

Active filters

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Resources and methods for learning about these subjects (list a few here, in preparation for your research):

Questions

Question 1

In very simple, qualitative terms, rate the impedance of capacitors and inductors as "seen" by low-frequency and high-frequency signals alike:

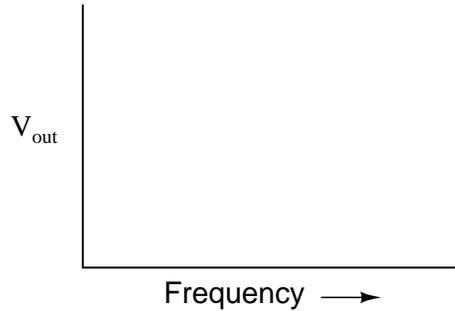
- Capacitor as it "appears" to a low frequency signal: (high or low) impedance?
- Capacitor as it "appears" to a high frequency signal: (high or low) impedance?

- Inductor as it "appears" to a low frequency signal: (high or low) impedance?
- Inductor as it "appears" to a high frequency signal: (high or low) impedance?

file 00616

Question 2

Draw the Bode plot for an *ideal* high-pass filter circuit:

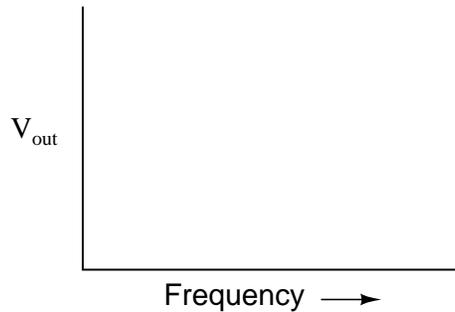


Be sure to note the "cutoff frequency" on your plot.

file 00618

Question 3

Draw the Bode plot for an *ideal* low-pass filter circuit:

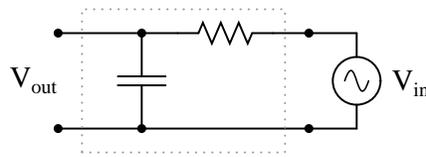


Be sure to note the "cutoff frequency" on your plot.

file 01245

Question 4

Identify what type of filter this circuit is, and calculate its cutoff frequency given a resistor value of $1\text{ k}\Omega$ and a capacitor value of $0.22\text{ }\mu\text{F}$:

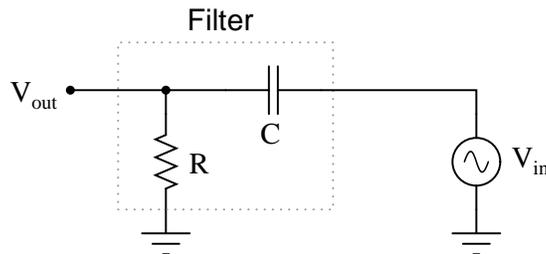


Calculate the impedance of both the resistor and the capacitor at this frequency. What do you notice about these two impedance values?

[file 00617](#)

Question 5

Identify what factor(s) determine the cutoff frequency of this passive filter circuit:

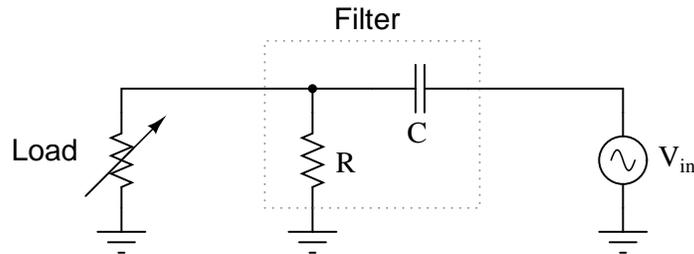


Give an exact equation predicting this filter circuit's cutoff frequency, and also identify what type of filter it is.

