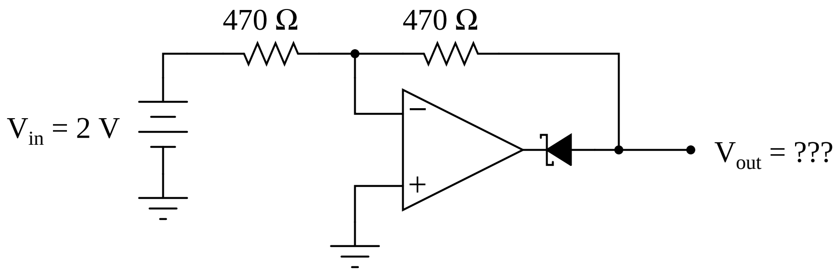
An application that really shows the value of a high CMRR is differential signal transmission, as shown in question #02519. For those students not grasping the significance of CMRR, this would be a good example circuit to show them.

Question 51

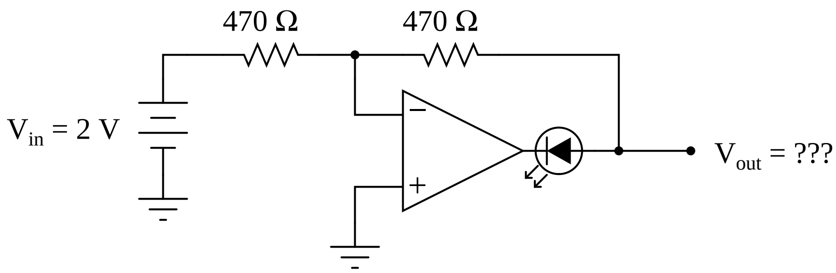
Determine the output voltage of this circuit, assuming a silicon diode (0.7 volts typical forward drop):



Now, determine the output voltage of the same circuit with a Schottky diode (0.4 volts typical forward drop) instead of a silicon PN junction diode:



Now, determine the output voltage of the same circuit with a light-emitting diode (1.7 volts typical forward drop):



Comment on these three circuits' output voltages: what does this indicate about the effect of the diode's voltage drop on the opamp output?

file 02542

Answer 51

In both circuits, the output voltage is precisely -2 volts.

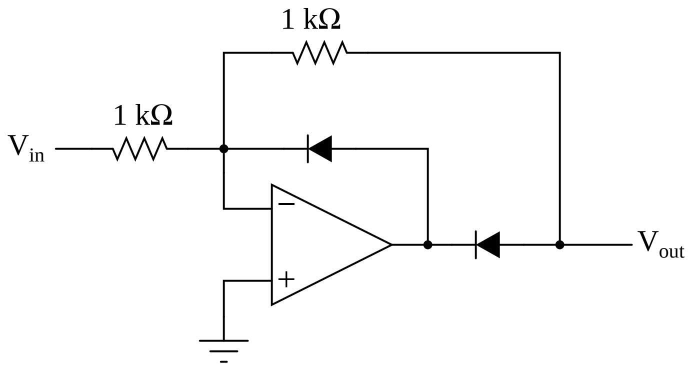
Follow-up question: what *is* different within these three circuits, if not the output voltage?

Notes 51

By itself, these circuits are fairly useless. Their purpose is to prepare students to understand how precision rectifier circuits work, by showing how negative feedback makes the diode's forward voltage drop irrelevant. This is another example of the power of negative feedback, and an essential concept for understanding all precise (opamp-driven) diode circuits.

Question 52

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 52

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

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

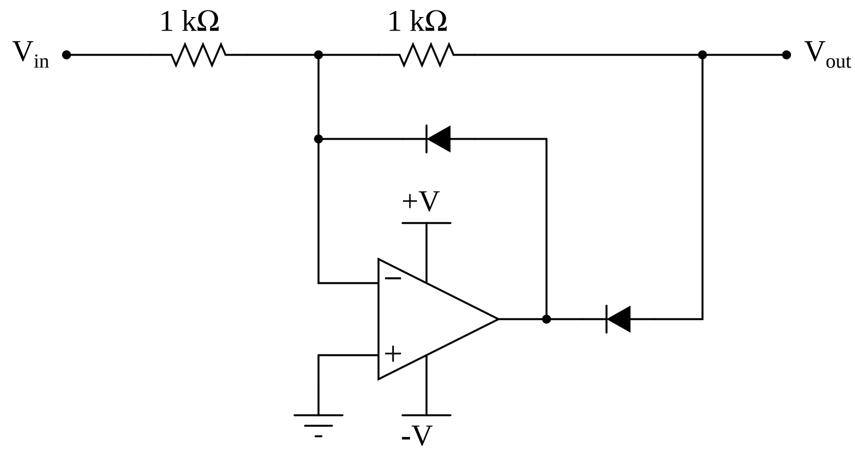
This circuit is a precision rectifier.

Notes 52

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 53

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 53

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.

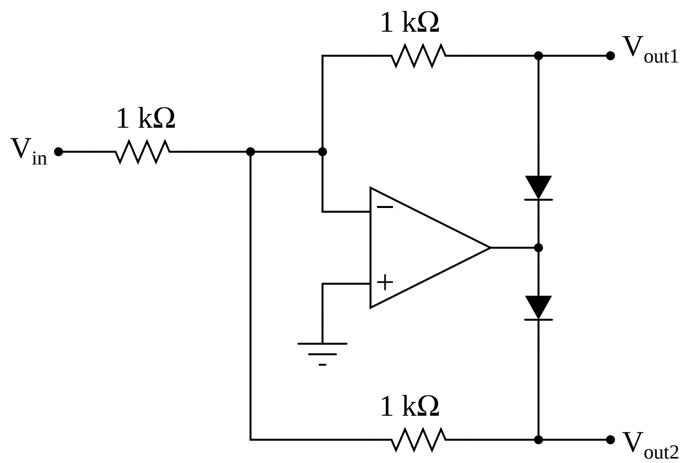
Notes 53

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 54

The following circuit is sometimes referred to as a *polarity separator*. Invent some test conditions you would use to "prove" the operation of the circuit, then analyze the circuit under those imagined conditions and see what the results are:



Explain what each output does in this "polarity separator" circuit for any given input voltage.

file 02557

Answer 54

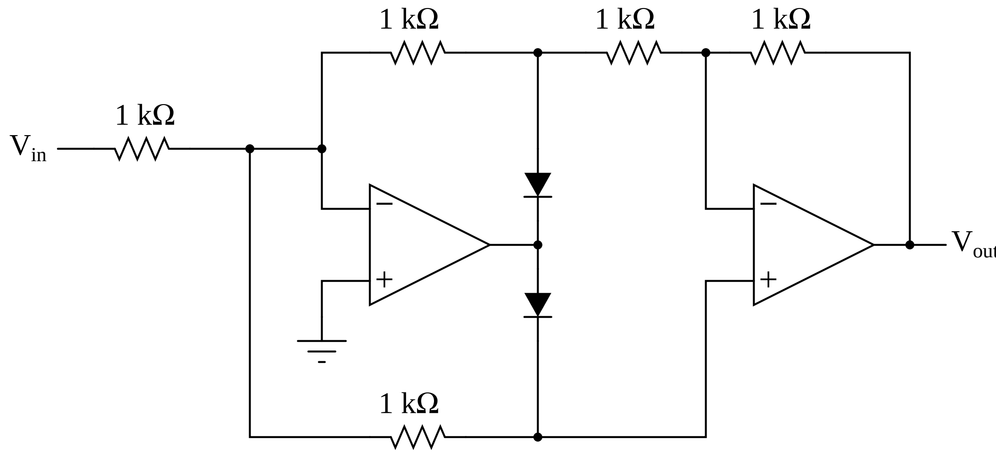
The V_{out1} output is the inverse (negative) of any positive input voltage, while the V_{out2} output is the inverse (positive) of any negative input voltage.

Notes 54

This circuit is a good introduction to the full-wave precision rectifier circuit, although its operation there is a bit more difficult to understand than it is here.

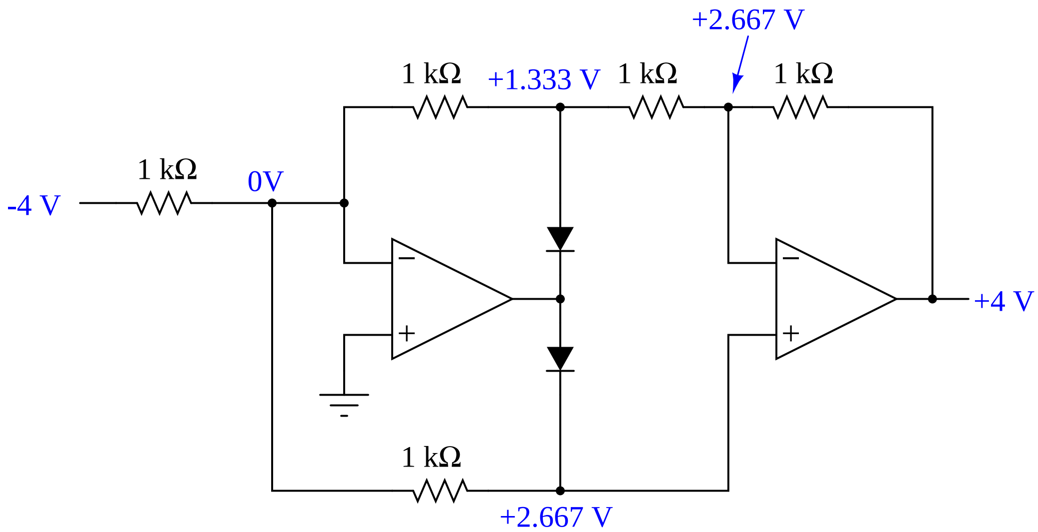
Question 55

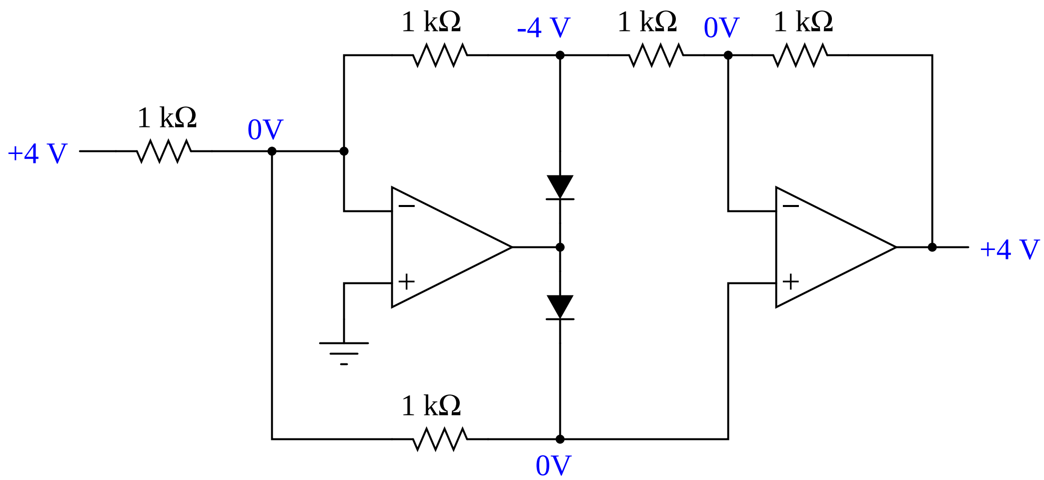
Determine the output voltage of this circuit for two different input voltage values: +4 volts, and -4 volts. Determine the voltage at each and every node with respect to ground as part of your analysis:



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

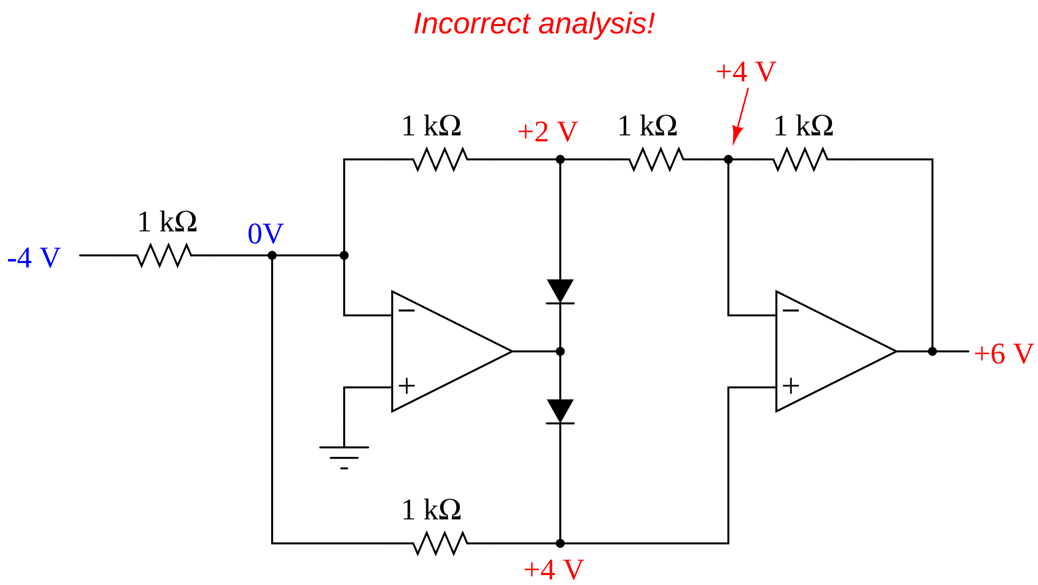
file 01026



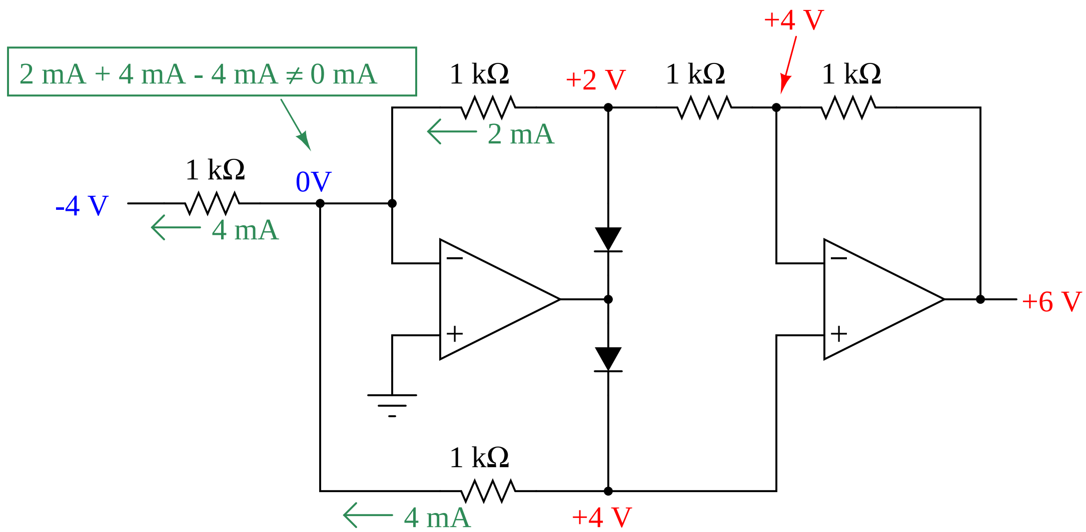


This circuit is a precision full-wave rectifier.

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:

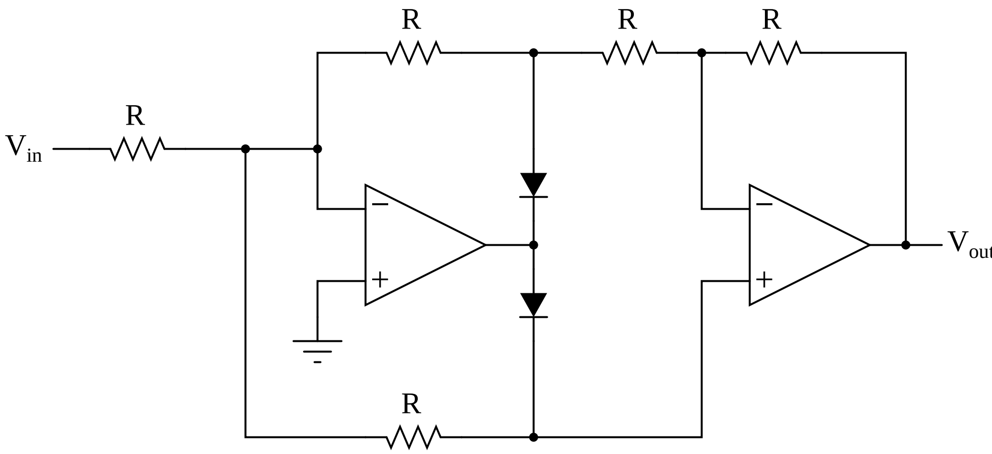


The error seems reasonable until an analysis of *current* is made. If these voltages were true, Kirchhoff's Current Law would be violated at the first opamp's virtual ground:



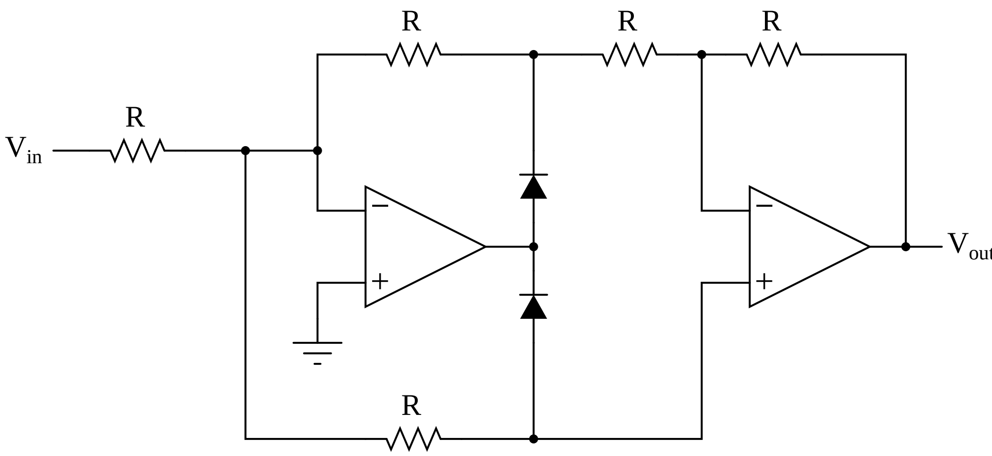
Question 56

Explain how you could reverse the output polarity of this precision rectifier circuit:



file 02558

Answer 56

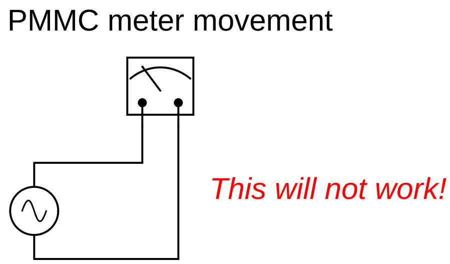


Notes 56

The answer to this question may seem too obvious to both asking. In reality, it's just another excuse to analyze the full-wave rectifier circuit, complete with all currents and voltage drops!

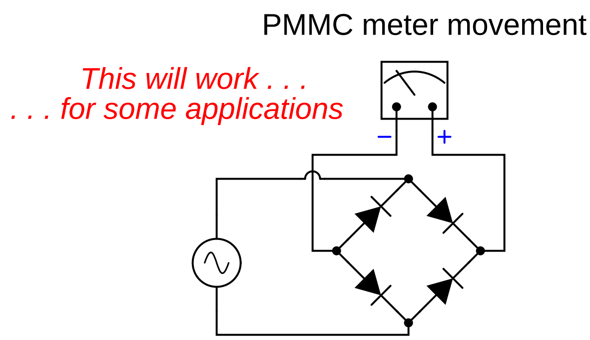
Question 57

One problem with PMMC (permanent magnet moving coil) meter movements is trying to get them to register AC instead of DC. Since these meter movements are polarity-sensitive, their needles merely vibrate back and forth in a useless fashion when powered by alternating current:



The same problem haunts other measurement devices and circuits designed to work with DC, including most modern analog-to-digital conversion circuits used in digital meters. Somehow, we must be able to *rectify* the measured AC quantity into DC for these measurement circuits to properly function.

A seemingly obvious solution is to use a bridge rectifier made of four diodes to perform the rectification:



The problem here is the forward voltage drop of the rectifying diodes. If we are measuring large voltages, this voltage loss may be negligible. However, if we are measuring small AC voltages, the drop may be unacceptable.

Explain how a precision full-wave rectifier circuit built with an opamp may adequately address this situation.

file 02559

Answer 57

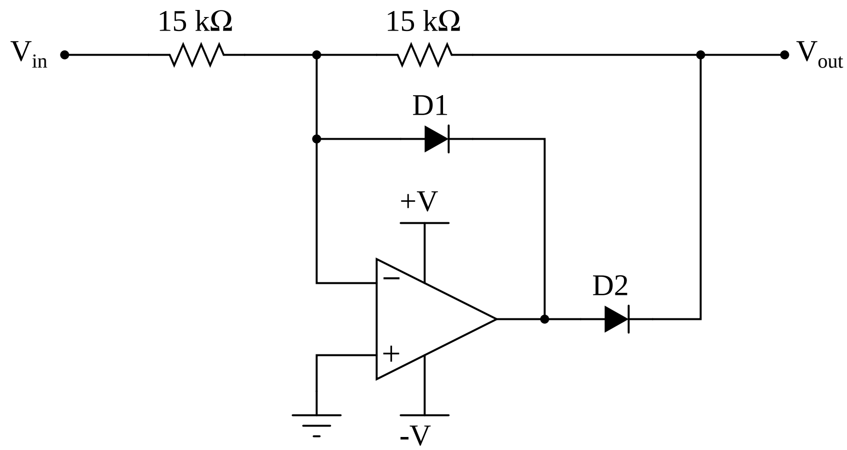
A precision opamp circuit is able to rectify the AC voltage with no voltage loss whatsoever, allowing the DC meter movement (or analog-to-digital conversion circuit) to function as designed.

Notes 57

The purpose of this question is to provide a practical context for precision rectifier circuits, where students can envision a real application.

Question 58

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 58

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?

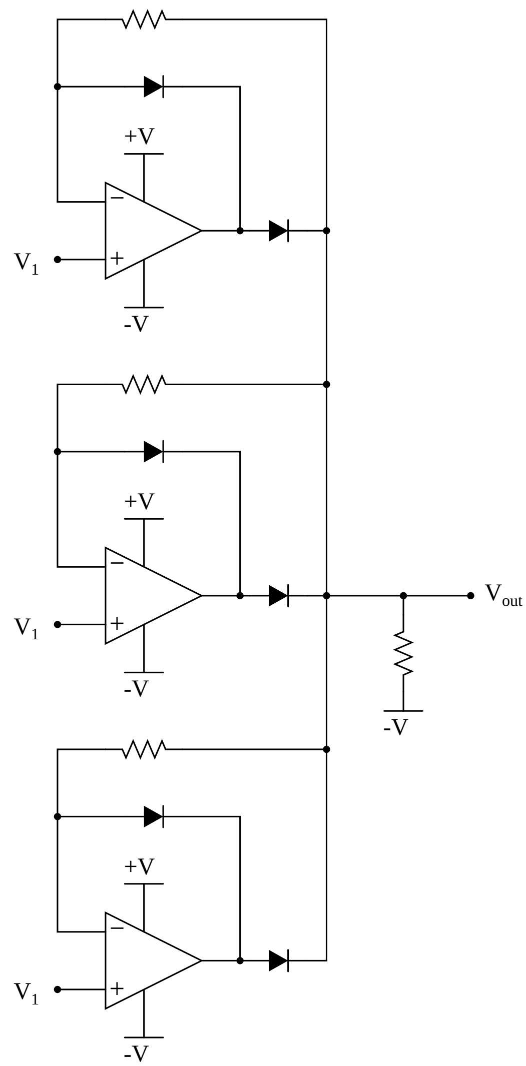
Notes 58

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 59

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 59

The output voltage will be +2.2 volts, precisely.

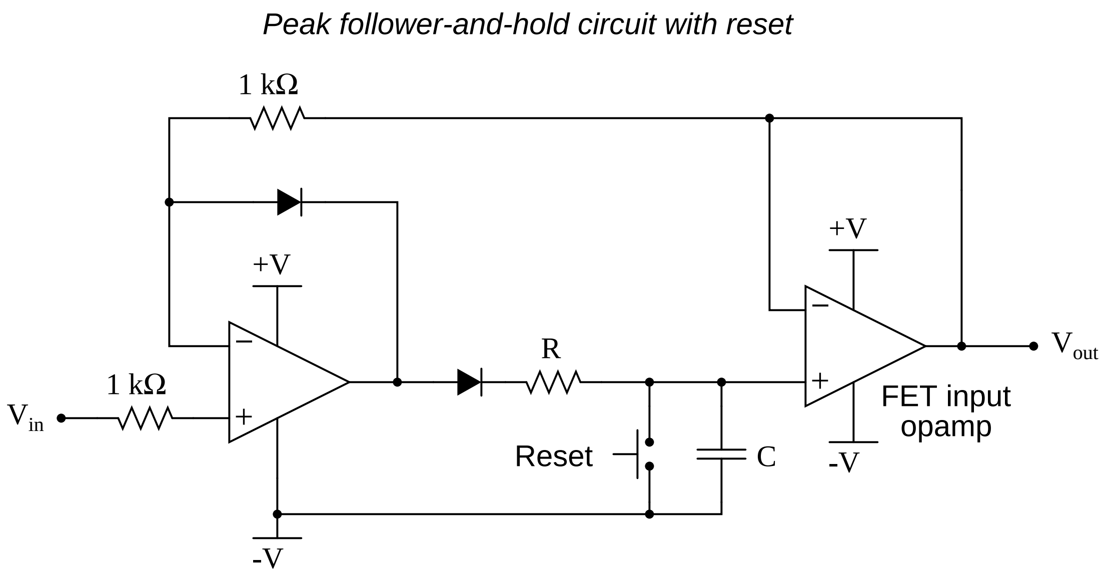
Follow-up question: what function does this circuit perform? Can you think of any practical applications for it?

Notes 59

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 60

This circuit is referred to as a *peak follower-and-hold*, taking the last greatest positive input voltage and "holding" that value at the output until a greater positive input voltage comes along:



Give a brief explanation of how this circuit works, as well as the purpose and function of the "reset" switch. Also, explain why a FET input opamp is required for the last stage of amplification.

file 02639

Answer 60

I'll let you figure out how the circuit works! With regard to the necessity of FET inputs, let me say this: if the bias current of the last opamp were too great, the circuit would "lose its memory" of the last positive peak value over time.

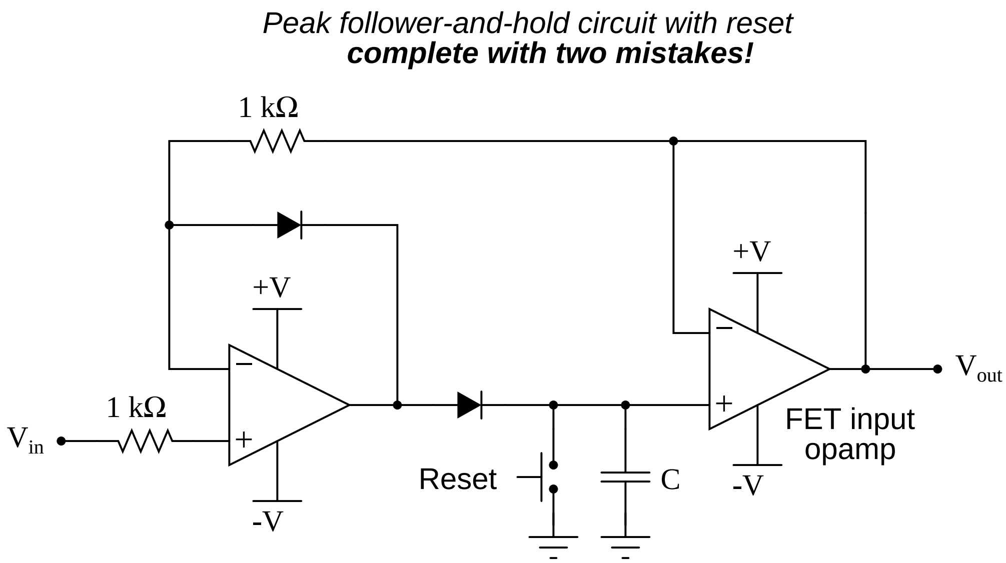
Follow-up question: how would you suggest choosing the values of resistor R and capacitor C?

Challenge question: redraw the circuit, replacing the mechanical reset switch with a JFET for electronic reset capability.

Notes 60

Ask your students if they can think of any practical applications for this type of circuit. There are many!

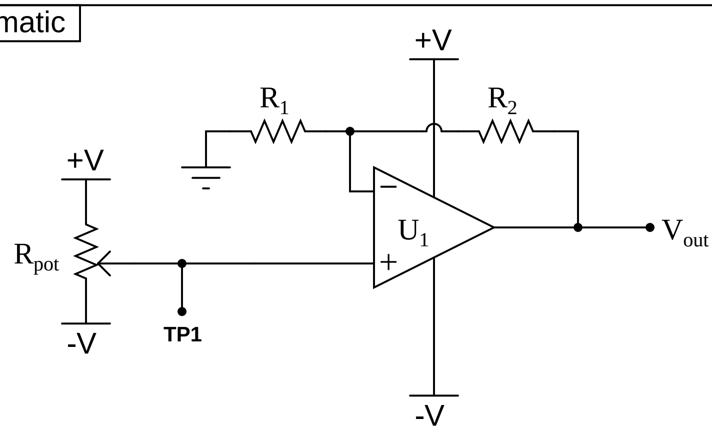
I find it interesting that in two very respectable texts on opamp circuitry, I have found the following peak follower-and-hold circuit given as a practical example:



This circuit contains two mistakes: the first is by having the reset switch go to ground, rather than -V. This makes the reset function set the default output to 0 volts, which makes it impossible for the circuit to subsequently follow and hold any input signal below ground potential. The second mistake is not having a resistor before the reset switch. Without a resistor in place, closing the reset switch places a momentary short-circuit on the output of the first opamp. Granted, the presence of a resistor creates a passive integrator stage (RC time constant) which must be kept considerably fast in order that rapid changes in input will be followed and held, but this is not a difficult factor to engineer.

Competency: **Opamp noninverting amplifier** Version:

Schematic



Given conditions

+V = R_{pot} = V_{TP1} =

-V = R_1 = R_2 =

Parameters

	Predicted	Measured
V_{out}		
A_V (ratio)		
A_V (dB)		

Fault analysis

Suppose component ☐ fails ☐ open ☐ other ______ ☐ shorted

What will happen in the circuit?

file 01969

Answer 61

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

Notes 61

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

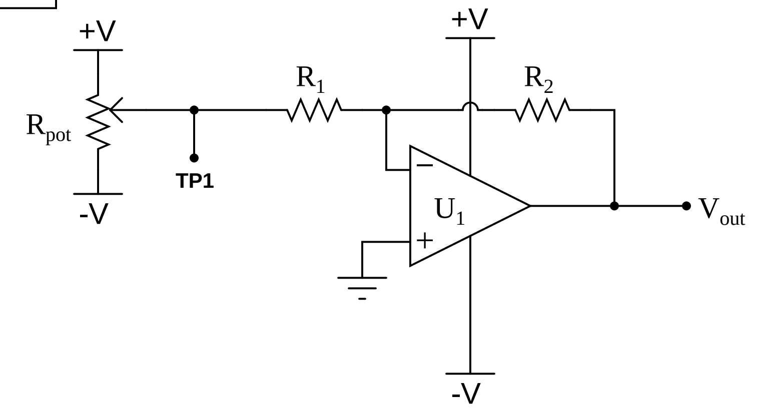
- +V = +12 volts
- -V = -12 volts
- V_{TP1} = Any voltage well between +V and -V not resulting in output saturation
- R_1 = 10 kΩ
- R_2 = 27 kΩ
- R_{pot} = 10 kΩ linear potentiometer
- U_1 = TL081 BiFET operational amplifier (or one-half of a TL082)

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

Question 62

Competency: **Opamp inverting amplifier** Version:

Schematic



Given conditions

+V = R_{pot} = V_{TP1} =

-V = R_1 = R_2 =

Parameters

	Predicted	Measured
V_{out}		
A_V (ratio)		
A_V (dB)		

Fault analysis

Suppose component ______ fails ☐ open ☐ shorted ☐ other ______

What will happen in the circuit?

file 01970

Answer 62

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

Notes 62

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

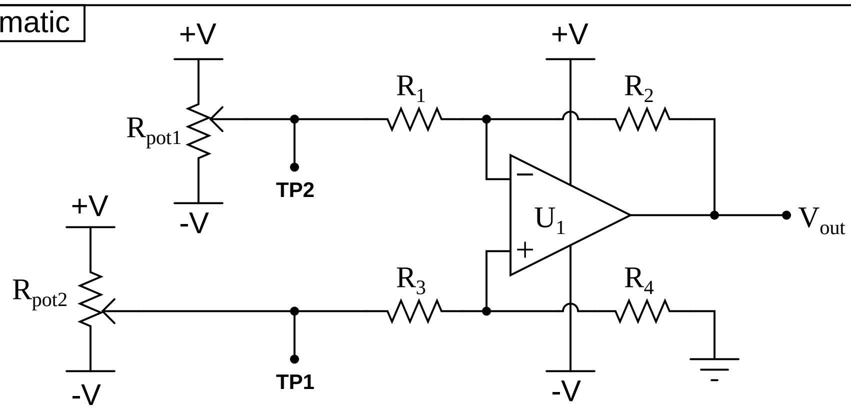
- +V = +12 volts
- -V = -12 volts
- V_{TP1} = Any voltage well between +V and -V not resulting in output saturation
- R_1 = 10 kΩ
- R_2 = 27 kΩ
- R_{pot} = 10 kΩ linear potentiometer
- U_1 = TL081 BiFET operational amplifier (or one-half of a TL082)

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

Question 63

Competency: **Opamp difference amplifier** Version:

Schematic



Given conditions

+V = $R_{pot1} = R_{pot2}$ = R_1 = R_2 =

-V = R_3 = R_4 =

Parameters

	Predicted	Measured	
V_{out}			V_{TP1} = ____ V V_{TP2} = ____ V
V_{out}			V_{TP1} = ____ V V_{TP2} = ____ V
V_{out}			V_{TP1} = ____ V V_{TP2} = ____ V
V_{out}			$V_{TP1} = V_{TP2}$ = ____ V
V_{out}			$V_{TP1} = V_{TP2}$ = ____ V

Common mode voltage

	Predicted	Calculated		
A_V (ratio)			Differential	$\frac{V_{out}}{V_{TP1} - V_{TP2}}$

	Predicted	Calculated		
A_V (ratio)			Common-mode	$\frac{\Delta V_{out}}{\Delta V_{in}}$

file 02466

Answer 63

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

Notes 63

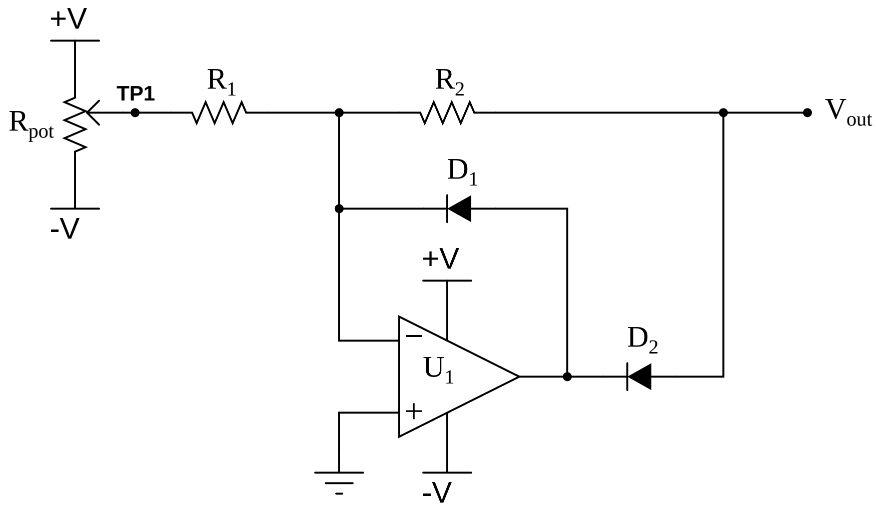
Use a dual-voltage, regulated power supply to supply power to the opamp. Specify all four resistors as equal value, between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.). This will ensure a differential voltage gain of unity. If you *want* to have a different voltage gain, then by all means specify these resistor values however you see fit!