[file 02572](#)

Question 6

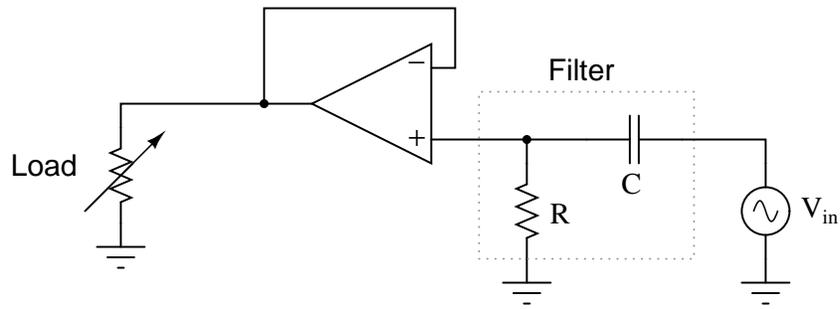
In this passive filter circuit, how will the filter's cutoff frequency be affected by changes in the load resistance? Be as specific as you can in your answer.



[file 00701](#)

Question 7

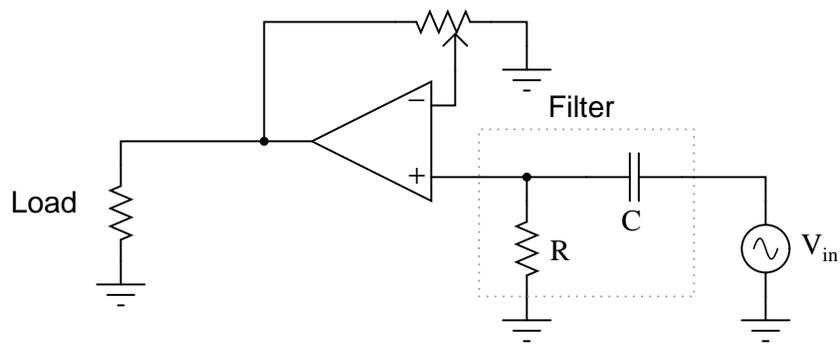
In this active filter circuit, how will the filter's cutoff frequency be affected by changes in the load resistance? Be as specific as you can in your answer.



[file 00702](#)

Question 8

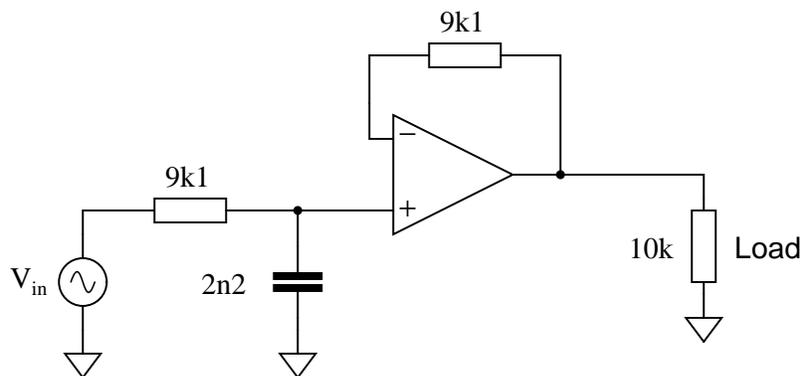
In this filter circuit, how will the filter's cutoff frequency be affected by changes in the potentiometer position? Be as specific as you can in your answer.



[file 00703](#)

Question 9

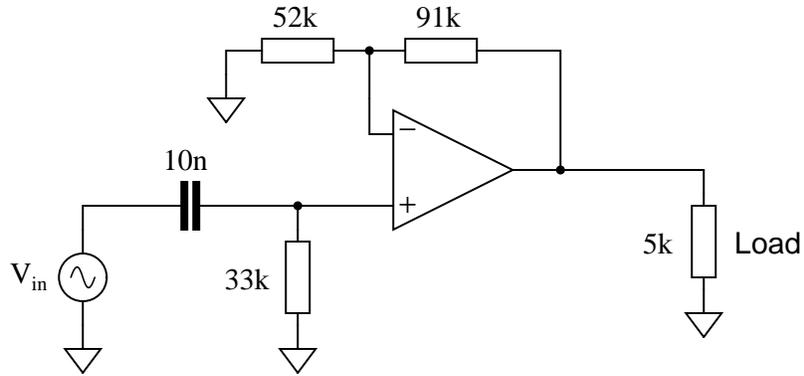
Determine the type (LP, HP, BP, BS) and cutoff frequency of this active filter circuit:



[file 02476](#)

Question 10

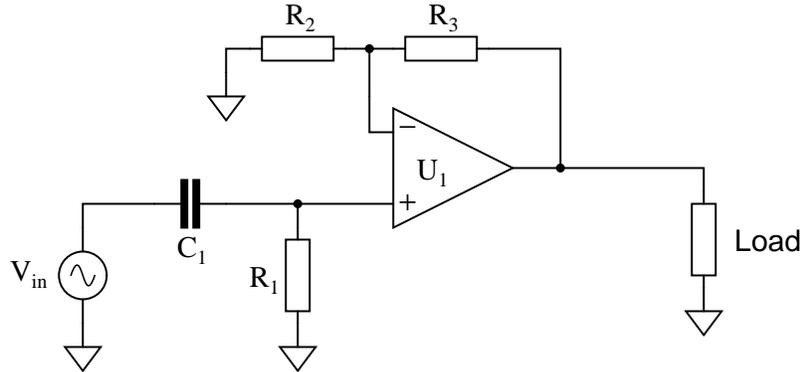
Determine the type (LP, HP, BP, BS) and cutoff frequency of this active filter circuit:



[file 02475](#)

Question 11

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



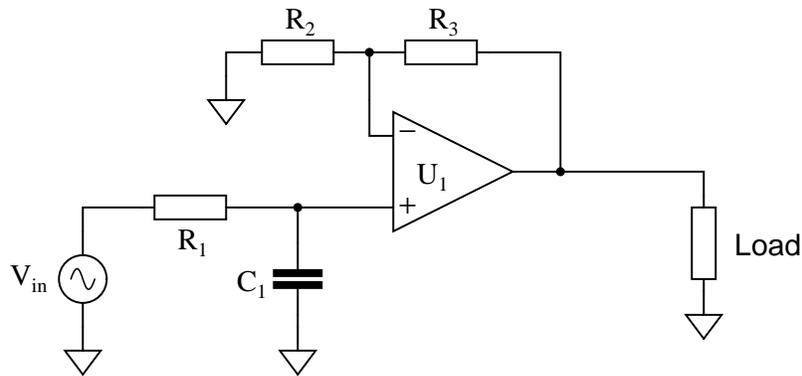
- Resistor R_1 fails open:
- Capacitor C_1 fails open:
- Solder bridge (short) across resistor R_1 :
- Solder bridge (short) across capacitor C_1 :
- Resistor R_2 fails open:
- Resistor R_3 fails open:

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

[file 03786](#)

Question 12

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

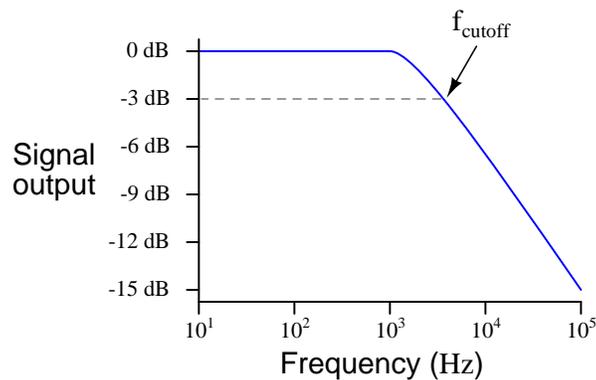


- Resistor R_1 fails open:
- Capacitor C_1 fails open:
- Solder bridge (short) across resistor R_1 :
- Solder bridge (short) across capacitor C_1 :
- Resistor R_2 fails open:
- Resistor R_3 fails open:

For each of these conditions, explain *why* the resulting effects will occur.
[file 03787](#)

Question 13

Real filters never exhibit perfect "square-edge" Bode plot responses. A typical low-pass filter circuit, for example, might have a frequency response that looks like this:



What does the term *rolloff* refer to, in the context of filter circuits and Bode plots? Why would this parameter be important to a technician or engineer?