Differential gain is calculated by averaging the quotients of each measured V_{out} value with its respective $V_{in(+)} - V_{in(-)}$ differential input voltage. Common-mode gain is calculated by dividing the difference in output voltages (ΔV_{out}) by the difference in common-mode input voltages (ΔV_{in}).

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

Competency: **Precision rectifier, half wave** Version:

Schematic



Given conditions

+V = -V = $R_1 = R_2 =$ $R_{pot} =$

Parameters

	Predicted	Measured	
V_{out}			V_{TP1} = ____
V_{out}			V_{TP1} = ____
V_{out}			V_{TP1} = ____

Fault analysis

Suppose component ______ fails ☐ open ☐ shorted ☐ other ____________

What will happen in the circuit?

file 02540

Answer 64

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

Notes 64

Choose both positive input voltage values and negative input voltage values, so that students may predict and measure the output of this circuit under both types of conditions. The choice of diodes is not critical, as any rectifier diodes will work. The two resistor values should be equal, and at least as high as the potentiometer value. I recommend a 10 kΩ potentiometer and 15 kΩ resistors.

A good follow-up question to ask is what would be required to change the polarity of this half-wave precision rectifier circuit.

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

Troubleshooting log

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

file 03933

Answer 65

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

Notes 65

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

Question 66

NAME: _______________ **Troubleshooting Grading Criteria**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

A. Working prototype circuit built and demonstrated

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

A. Unsafe procedure(s) used at any point

file 03932

Answer 66

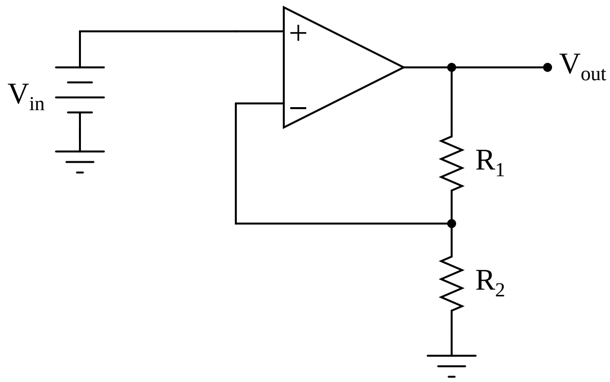
Be sure to document all steps taken and conclusions made in your troubleshooting!

Notes 66

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

Question 67

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



- Resistor R_1 fails open:
- Solder bridge (short) across resistor R_1:
- Resistor R_2 fails open:
- Solder bridge (short) across resistor R_2:
- Broken wire between R_1/R_2 junction and inverting opamp input:

For each of these conditions, explain *why* the resulting effects will occur.
file 03774

Answer 67

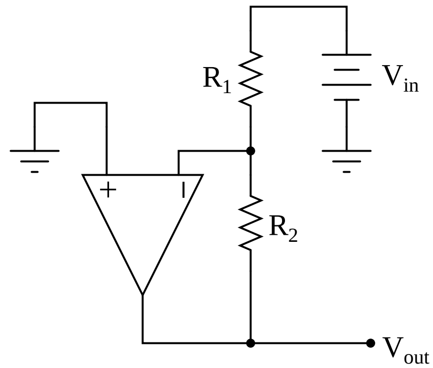
- Resistor R_1 fails open: *Output saturates positive.*
- Solder bridge (short) across resistor R_1: $V_{out} = V_{in}$.
- Resistor R_2 fails open: $V_{out} = V_{in}$.
- Solder bridge (short) across resistor R_2: *Output saturates positive.*
- Broken wire between R_1/R_2 junction and inverting opamp input: *Output voltage unpredictable.*

Notes 67

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

Question 68

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



- Resistor R_1 fails open:
- Solder bridge (short) across resistor R_1:
- Resistor R_2 fails open:
- Solder bridge (short) across resistor R_2:
- Broken wire between R_1/R_2 junction and inverting opamp input:

For each of these conditions, explain *why* the resulting effects will occur.
file 03775

Answer 68

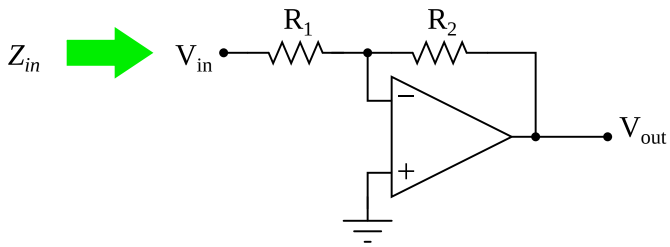
- Resistor R_1 fails open: V_{out} *= 0 volts.*
- Solder bridge (short) across resistor R_1: *Output saturates negative.*
- Resistor R_2 fails open: *Output saturates negative.*
- Solder bridge (short) across resistor R_2: V_{out} *= 0 volts.*
- Broken wire between R_1/R_2 junction and inverting opamp input: *Output voltage unpredictable.*

Notes 68

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

Question 69

Predict how the input impedance (Z_{in}) of this inverting operational amplifier circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



- Resistor R_1 fails open:
- Solder bridge (short) across resistor R_1:
- Resistor R_2 fails open:
- Solder bridge (short) across resistor R_2:
- Broken wire between R_1/R_2 junction and inverting opamp input:
- Operational amplifier loses power:

For each of these conditions, explain *why* the input impedance changes as it does.
file 03776

Answer 69

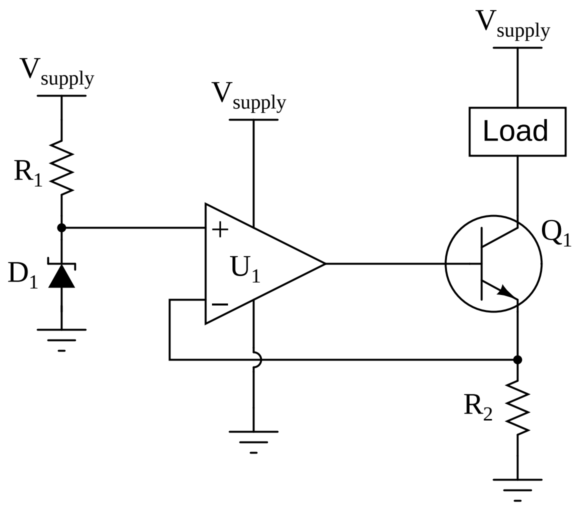
- Resistor R_1 fails open: Z_{in} *increases to infinity.*
- Solder bridge (short) across resistor R_1: Z_{in} *decreases to (nearly) zero.*
- Resistor R_2 fails open: Z_{in} *increases to (nearly) infinity.*
- Solder bridge (short) across resistor R_2: Z_{in} *remains equal in value to* R_1*, as normal.*
- Broken wire between R_1/R_2 junction and inverting opamp input: Z_{in} *increases to (approximately)* $R_1 + R_2$.
- Operational amplifier loses power: Z_{in} *increases to (nearly) infinity.*

Notes 69

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

Question 70

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



- Resistor R_1 fails open:
- Zener diode D_1 fails shorted:
- Resistor R_2 fails open:
- Zener diode D_1 fails open:
- Load fails shorted:
- Wire between opamp output and transistor base breaks open:

For each of these conditions, explain *why* the resulting effects will occur.
file 03777

Answer 70

- Resistor R_1 fails open: *Load current falls to zero.*
- Zener diode D_1 fails shorted: *Load current falls to zero.*
- Resistor R_2 fails open: *Load current falls to zero.*
- Zener diode D_1 fails open: *Load current increases.*
- Load fails shorted: *Load current remains the same.*
- Wire between opamp output and transistor base breaks open: *Load current falls to zero.*

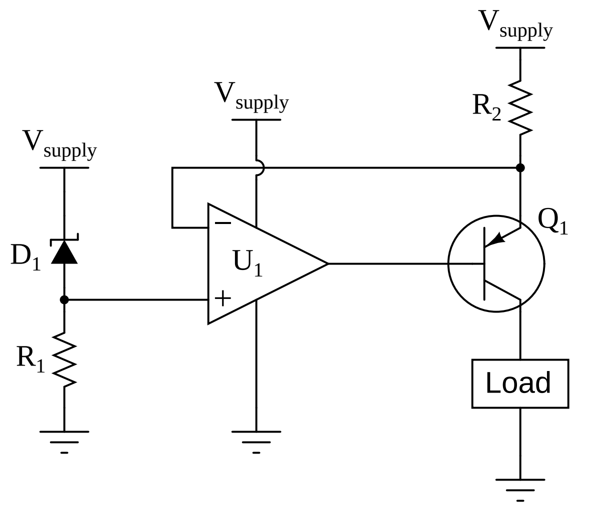
Follow-up question: which of the two opamp power terminals (V_{supply} or Ground) carries more current during normal operation, and why?

Notes 70

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

Question 71

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



- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Solder bridge (short) across resistor R_2:
- Zener diode D_1 fails shorted:
- Zener diode D_1 fails open:
- Load fails shorted:
- Wire between opamp output and transistor base breaks open:

For each of these conditions, explain *why* the resulting effects will occur.
file 03778

Answer 71

- Resistor R_1 fails open: *Load current falls to zero.*
- Resistor R_2 fails open: *Load current falls to zero.*
- Solder bridge (short) across resistor R_2: *Load current increases.*
- Zener diode D_1 fails shorted: *Load current falls to zero.*
- Zener diode D_1 fails open: *Load current increases.*
- Load fails shorted: *Load current remains the same.*
- Wire between opamp output and transistor base breaks open: *Load current falls to zero.*

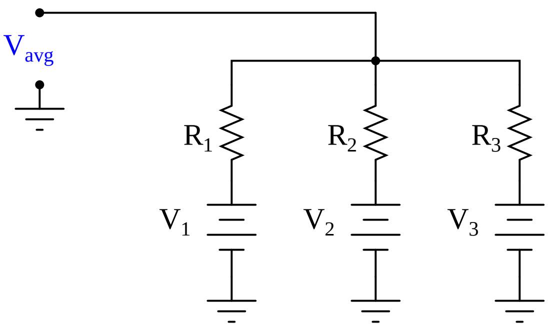
Follow-up question: which of the two opamp power terminals (V_{supply} or Ground) carries more current during normal operation, and why?

Notes 71

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

Question 72

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



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

For each of these conditions, explain *why* the resulting effects will occur.
file 03779

Answer 72

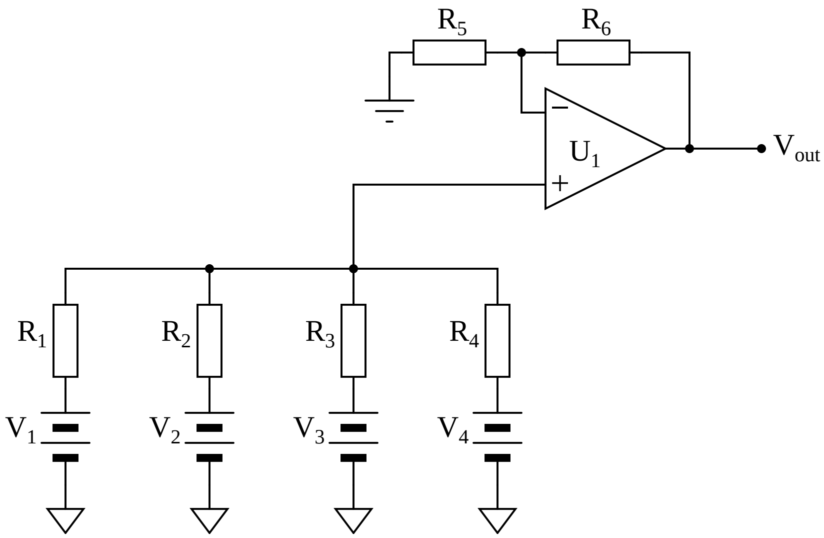
- Resistor R_1 fails open: *V_{avg} becomes the average of V_2 and V_3 only.*
- Solder bridge (short) across resistor R_1: *V_{avg} becomes exactly equal to V_1.*
- Resistor R_2 fails open: *V_{avg} becomes the average of V_1 and V_3 only.*
- Solder bridge (short) across resistor R_2: *V_{avg} becomes exactly equal to V_2.*
- Resistor R_3 fails open: *V_{avg} becomes the average of V_1 and V_2 only.*
- Solder bridge (short) across resistor R_3: *V_{avg} becomes exactly equal to V_3.*

Notes 72

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

Question 73

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



- Resistor R_1 fails open:
- Solder bridge (short) across resistor R_3:
- Resistor R_4 fails open:
- Resistor R_5 fails open:
- Solder bridge (short) across resistor R_5:
- Resistor R_6 fails open:

For each of these conditions, explain *why* the resulting effects will occur.
file 03780

Answer 73

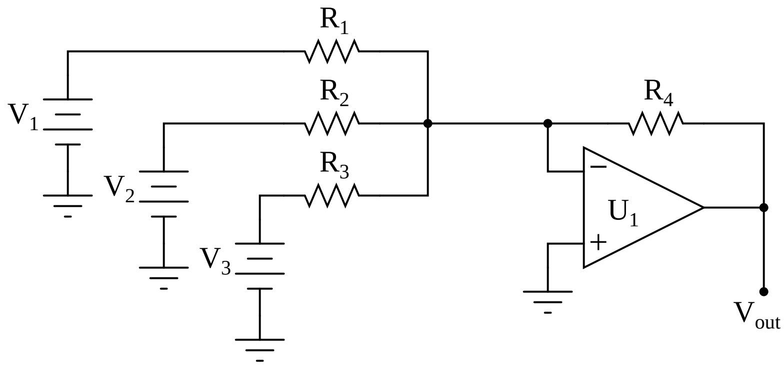
- Resistor R_1 fails open: V_{out} *becomes equal to* $\frac{4}{3}$ *the sum of voltages* V_2*,* V_3*, and* V_4*.*
- Solder bridge (short) across resistor R_3: V_{out} *becomes equal to 4 times* V_3*.*
- Resistor R_4 fails open: V_{out} *becomes equal to* $\frac{4}{3}$ *the sum of voltages* V_1*,* V_2*, and* V_3*.*
- Resistor R_5 fails open: *Circuit operates as an averager, not a summer.*
- Solder bridge (short) across resistor R_5: V_{out} *saturates in a positive direction.*
- Resistor R_6 fails open: V_{out} *saturates in a positive direction.*

Notes 73

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

Question 74

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



- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Solder bridge (short) across resistor R_3:
- Resistor R_4 fails open:
- Solder bridge (short) across resistor R_4:

For each of these conditions, explain *why* the resulting effects will occur.
file 03781

Answer 74

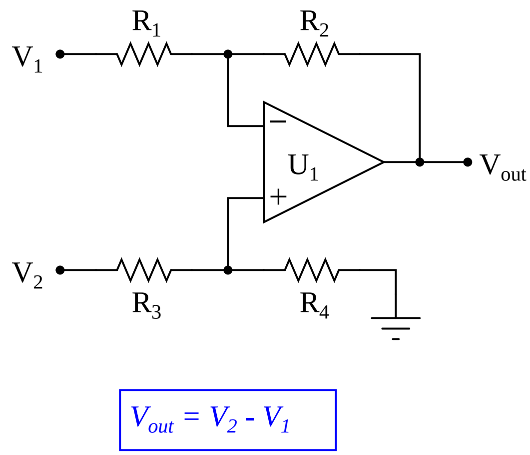
- Resistor R_1 fails open: *V_{out} becomes (inverted) sum of V_2 and V_3 only.*
- Resistor R_2 fails open: *V_{out} becomes (inverted) sum of V_1 and V_3 only.*
- Solder bridge (short) across resistor R_3: *V_{out} saturates in a negative direction.*
- Resistor R_4 fails open: *V_{out} saturates in a negative direction.*
- Solder bridge (short) across resistor R_4: *V_{out} goes to 0 volts.*

Notes 74

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

Question 75

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



- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Solder bridge (short) across resistor R_3:
- Resistor R_4 fails open:
- Solder bridge (short) across resistor R_4:

For each of these conditions, explain *why* the resulting effects will occur.
file 03782

Answer 75

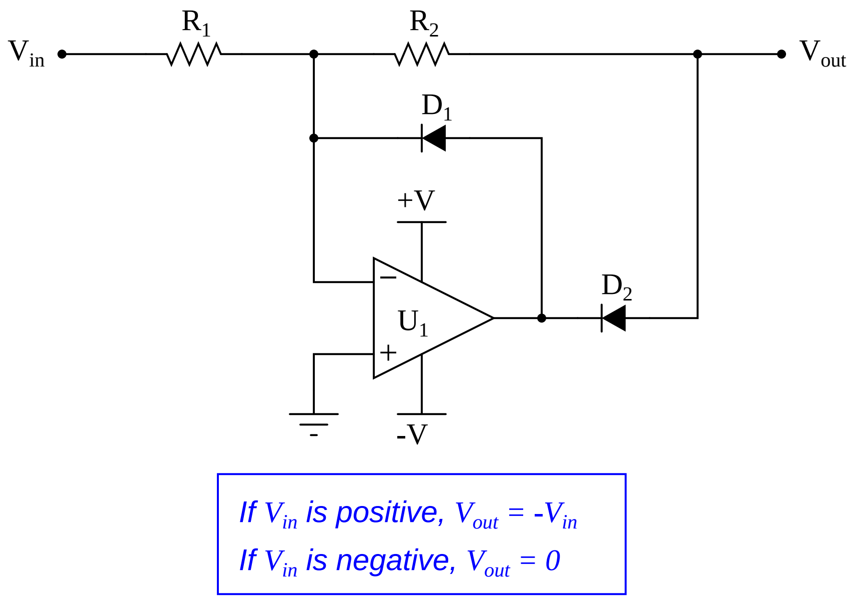
- Resistor R_1 fails open: *V_{out} becomes equal to $\frac{1}{2}$ V_2.*
- Resistor R_2 fails open: *V_{out} saturates.*
- Solder bridge (short) across resistor R_3: *V_{out} becomes equal to $2V_2 - V_1$ instead of $V_2 - V_1$.*
- Resistor R_4 fails open: *V_{out} becomes equal to $2V_2 - V_1$ instead of $V_2 - V_1$.*
- Solder bridge (short) across resistor R_4: *V_{out} becomes equal to $-V_1$.*

Notes 75

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

Question 76

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



- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Diode D_1 fails open:
- Diode D_2 fails open:

For each of these conditions, explain *why* the resulting effects will occur.
file 03783

Answer 76

- Resistor R_1 fails open: *V_{out} becomes equal to 0 volts all the time.*
- Resistor R_2 fails open: *V_{out} saturates negative when V_{in} is positive, and V_{out} floats up to +1.4 volts when V_{in} is negative (depending on how the output is loaded by another circuit).*
- Diode D_1 fails open: *Normal operation when V_{in} is positive ($V_{out} = -V_{in}$), $V_{out} = V_{in}$ when V_{in} is negative (full-wave, inverted rectification!).*
- Diode D_2 fails open: *Normal operation when V_{in} is negative (V_{out} = 0 volts), $V_{out} = V_{in}$ when V_{in} is positive (half-wave, non-inverted rectification!).*

Notes 76

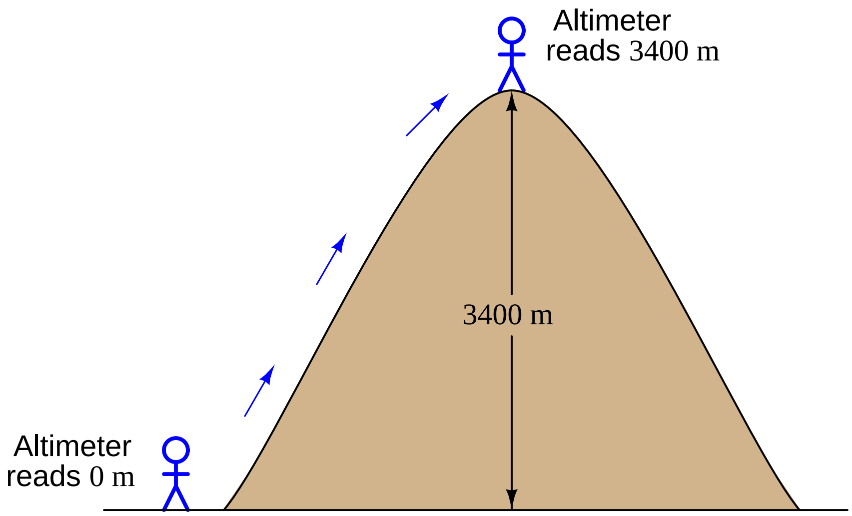
The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to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

Question 77

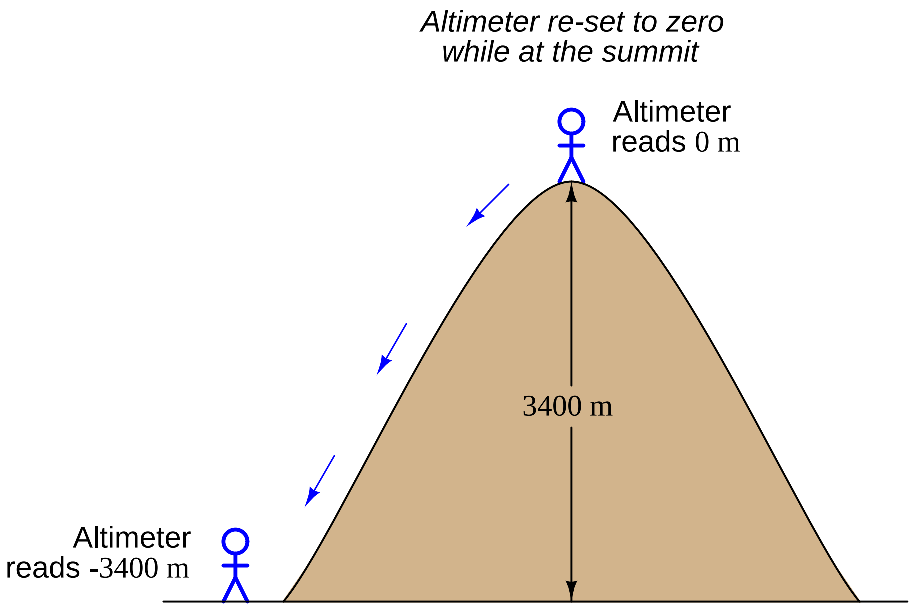
A *barometric altimeter* is a device used to measure altitude (height) by means of atmospheric pressure. The higher you go up from sea level, the less air pressure you encounter. This decrease in air pressure is closely correlated with height, and thus can be used to infer altitude.

This type of altimeter usually comes equipped with a "zero" adjustment, so that the instrument's indication may be offset to compensate for changes in air pressure resulting from different weather conditions. This same "zero" adjustment may also be used to establish the altimeter's zero indication at any arbitrary height.

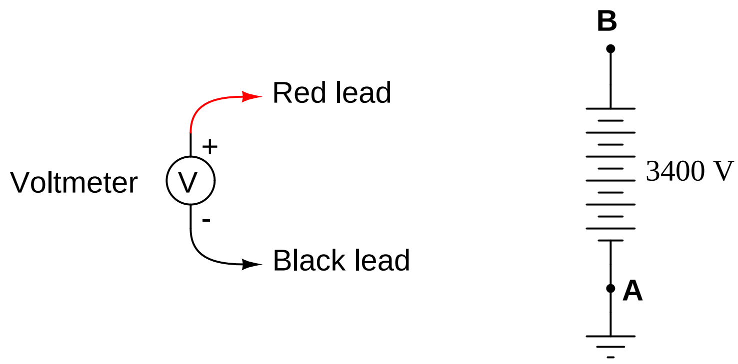
For example, if a mountain climber sets her barometric altimeter to zero meters at the base of a mountain, then climbs to the summit of that mountain (3400 meters higher than the base), the altimeter should register 3400 meters at the summit:



While at the summit, the climber may re-set the altimeter's "zero" adjustment to register 0 meters once again. If the climber then descends to the base of the mountain, the altimeter will register -3400 meters:



Explain how this scenario of mountain climbing and altimeter calibration relates to the measurement of voltage between points **A** and **B** in the following circuit:



file 01960

Answer 77

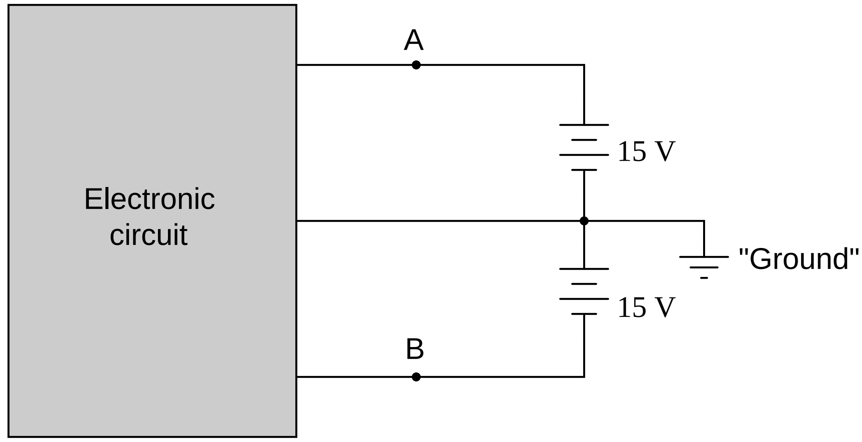
The voltmeter's black lead is analogous to the "zero reference" level in the mountain-climbing altimeter scenario: the point at which the altimeter is calibrated to register 0 meters height.

Notes 77

Physical height (and depth) is a very useful analogy for electrical potential, helping students relate this abstract thing called "voltage" to more common differential measurements.

Question 78

Many electronic circuits use what is called a *split* or a *dual* power supply:



Determine what a digital voltmeter would indicate if connected between the following points:

- Red lead on "A", black lead on ground
- Red lead on "B", black lead on ground
- Red lead on "A", black lead on "B"
- Red lead on "B", black lead on "A"

NOTE: *in electronic systems, "ground" is often not associated with an actual earth-soil contact. It usually only refers to a common point of reference somewhere in the circuit used to take voltage measurements. This allows us to specify voltages at single points in the circuit, with the implication that "ground" is the* other *point for the voltmeter to connect to.*

file 00267

Answer 78

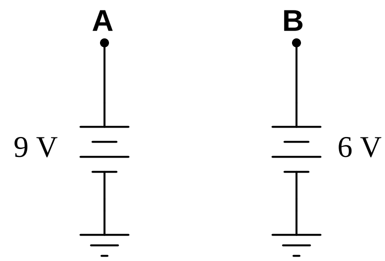
- Red lead on "A", black lead on ground (*Digital voltmeter reads +15 volts*)
- Red lead on "B", black lead on ground (*Digital voltmeter reads -15 volts*)
- Red lead on "A", black lead on "B" (*Digital voltmeter reads +30 volts*)
- Red lead on "B", black lead on "A" (*Digital voltmeter reads -30 volts*)

Notes 78

This question may be easily answered with only a voltmeter, two batteries, and a single "jumper" wire to connect the two batteries in series. It does not matter if the batteries are 15 volts each! The fundamental principle may still be investigated with batteries of any voltage, so this is a very easy demonstration to set up during discussion time.

Question 79

Determine the amount of voltage measured at points **A** and **B** with reference to ground, and also determine voltage V_{AB} (defined here as the voltage indicated by a voltmeter with the red test lead touching point **A** and the black test lead touching point **B**):



file 01958

Answer 79

$V_A = +9$ volts
$V_B = +6$ volts
$V_{AB} = +3$ volts

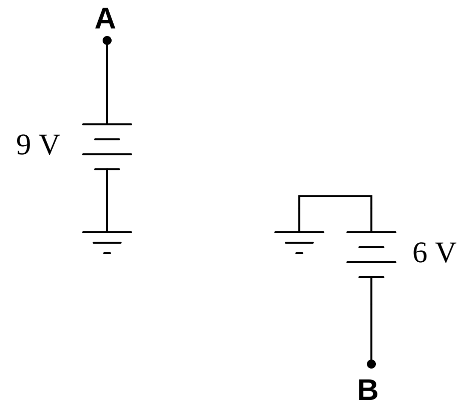
Follow-up question: explain why the mathematical signs ("+") are important in these answers.

Notes 79

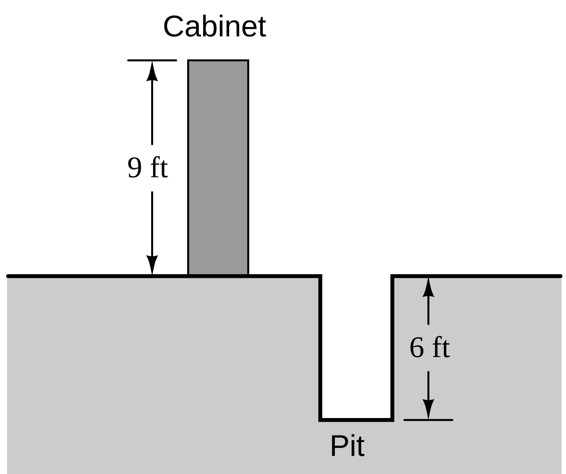
Determining differential voltages is a skill that many students find frustrating to attain. There is more than one way to explain how to arrive at +3 volts as the answer for V_{AB}, and it is good for students to see more than one way presented.

Question 80

A student is puzzled by a problem given by her instructor. The task is to determine the voltage V_{AB} (defined by the instructor as the voltage indicated by a voltmeter with the red test lead touching point **A** and the black test lead touching point **B**) in this circuit:



The student has already figured out that $V_A = +9$ V and $V_B = -6$ V, but does not know for certain how to calculate the voltage between points **A** and **B**. Asking her instructor for an explanation, the instructor begins to draw this illustration:



Before the instructor begins to explain what the illustration means, however, he receives a call on his telephone and must leave the student momentarily. The student then asks you to help explain what the instructor's illustration might mean, and how it applies to the problem of determining voltage V_{AB} in the original circuit.

What would your explanation be? Where do you think the instructor was going with this illustration, and how it might relate to voltages in a circuit?

file 01959

Answer 80

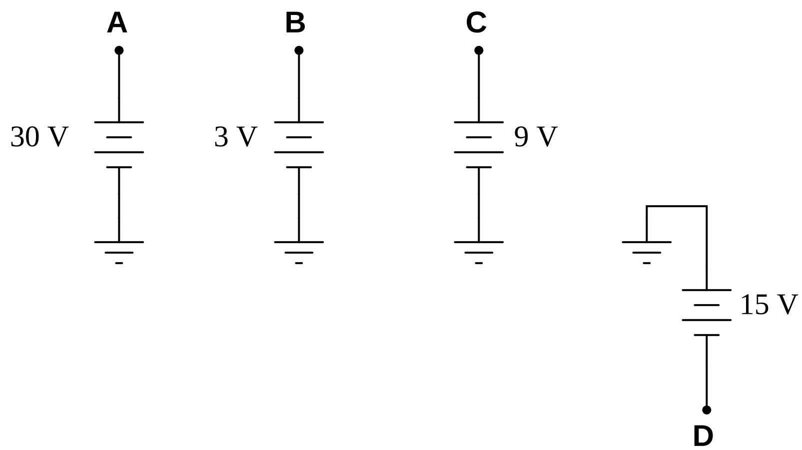
The height of the cabinet (*above* ground) represents the *positive* voltage at point **A**, while the depth of the pit (*below* ground) represents the *negative* voltage at point **B**. The *difference* in altitude between the cabinet's height and the pit's depth represents the voltage V_{AB} in the circuit.

Notes 80

It may be good to remind your students that voltage is and forever will be a quantity *between two points* and never defined at a single point. The only reason we can say $V_A = +9$ volts and $V_B = -6$ volts is because there is a *ground point* in the circuit, which by convention is the point of reference for any voltages defined at other, single points in the circuit.