[file 01246](#)

Question 14

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

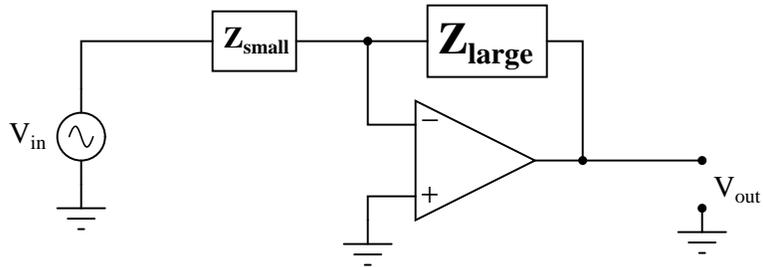
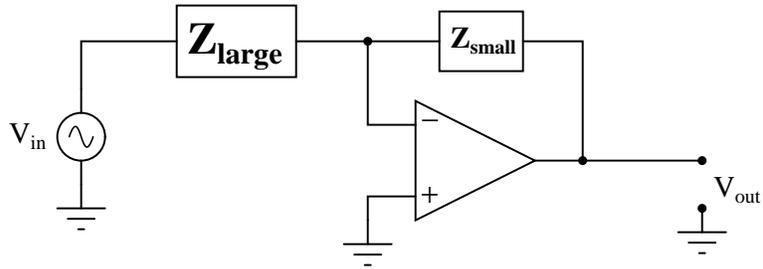
- Chebyshev
- Butterworth
- Bessel

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

[file 00766](#)

Question 15

Compare the voltage gains of these two opamp circuits:

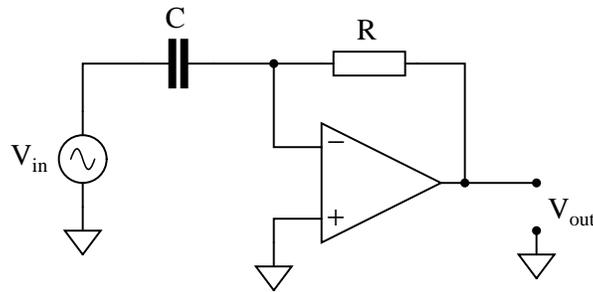


Which one has the greater A_V , and why?

[file 00700](#)

Question 16

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

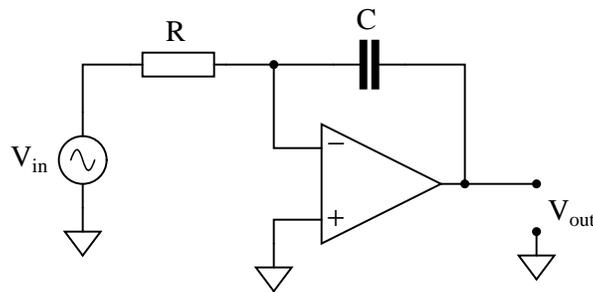


Also, describe what result the change in impedances will have on the op-amp circuit's voltage gain. If the input signal amplitude remains constant as frequency increases, what will happen to the amplitude of the output voltage? What type of filtering function does this behavior represent?

[file 00704](#)

Question 17

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

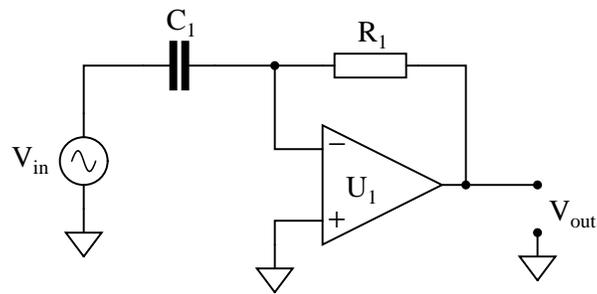


Also, describe what result the change in impedances will have on the op-amp circuit's voltage gain. If the input signal amplitude remains constant as frequency increases, what will happen to the amplitude of the output voltage? What type of filtering function does this behavior represent?