Question 81

Determine the voltages registered by a voltmeter between the following points in this circuit:



$V_A =$ _____ (red lead on **A**, black lead on ground)

$V_B =$ _____ (red lead on **B**, black lead on ground)

$V_C =$ _____ (red lead on **C**, black lead on ground)

$V_D =$ _____ (red lead on **D**, black lead on ground)

$V_{AC} =$ _____ (red lead on **A**, black lead on **C**)

$V_{DB} =$ _____ (red lead on **D**, black lead on **B**)

$V_{BA} =$ _____ (red lead on **B**, black lead on **A**)

$V_{BC} =$ _____ (red lead on **B**, black lead on **C**)

$V_{CD} =$ _____ (red lead on **C**, black lead on **D**)

file 02750

Answer 81

$V_A =$ +30 volts (red lead on **A**, black lead on ground)

$V_B =$ +3 volts (red lead on **B**, black lead on ground)

$V_C =$ +9 volts (red lead on **C**, black lead on ground)

$V_D =$ -15 volts (red lead on **D**, black lead on ground)

$V_{AC} =$ +21 volts (red lead on **A**, black lead on **C**)

$V_{DB} =$ -18 volts (red lead on **D**, black lead on **B**)

$V_{BA} =$ -27 volts (red lead on **B**, black lead on **A**)

$V_{BC} =$ -6 volts (red lead on **B**, black lead on **C**)

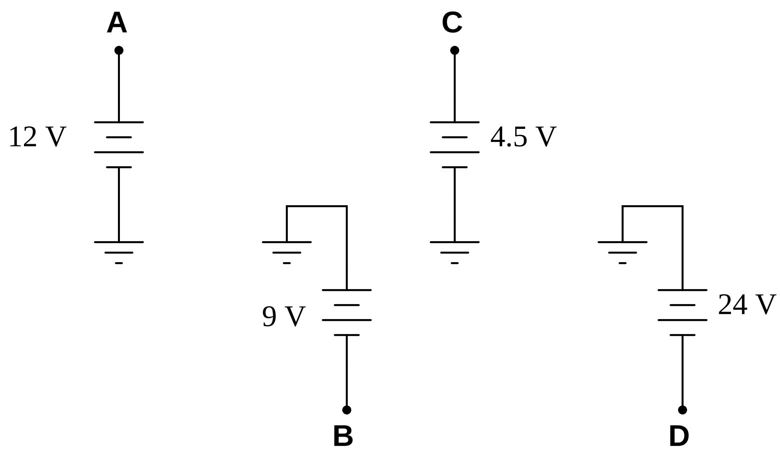
$V_{CD} =$ +24 volts (red lead on **C**, black lead on **D**)

Notes 81

Discuss with your students multiple techniques of solving for these voltages, asking them first for their solution strategies.

Question 82

Determine the voltages registered by a voltmeter between the following points in this circuit:



$V_A =$ _____ (red lead on **A**, black lead on ground)

$V_B =$ _____ (red lead on **B**, black lead on ground)

$V_C =$ _____ (red lead on **C**, black lead on ground)

$V_D =$ _____ (red lead on **D**, black lead on ground)

$V_{AC} =$ _____ (red lead on **A**, black lead on **C**)

$V_{DB} =$ _____ (red lead on **D**, black lead on **B**)

$V_{BA} =$ _____ (red lead on **B**, black lead on **A**)

$V_{BC} =$ _____ (red lead on **B**, black lead on **C**)

$V_{CD} =$ _____ (red lead on **C**, black lead on **D**)

file 01961

Answer 82

$V_A =$ +12 volts (red lead on **A**, black lead on ground)

$V_B =$ -9 volts (red lead on **B**, black lead on ground)

$V_C =$ +4.5 volts (red lead on **C**, black lead on ground)

$V_D =$ -24 volts (red lead on **D**, black lead on ground)

$V_{AC} =$ +7.5 volts (red lead on **A**, black lead on **C**)

$V_{DB} =$ -15 volts (red lead on **D**, black lead on **B**)

$V_{BA} =$ -21 volts (red lead on **B**, black lead on **A**)

$V_{BC} =$ -13.5 volts (red lead on **B**, black lead on **C**)

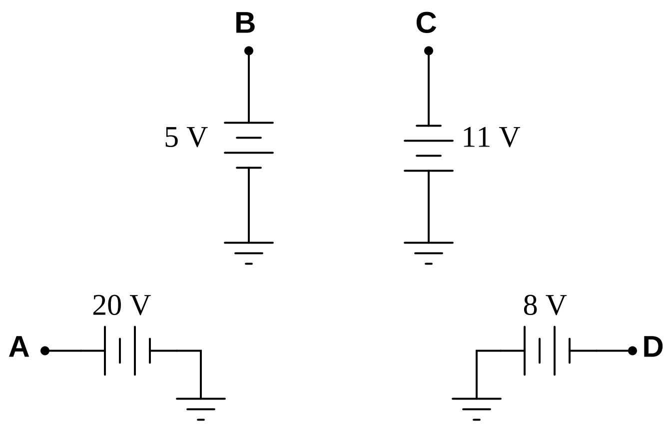
$V_{CD} =$ +28.5 volts (red lead on **C**, black lead on **D**)

Notes 82

Discuss with your students multiple techniques of solving for these voltages, asking them first for their solution strategies.

Question 83

Determine the voltages registered by a voltmeter between the following points in this circuit:



$V_A =$ ____ (red lead on **A**, black lead on ground)

$V_B =$ ____ (red lead on **B**, black lead on ground)

$V_C =$ ____ (red lead on **C**, black lead on ground)

$V_D =$ ____ (red lead on **D**, black lead on ground)

$V_{AC} =$ ____ (red lead on **A**, black lead on **C**)

$V_{DB} =$ ____ (red lead on **D**, black lead on **B**)

$V_{BA} =$ ____ (red lead on **B**, black lead on **A**)

$V_{BC} =$ ____ (red lead on **B**, black lead on **C**)

$V_{CD} =$ ____ (red lead on **C**, black lead on **D**)

file 02751

Answer 83

$V_A =$ +20 volts (red lead on **A**, black lead on ground)

$V_B =$ +5 volts (red lead on **B**, black lead on ground)

$V_C =$ -11 volts (red lead on **C**, black lead on ground)

$V_D =$ -8 volts (red lead on **D**, black lead on ground)

$V_{AC} =$ +31 volts (red lead on **A**, black lead on **C**)

$V_{DB} =$ -13 volts (red lead on **D**, black lead on **B**)

$V_{BA} =$ -15 volts (red lead on **B**, black lead on **A**)

$V_{BC} =$ +16 volts (red lead on **B**, black lead on **C**)

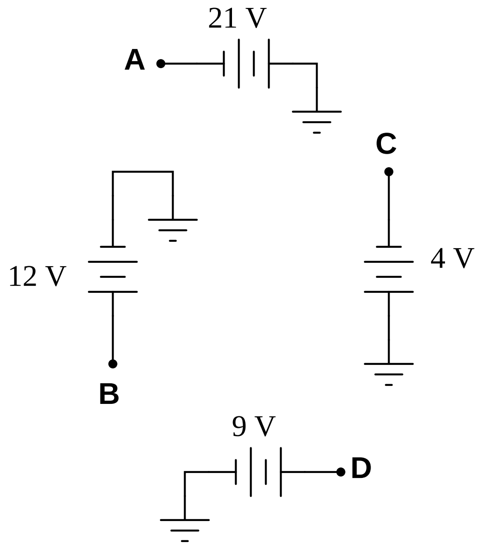
$V_{CD} =$ -3 volts (red lead on **C**, black lead on **D**)

Notes 83

Discuss with your students multiple techniques of solving for these voltages, asking them first for their solution strategies.

Question 84

Determine the voltages registered by a voltmeter between the following points in this circuit:



$V_A =$ _____ (red lead on **A**, black lead on ground)

$V_B =$ _____ (red lead on **B**, black lead on ground)

$V_C =$ _____ (red lead on **C**, black lead on ground)

$V_D =$ _____ (red lead on **D**, black lead on ground)

$V_{AC} =$ _____ (red lead on **A**, black lead on **C**)

$V_{DB} =$ _____ (red lead on **D**, black lead on **B**)

$V_{BA} =$ _____ (red lead on **B**, black lead on **A**)

$V_{BC} =$ _____ (red lead on **B**, black lead on **C**)

$V_{CD} =$ _____ (red lead on **C**, black lead on **D**)

file 02752

Answer 84

$V_A =$ -21 volts (red lead on **A**, black lead on ground)

$V_B =$ +12 volts (red lead on **B**, black lead on ground)

$V_C =$ -4 volts (red lead on **C**, black lead on ground)

$V_D =$ +9 volts (red lead on **D**, black lead on ground)

$V_{AC} =$ -17 volts (red lead on **A**, black lead on **C**)

$V_{DB} =$ -3 volts (red lead on **D**, black lead on **B**)

$V_{BA} =$ +33 volts (red lead on **B**, black lead on **A**)

$V_{BC} =$ +16 volts (red lead on **B**, black lead on **C**)

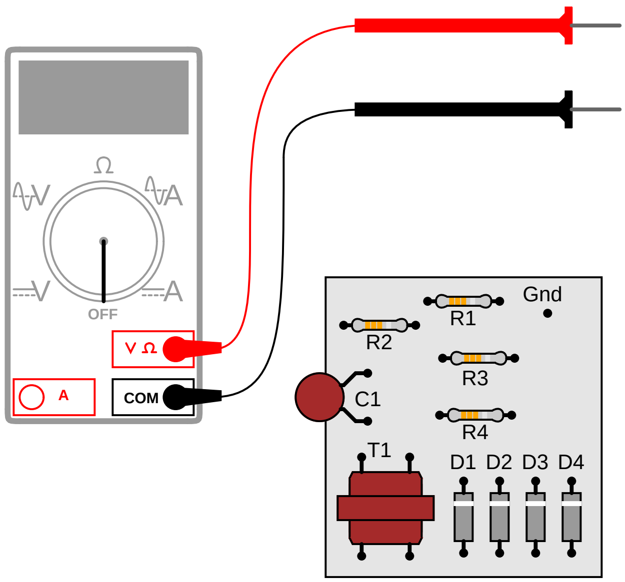
$V_{CD} =$ -13 volts (red lead on **C**, black lead on **D**)

Notes 84

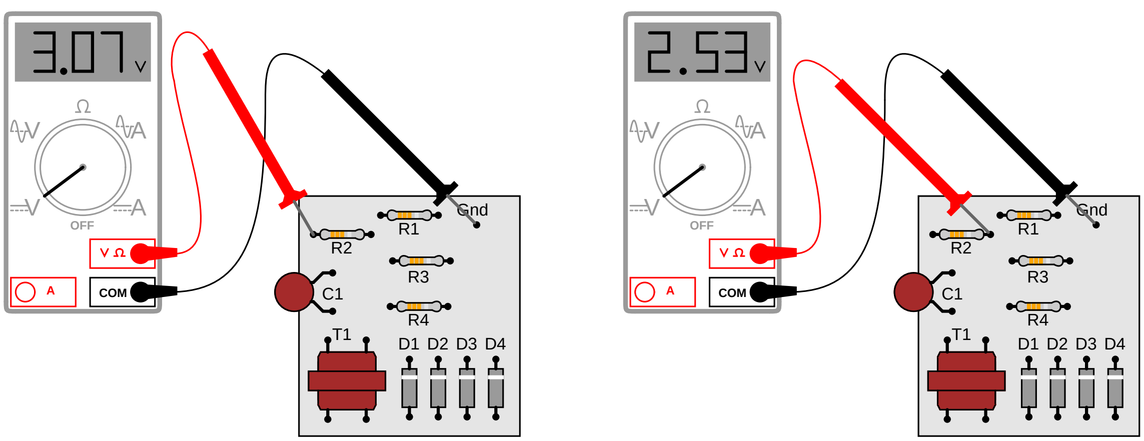
Discuss with your students multiple techniques of solving for these voltages, asking them first for their solution strategies.

Question 85

Suppose you wanted to measure the amount of current going through resistor R2 on this printed circuit board, but did not have the luxury of breaking the circuit to do so (unsoldering one end of the resistor, detaching it from the PCB, and connecting an ammeter in series). All you can do while the circuit is powered is measure voltage with a voltmeter:



So, you decide to touch the black probe of the voltmeter to the circuit's "Gnd" (ground) test point, and measure the voltage with reference to ground on both sides of R2. The results are shown here:



R2's color code is Orange, Orange, Red, Gold. Based on this information, determine both the direction and the magnitude of DC current through resistor R2, and explain how you did so.

file 01729

Answer 85

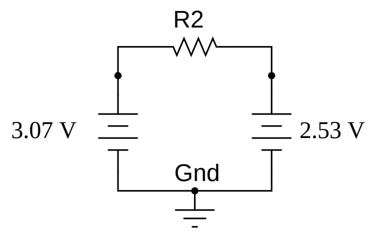
$I_{R2} \approx 160\,\mu$A, conventional flow from left to right (electron flow from right to left).

Follow-up question: this technique for estimating resistor current depends on one important assumption. Describe what this assumption is, and how the accuracy of your current calculation may be affected if the assumption is invalid.

Notes 85

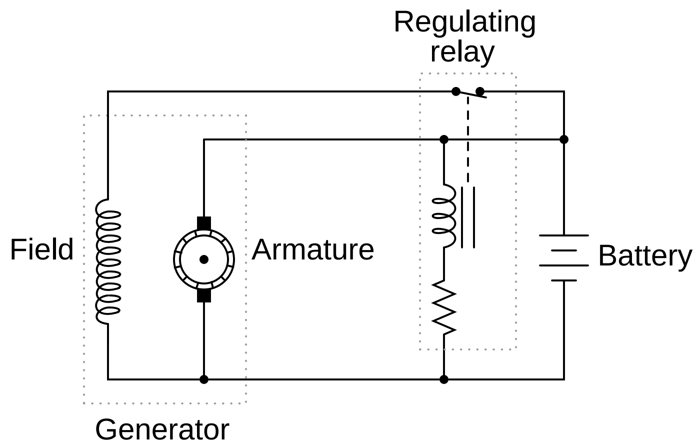
This is a good example of how Kirchhoff's Voltage Law is more than just an abstract tool for mathematical analysis – it is also a powerful technique for practical circuit diagnosis. Students must apply KVL to determine the voltage drop across R2, and then use Ohm's Law to calculate its current.

If students experience difficulty visualizing how KVL plays a part in the solution of this problem, show them this illustration:



Question 86

Generators used in battery-charging systems must be *regulated* so as to not overcharge the battery(ies) they are connected to. Here is a crude, relay-based voltage regulator for a DC generator:



Simple electromechanical relay circuits such as this one were very common in automotive electrical systems during the 1950's, 1960's, and 1970's. The fundamental principle upon which their operation is based is called *negative feedback*: where a system takes action to *oppose* any change in a certain variable. In this case, the variable is generator output voltage. Explain how the relay works to prevent the generator from overcharging the battery with excessive voltage.

file 01021

Answer 86

If the battery voltage becomes excessive, the relay opens and de-energizes the field winding. When the voltages sags back down to an acceptable level, the relay re-closes and re-energizes the field winding so that the generator can begin generating voltage again.

Challenge question: what would we have to change in this circuit to alter the generator's voltage regulation set-point (the "target" voltage at which the generator's output is supposed to be regulated)?

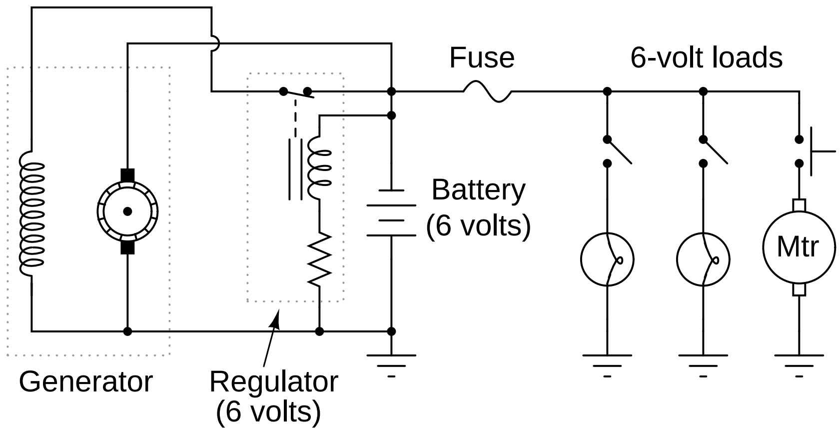
Notes 86

The circuit drawn here is very similar to real generator regulator circuits used in American automobiles before the advent of inexpensive, reliable semiconductor circuits. I show it here not just for historical background, but also to demonstrate how relatively crude circuits are still able to perform certain tasks reasonably well.