[file 00710](#)

Question 18

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

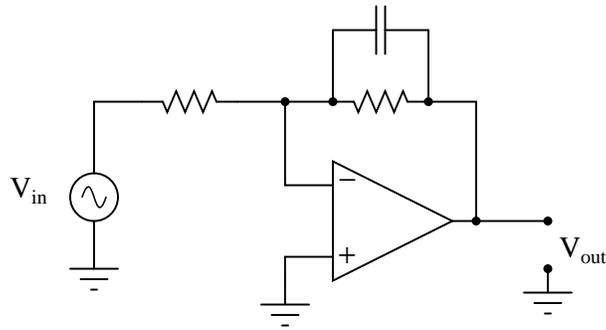


- Resistor R_1 fails open:
- Capacitor C_1 fails open:
- Solder bridge (short) across resistor R_1 :
- Solder bridge (short) across capacitor C_1 :

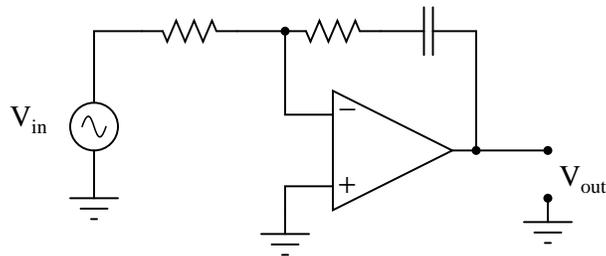
For each of these conditions, explain *why* the resulting effects will occur.
[file 03793](#)

Question 19

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



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

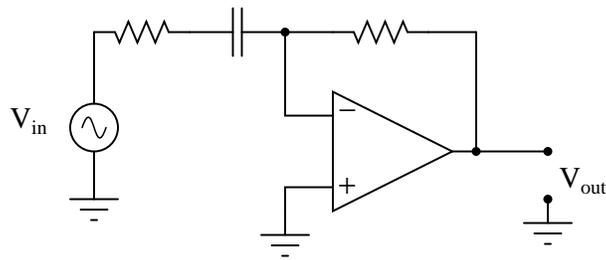


What type of filtering function (low pass, high pass, band pass, band stop) is provided by both these filter circuits? Comparing these two circuit designs, which one do you think is more practical? Explain your answer.

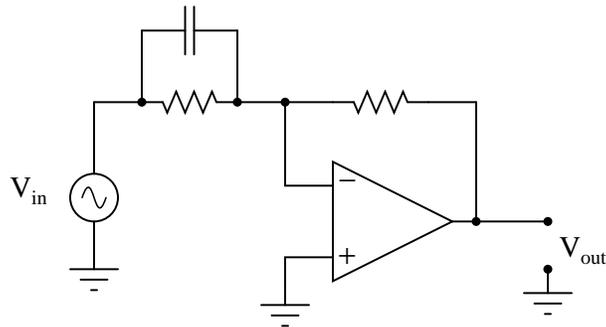
file 00706

Question 20

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



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

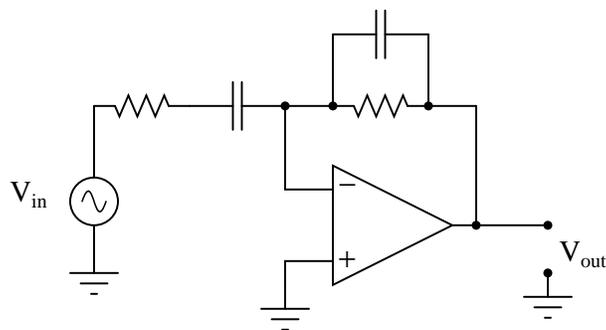


What type of filtering function (low pass, high pass, band pass, band stop) is provided by both these filter circuits? Comparing these two circuit designs, which one do you think is more practical? Explain your answer.

[file 00707](#)

Question 21

Identify the function of this active filter:

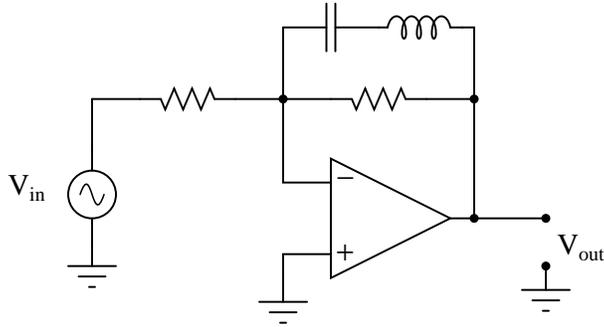


It is low pass, high pass, band pass, or band stop? Explain your answer.

[file 00708](#)

Question 22

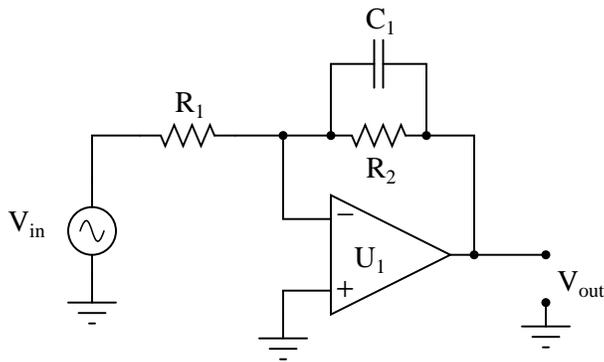
Identify the function of this active filter:



It is low pass, high pass, band pass, or band stop? Explain your answer.
[file 00709](#)

Question 23

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

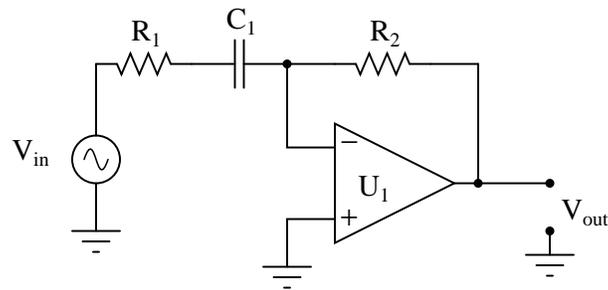


- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Capacitor C_1 fails open:
- Solder bridge (short) across resistor R_1 :
- Solder bridge (short) across resistor R_2 :
- Solder bridge (short) across capacitor C_1 :

For each of these conditions, explain *why* the resulting effects will occur.
[file 03794](#)

Question 24

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

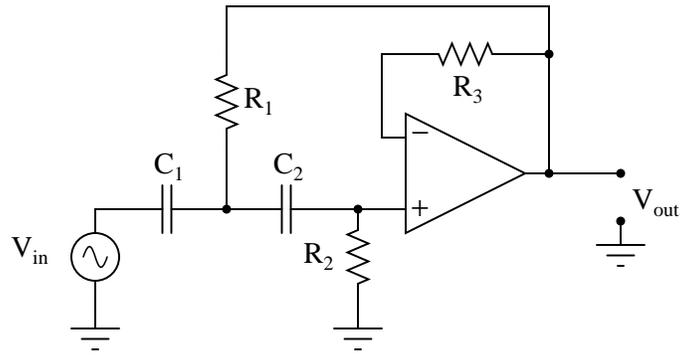
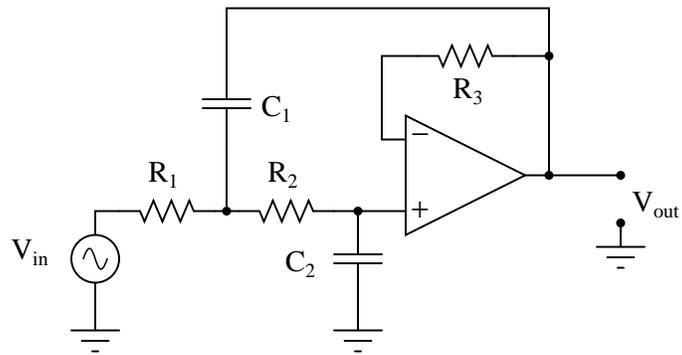


- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Capacitor C_1 fails open:
- Solder bridge (short) across resistor R_1 :
- Solder bridge (short) across resistor R_2 :
- Solder bridge (short) across capacitor C_1 :

For each of these conditions, explain *why* the resulting effects will occur.
[file 03795](#)