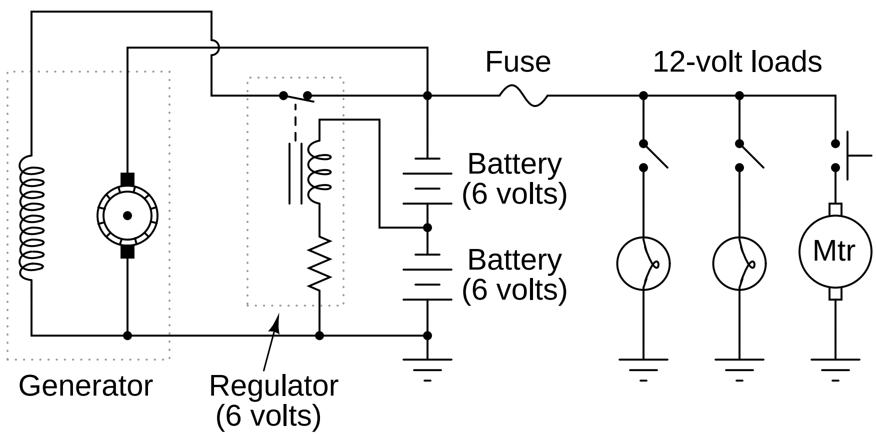
"Negative feedback" is one of the fundamental principles of electronics and electrical engineering. A simple system like this provides a good way to gently introduce students to this vital concept.

Question 87

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 87

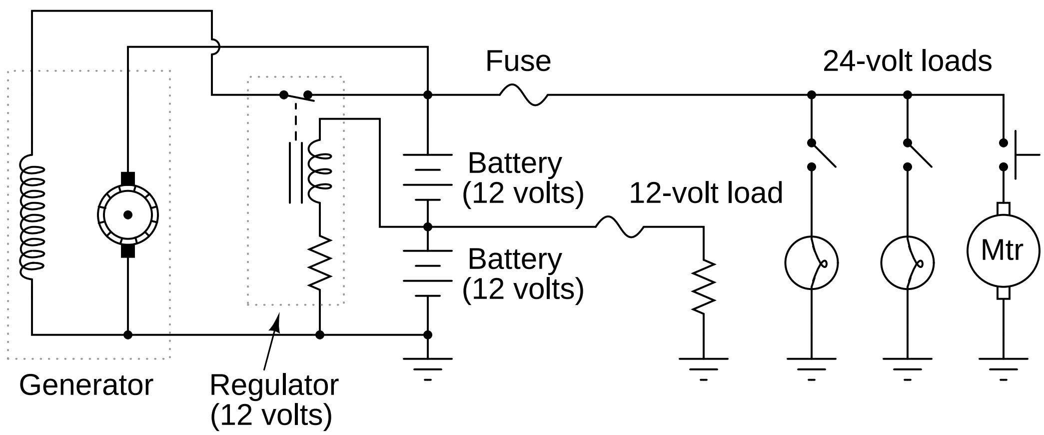
So long as the generator is capable of outputting 12 volts, this system will work!

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.

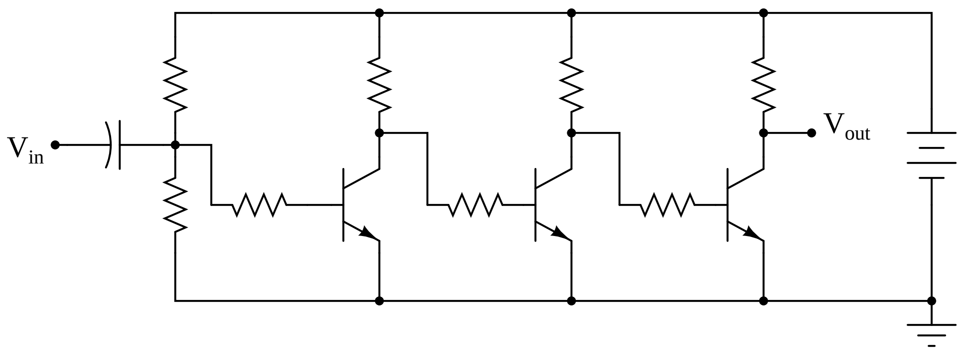
This idea actually came from one of the readers of my textbook series Lessons In Electric Circuits. He was trying to upgrade a vehicle from 12 volts to 24 volts, but the principle is the same. An important difference in his plan was that he was still planning on having some 12-volt loads in the vehicle (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.

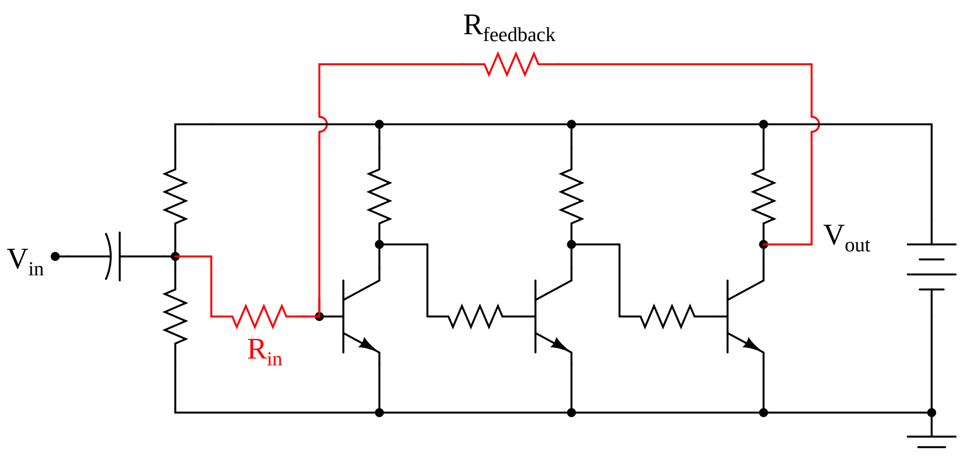
Question 88

Suppose the following three-stage transistor amplifier were constructed:



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

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



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

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

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

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

file 02252

Answer 88

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

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

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

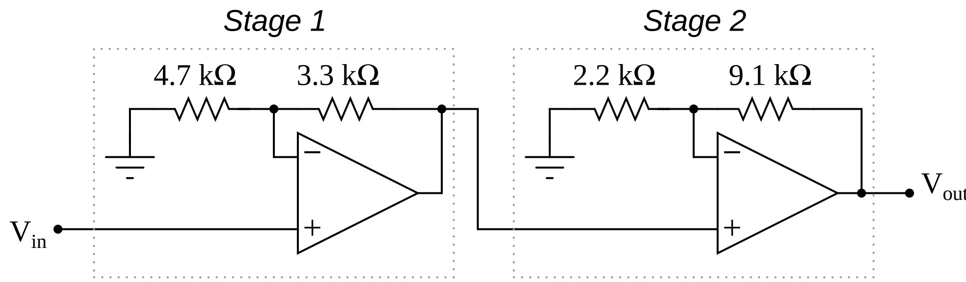
Notes 88

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

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

Question 89

Calculate the voltage gain for each stage of this amplifier circuit (both as a ratio and in units of decibels), then calculate the overall voltage gain:



file 02728

Answer 89

Stage 1:

- $A_V = 1.702 = 4.62$ dB

Stage 2:

- $A_V = 5.136 = 14.213$ dB

Overall:

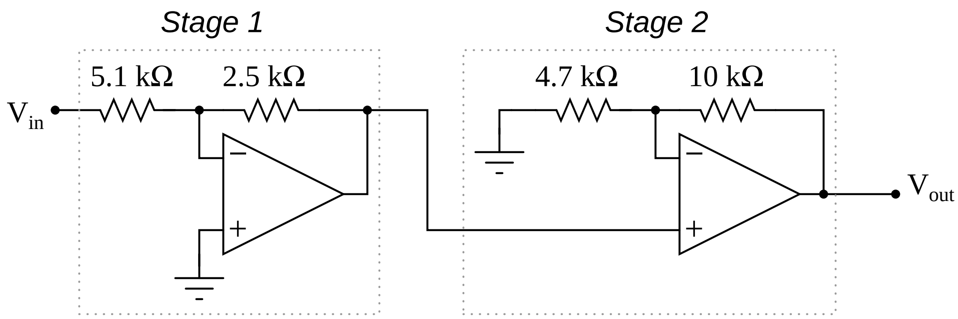
- $A_V = 8.743 = 18.833$ dB

Notes 89

Not only does this question review calculation of voltage gain for inverting amplifier circuits, but it also reviews decibel calculations (for both single and multi-stage amplifiers). Discuss how the decibel figures for each stage add to equal the total decibel gain, whereas the ratios multiply.

Question 90

Calculate the voltage gain for each stage of this amplifier circuit (both as a ratio and in units of decibels), then calculate the overall voltage gain:



file 02731

Answer 90

Stage 1:
- $A_V = 0.490 =$ -6.193 dB

Stage 2:
- $A_V = 3.128 =$ 9.904 dB

Overall:
- $A_V = 1.533 =$ 3.712 dB

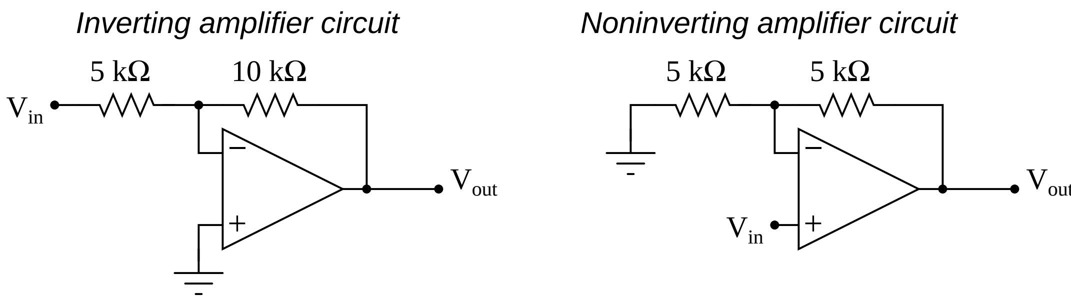
Follow-up question: is this circuit inverting or noninverting, overall?

Notes 90

Not only does this question review calculation of voltage gain for inverting amplifier circuits, but it also reviews decibel calculations (for both single and multi-stage amplifiers). Discuss how the decibel figures for each stage add to equal the total decibel gain, whereas the ratios multiply.

Question 91

Shown here are two different voltage amplifier circuits with the same voltage gain. Which of them has greater input impedance, and why? Try to give as specific an answer for each circuit's input impedance as possible.



file 02709

Answer 91

The noninverting amplifier circuit has extremely high input impedance (most likely many millions of ohms), while the inverting amplifier circuit only has 5 kΩ of input impedance.

Notes 91

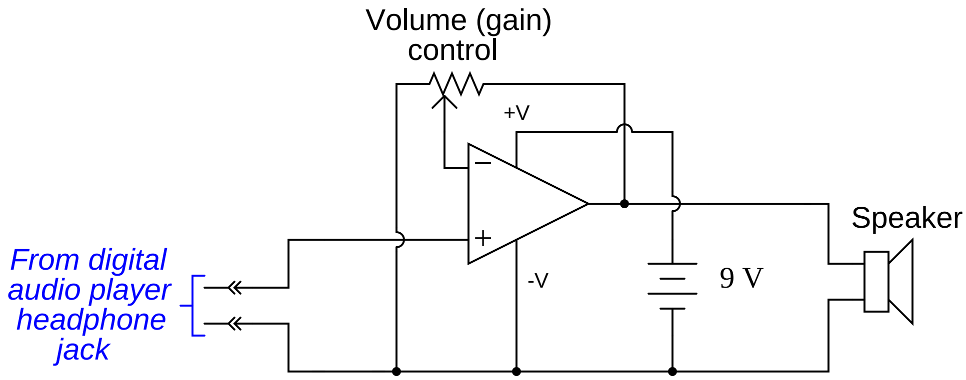
If students have difficulty grasping the concept of input impedance, and how to figure that out for circuits such as these, remind them that input impedance is fundamentally defined by the following equation:

$$Z_{in} = \frac{V_{in}}{I_{in}}$$

With this in mind, encourage them to set up a "thought experiment" by where they assume a given input voltage and analyze the circuit step-by-step using Ohm's Law, Kirchhoff's Laws, and the basic rules of closed-loop, negative feedback opamp behavior. The results of the "thought experiment" should conclusively demonstrate which circuit has the greater input impedance.

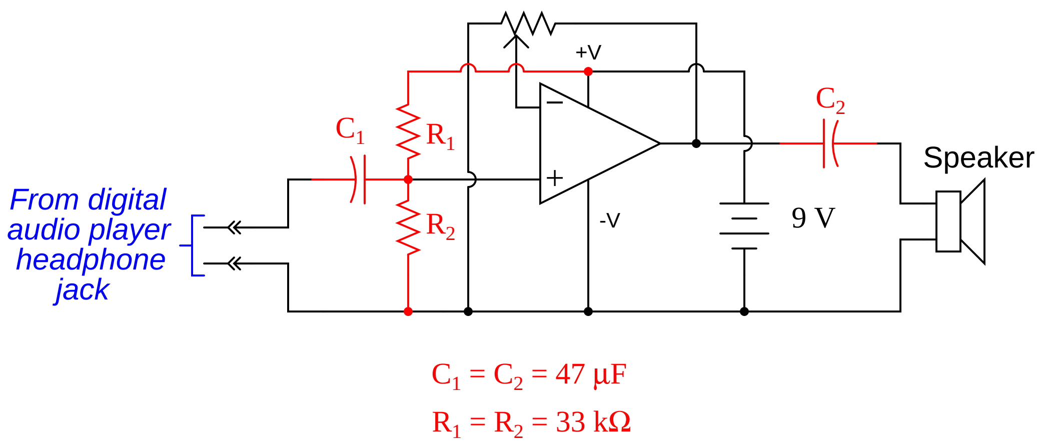
Question 92

A student wishes to build a variable-gain amplifier circuit using an operational amplifier and a potentiometer. The purpose of this circuit is to act as an audio amplifier for a small speaker, so he can listen to the output of a digital audio player without having to use headphones:



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

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



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

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

file 02461

Answer 92

The output of the audio player is true AC (alternating positive and negative polarity), but the original circuit could only handle input voltages ranging from 0 volts to +V, nothing negative.

Notes 92

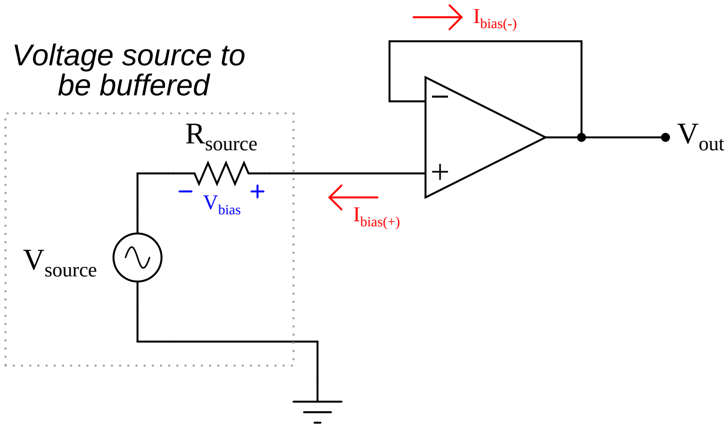
This question illustrates a common problem in opamp circuit design and usage: it is easy for students to overlook the importance of considering the power supply rail voltages. Despite the fact that the rails are labeled "+V" and "-V" at the opamp chip terminals, the input signal is actually referenced to the negative side of the power supply, which means that every negative half-cycle of the input voltage goes beyond the -V power supply rail voltage, and the opamp cannot handle that.

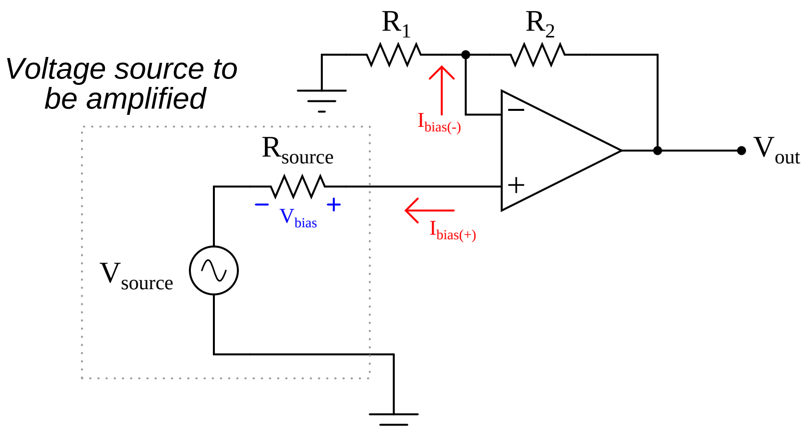
The instructor's solution to this problem should look very similar to voltage divider biasing in a single-transistor circuit, providing a good opportunity to review that concept with your students.

Some students may ask where the second speaker is, for stereo sound. If they do, tell them that this circuit only represents one channel's worth of amplification, and that the other channel's circuit would look just the same. If a single volume control were desired to control the gain of both amplifier circuits, a dual-ganged potentiometer could be used (another point of discussion for your students!).

Question 93

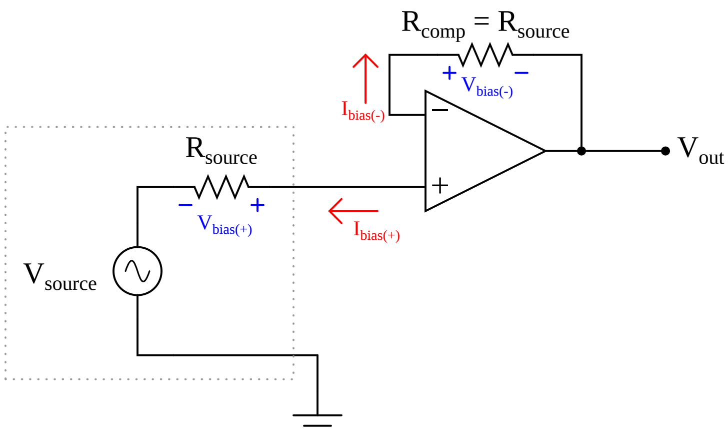
The same problem of input bias current affecting the precision of opamp voltage buffer circuits also affects noninverting opamp voltage amplifier circuits:





To fix this problem in the voltage buffer circuit, we added a "compensating" resistor:

Compensating resistor added to the voltage buffer circuit



To fix the same problem in the noninverting voltage amplifier circuit, we must carefully choose resistors R_1 and R_2 so that their parallel equivalent equals the source resistance:

$$R_1 || R_2 = R_{source}$$

Of course, we must also be sure the values of R_1 and R_2 are such that the voltage gain of the circuit is what we want it to be.

Determine values for R_1 and R_2 to give a voltage gain of 7 while compensating for a source resistance of 1.45 kΩ.

file 02463

Answer 93

$R_1 = 1.692$ kΩ $\qquad$ $R_2 = 10.15$ kΩ

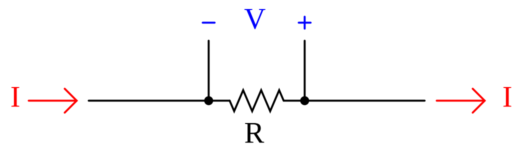
Notes 93

Students must apply algebra to solve for the values of these two resistances. The solution is an application of algebraic *substitution*, and it is worthwhile to examine and discuss together in class.

Discuss how this solution to the bias current problem is a practical application of Thévenin's theorem: looking at the two voltage divider resistors as a network that may be Thévenized to serve as a compensating resistance as well as a voltage divider for the necessary circuit gain.

Question 94

The simplest electronic device capable of converting a current signal into a voltage signal is a resistor:

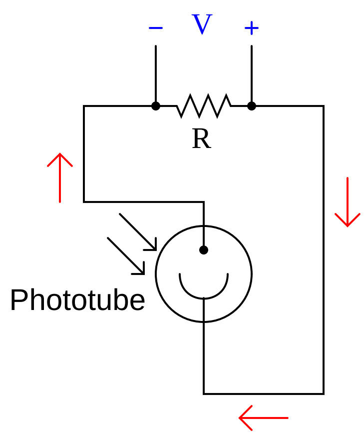


(electron flow notation used here)

Precision resistors typically work very well for this purpose, especially when the amount of voltage dropped across it is of little consequence. This is why *shunt resistors* are frequently used in power circuitry to measure current, a low-resistance "shunt" resistance element dropping voltage in precise proportion to the current going through it.

However, if we cannot afford to drop any voltage across a resistance in the circuit, this technique of current-to-voltage conversion will not be very practical. Consider the following scientific apparatus, used to measure the photoelectric effect (electrons emitted from a solid surface due to light striking it):

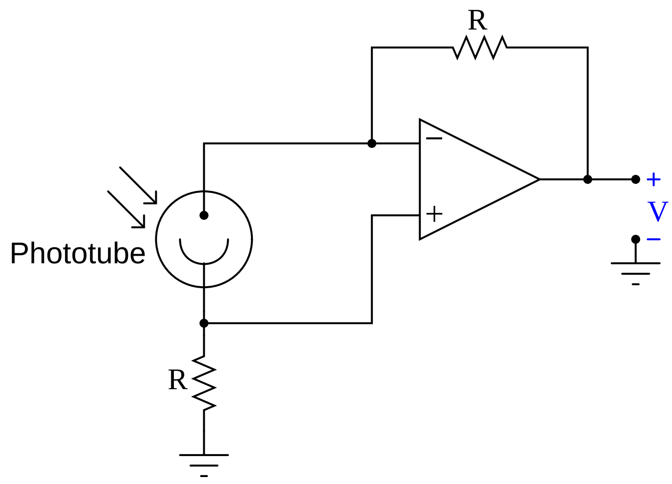
An impractical way to measure phototube current



(electron flow notation used here)

The current output by such a phototube is *very* small, and the voltage output by it is smaller yet. If we are to measure current through this device, we will have to find some way other than a shunt resistor to do it.

Enter the operational amplifier, to the rescue! Explain how the following opamp circuit is able to convert the phototube's weak current signal into a strong voltage signal, without imposing any significant resistance into the phototube circuit:

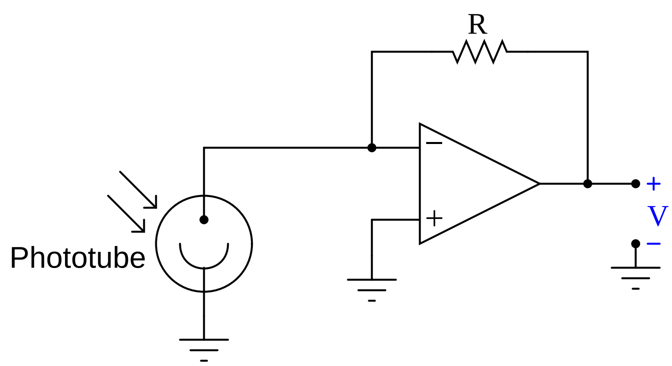


file 02514

Answer 94

The design of this circuit is complicated by the existence of bias currents at the opamp inputs. You may find it helpful to analyze a simplified version of the same circuit. Please bear in mind that this simplified circuit would only work if the opamp had absolutely no input bias currents at all:

Assuming zero input bias currents

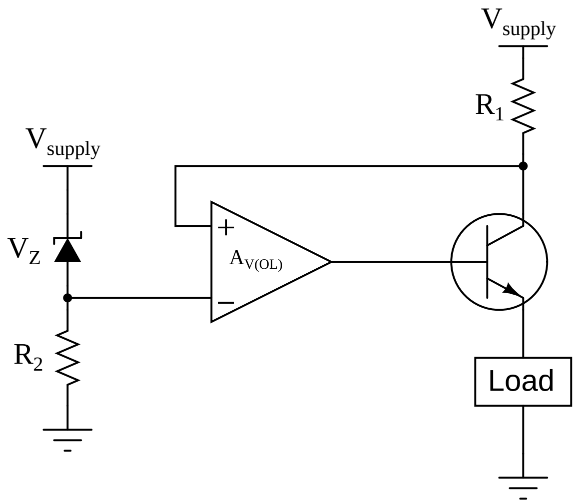


Notes 94

Note to your students that this is one of those applications where even "tiny" input bias currents can affect the results. In this particular case, the phototube outputs miniscule current at best, and so we *must* compensate for the existence of opamp bias currents.

Question 95

At first glance, the feedback appears to be wrong in this current-regulating circuit. Note how the feedback signal goes to the operational amplifier's *noninverting* (+) input, rather than the inverting input as one would normally expect for negative feedback:



Explain how this op-amp really does provide *negative* feedback, which of course is necessary for stable current regulation, as positive feedback would be completely unstable.

file 03942

Answer 95

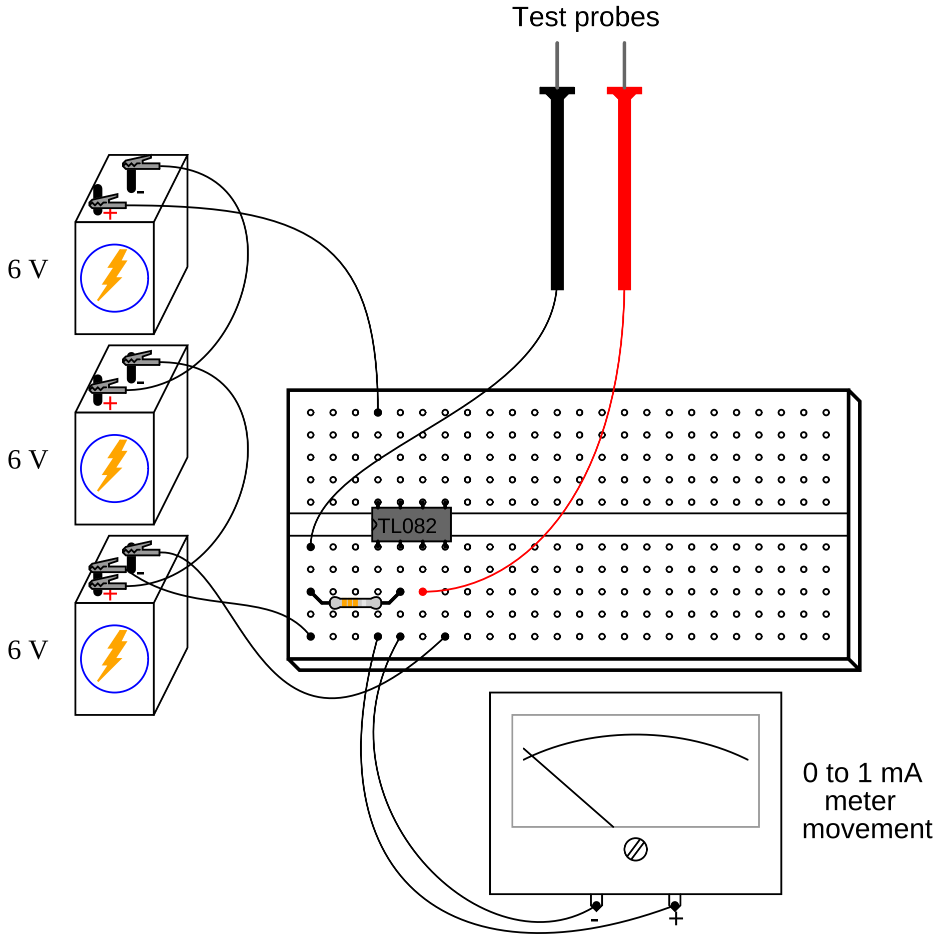
If current increases, the feedback voltage (as measured with reference to ground) will decrease, driving the op-amp's output in the negative direction. This tends to turn the transistor off, properly correcting for the excessive current condition.

Notes 95

The purpose of this question is to get students to realize negative feedback does not necessarily have to go into the inverting input. What makes the feedback "negative" is its self-correcting nature: the op-amp output drives in the direction opposite a perturbation in the measured signal in order to achieve stability at a control point.

Question 96

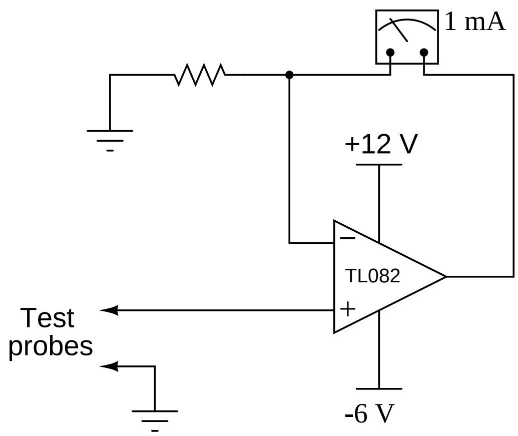
Shown here is a simple circuit for constructing an extremely high input impedance voltmeter on a wireless breadboard, using one half of a TL082 dual op-amp:



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 96



$R = 5 \text{ k}\Omega$

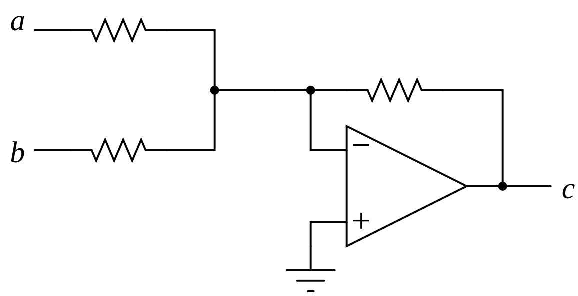
Follow-up question: determine the approximate input impedance of this voltmeter, and also the maximum voltage it is able to measure with *any* size resistor in the circuit.

Notes 96

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 97

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



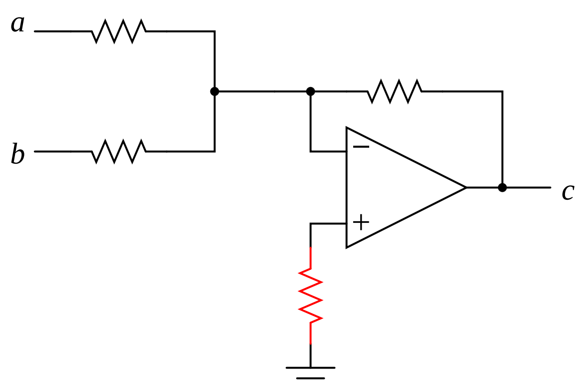
What is this circuit typically called?
file 01003

Answer 97

$c = -(a + b)$

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.



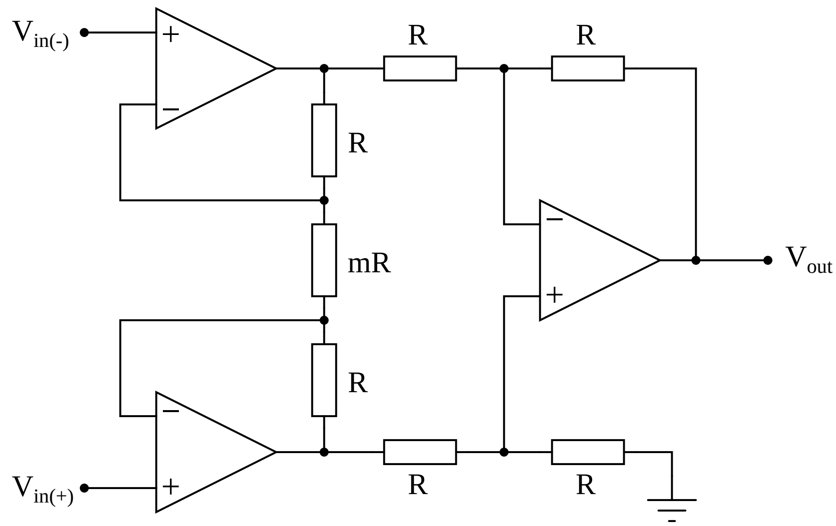
Challenge question: write an equation describing the proper value of this extra resistor.

Notes 97

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.

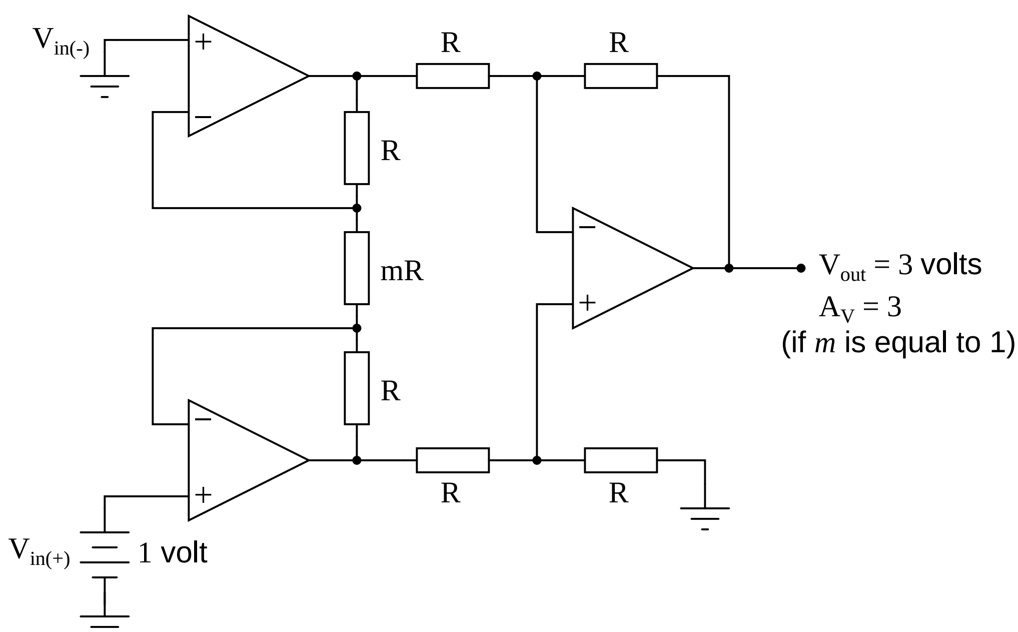
Question 98

The *instrumentation amplifier* is a popular circuit configuration for analog signal conditioning in a wide variety of electronic measurement applications. One of the reasons it is so popular is that its differential gain may be set by changing the value of a single resistor, the value of which is represented in this schematic by a multiplier constant named m:

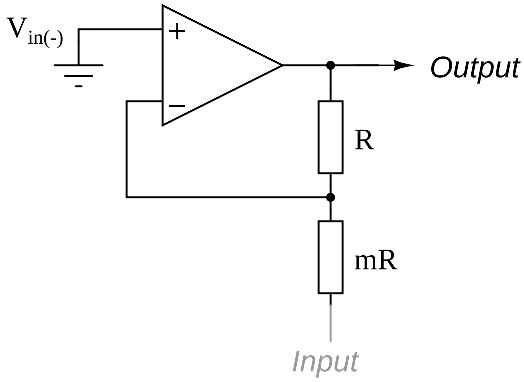


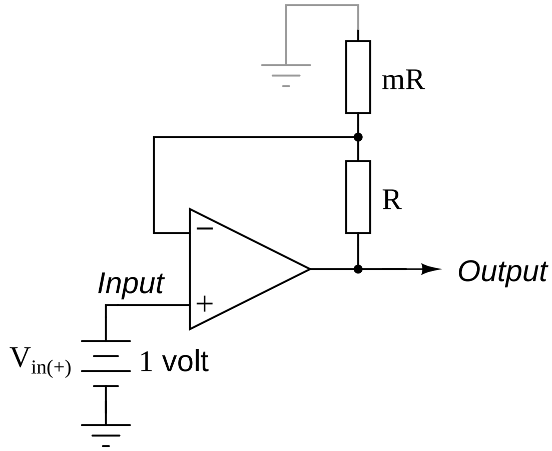
There is an equation describing the differential gain of an instrumentation amplifier, but it is easy enough to research so I'll leave that detail up to you. What I'd like you to do here is algebraically derive that equation based on what you know of inverting and noninverting operational amplifier circuits.