Question 25

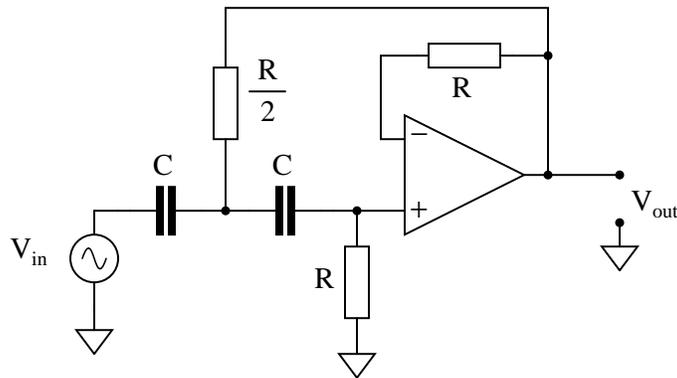
A very popular active filter topology is called the *Sallen-Key*. Two examples of Sallen-Key active filter circuits are shown here:



Determine which of these Sallen-Key filters is low pass, and which is high pass. Explain your answers.
[file 00765](#)

Question 26

Choose appropriate values for this Sallen-Key high-pass filter circuit to give it a cutoff frequency of 7 kHz with a "Butterworth" response:



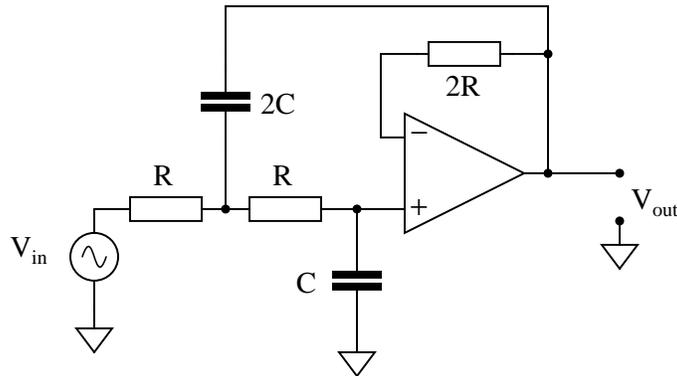
$$f_{-3dB} = \frac{\sqrt{2}}{2\pi RC}$$

A good guideline to follow is to make sure no component impedance (Z_R or Z_C) at the cutoff frequency is less than 1 k Ω or greater than 100 k Ω .

[file 02575](#)

Question 27

Choose appropriate values for this Sallen-Key low-pass filter circuit to give it a cutoff frequency of 4.2 kHz with a "Butterworth" response:



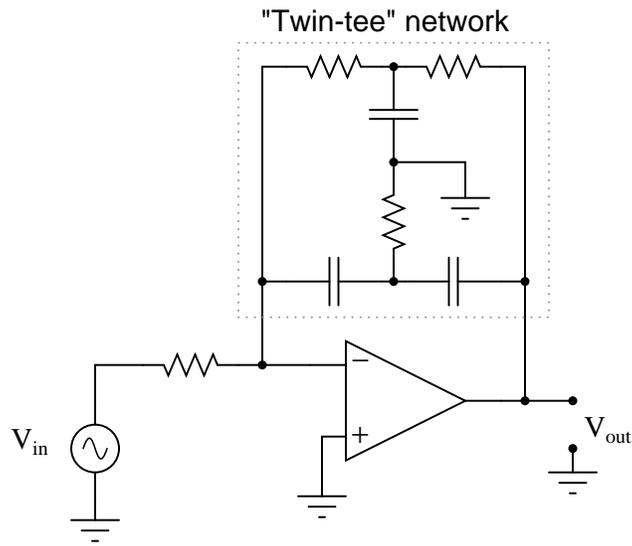
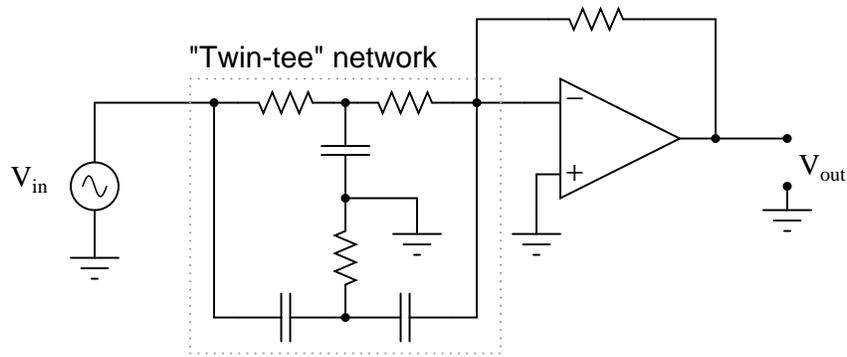
$$f_{-3dB} = \frac{1}{2\sqrt{2}\pi RC}$$