Suppose we apply +1 volt to the noninverting input and ground the inverting input, giving a differential input voltage of 1 volt. Whatever voltage appears at the output of the instrumentation amplifier circuit, then, directly represents the voltage gain:



A hint for constructing an algebraic explanation for the circuit's output voltage is to view the two "buffer" opamps separately, as inverting and noninverting amplifiers:





Note which configuration (inverting or noninverting) each of these circuits resemble, develop transfer functions for each (Output = $\cdots$ Input), then combine the two equations in a manner representing what the subtractor circuit will do. Your final result should be the gain equation for an instrumentation amplifier in terms of m.

file 02746

Answer 98

I won't show you the complete answer, but here's a start:

Equation for inverting side:

$$Output = -\left(\frac{R}{mR}\right) Input$$

Equation for noninverting side:

$$Output = \left(\frac{R}{mR} + 1\right) Input$$

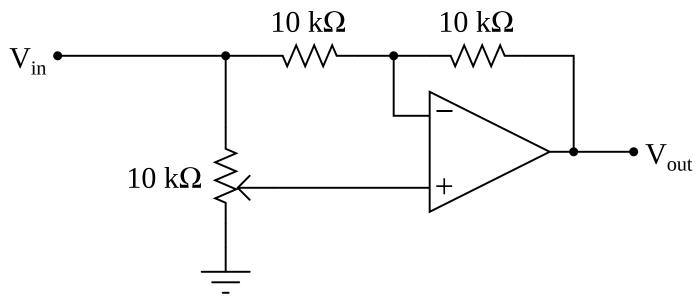
Notes 98

This question actually originated from one of my students as he tried to figure out an algebraic explanation for the instrumentation amplifier's gain! I thought the idea was so good that I decided to include it as a question in the Socratic Electronics project.

Astute students will note that the negative sign in the inverting amplifier equation becomes very important in this proof. As an instructor, I often avoid signs, choosing to figure out the polarity of the signal as a final step after all the other arithmetic has been completed for a circuit analysis. As such, I usually present the inverting amplifier equation as $\frac{R_f}{R_{in}}$ with the caveat of inverted polarity from input to output. Here, though, the negative sign becomes a vital part of the solution!

Question 99

Calculate the voltage gain of the following opamp circuit with the potentiometer turned fully up, precisely mid-position, and fully down:



- A_V (pot fully up) =
- A_V (pot mid-position) =
- A_V (pot fully down) =

file 03002

Answer 99

- A_V (pot fully up) = +1
- A_V (pot mid-position) = 0
- A_V (pot fully down) = -1

Follow-up question: can you think of any interesting applications for a circuit such as this?

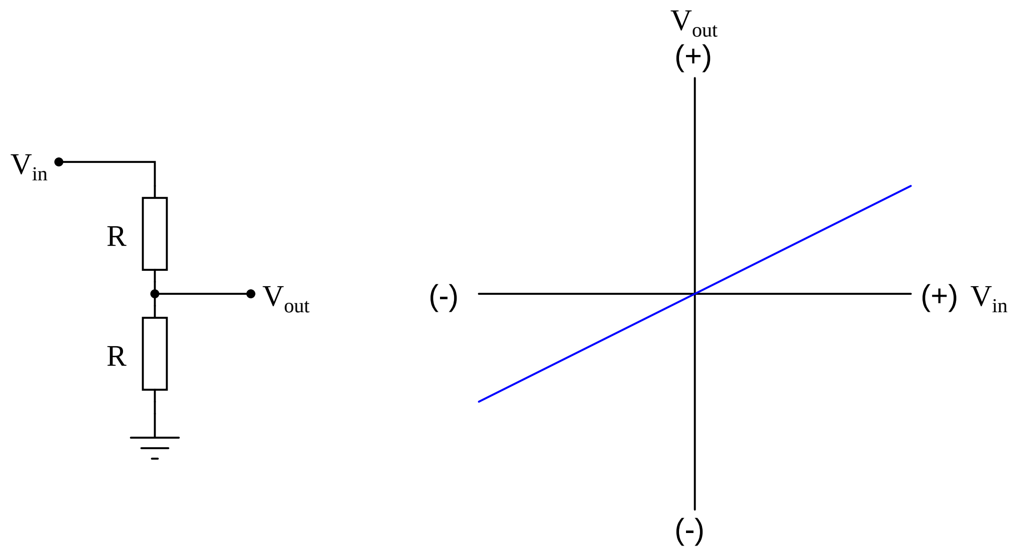
Challenge question: modify the circuit so that the range of voltage gain adjustment is -6 to +6 instead of -1 to +1.

Notes 99

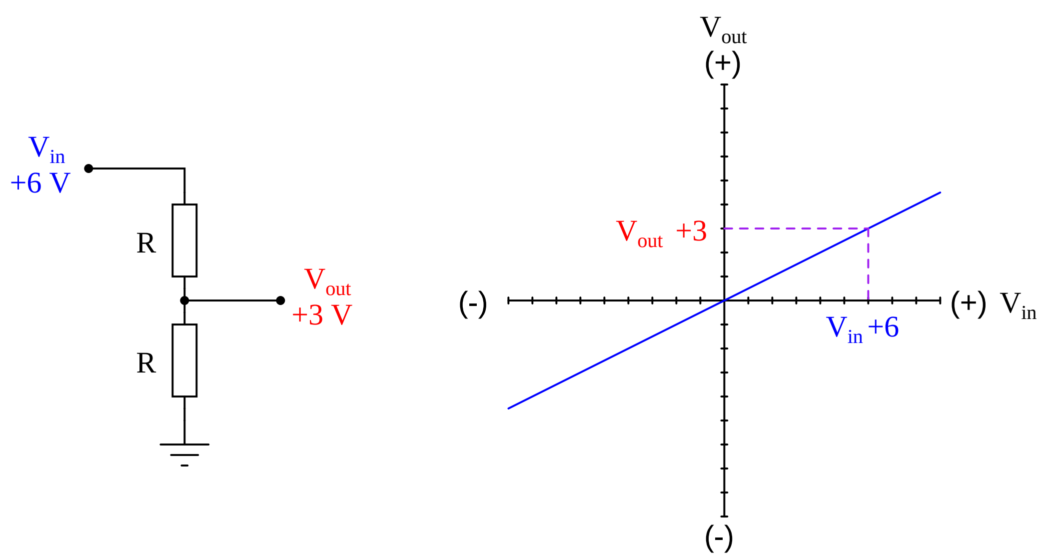
Ask your students how they approached this problem. How, exactly, did they choose to set it up so the solution became most apparent?

Question 100

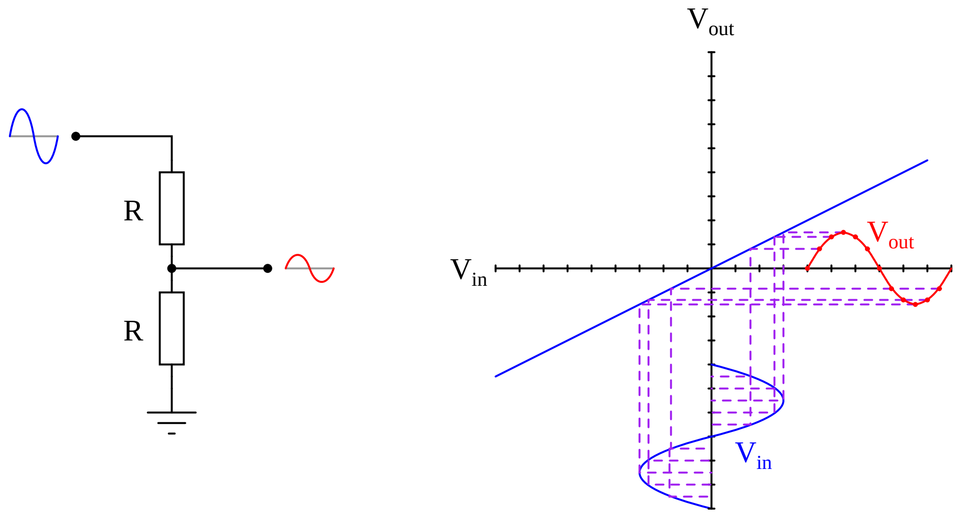
A common type of graph used to describe the operation of an electronic component or subcircuit is the *transfer characteristic*, showing the relationship between input signal and output signal. For example, the transfer characteristic for a simple resistive voltage divider circuit is a straight line:



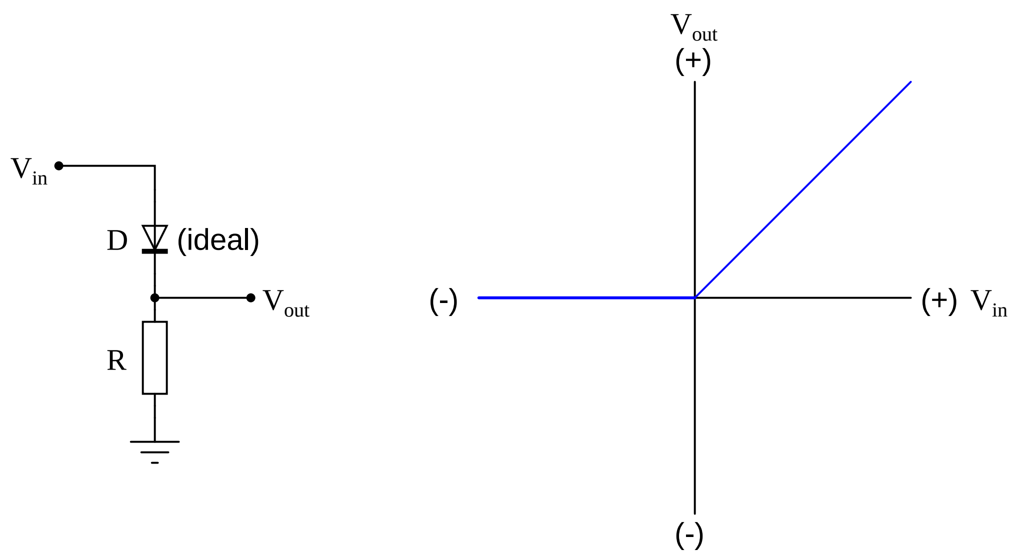
Once a transfer characteristic has been plotted, it may be used to predict the output signal of a circuit given any particular input signal. In this case, the transfer characteristic plot for the 2:1 voltage divider circuit tells us that the circuit will output +3 volts for an input of +6 volts:



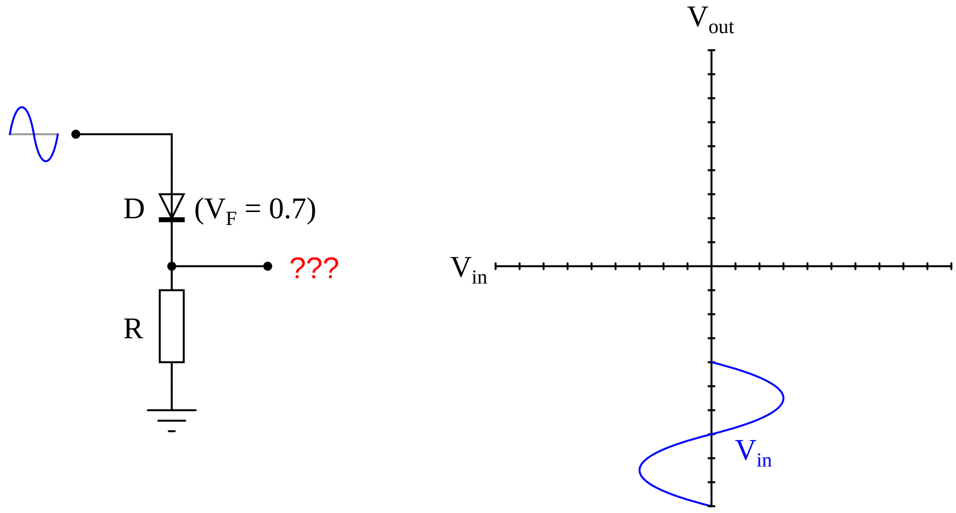
We may use the same transfer characteristic to plot the output of the voltage divider given an AC waveform input:



While this example (a voltage divider with a 2:1 ratio) is rather trivial, it shows how transfer characteristics may be used to predict the output signal of a network given a certain input signal condition. Where transfer characteristic graphs are more practical is in predicting the behavior of *nonlinear* circuits. For example, the transfer characteristic for an ideal half-wave rectifier circuit looks like this:

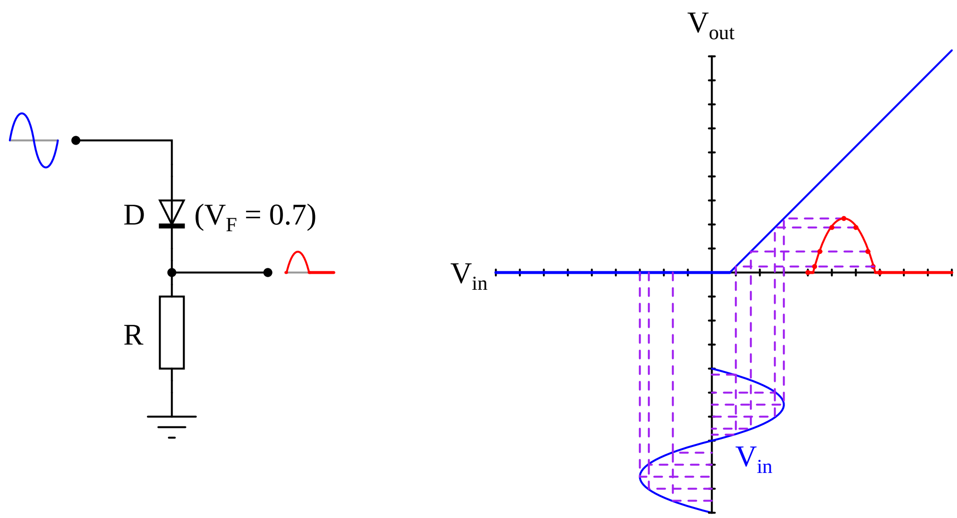


Sketch the transfer characteristic for a realistic diode (silicon, with 0.7 volts forward drop), and use this characteristic to plot the half-wave rectified output waveform given a sinusoidal input:



file 02541

Answer 100

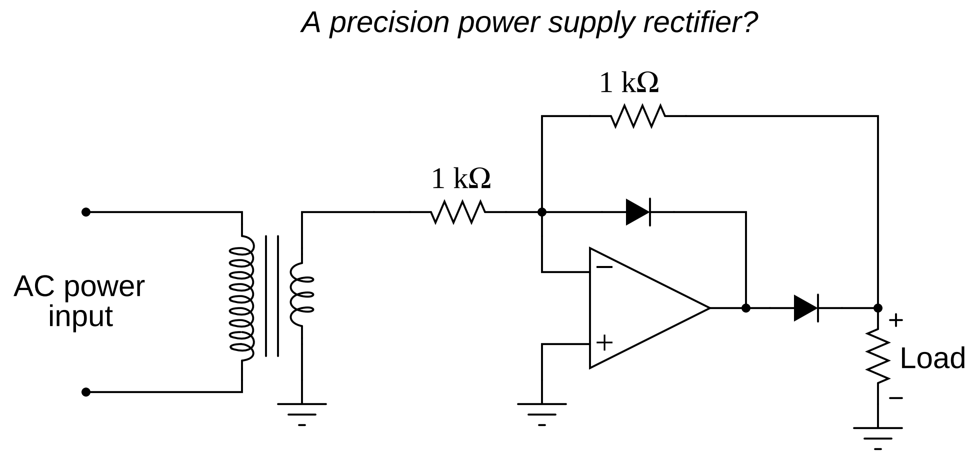


Notes 100

Transfer characteristic graphs provide an elegant method to sketch the output waveshape for any electrical network, linear or nonlinear. The method in which points along an input waveform are reflected and *transferred* to equivalent points on the output waveform justifies the name of this analytical tool. Make sure your students get the opportunity to learn how to use this tool, as it can provide great insight into distortion in electronic and electromagnetic devices.

Question 101

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



file 01025

Answer 101

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

Notes 101

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).