A good guideline to follow is to make sure no component impedance (Z_R or Z_C) at the cutoff frequency is less than 1 k Ω or greater than 100 k Ω .

[file 02574](#)

Question 28

A popular passive filtering network called the *twin-tee* is often coupled with an operational amplifier to produce an active filter circuit. Two examples are shown here:

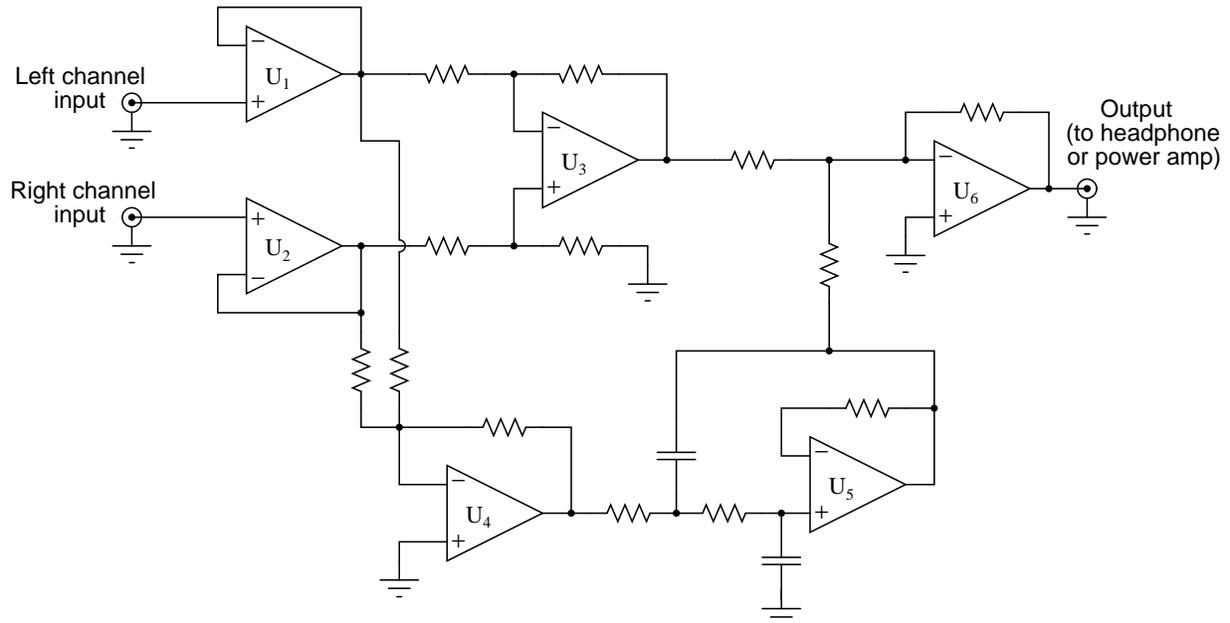


Identify which of these circuits is band-pass, and which is band-stop. Also, identify the type of response typically provided by the twin-tee network alone, and how that response is exploited to make *two* different types of active filter responses.

[file 02573](#)

Question 29

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.

Operational amplifiers U_1 and U_2 provide input buffering so that the other opamp circuits do not excessively load the left and right channel input signals. Opamp U_3 performs the subtraction function necessary to eliminate the vocal track.

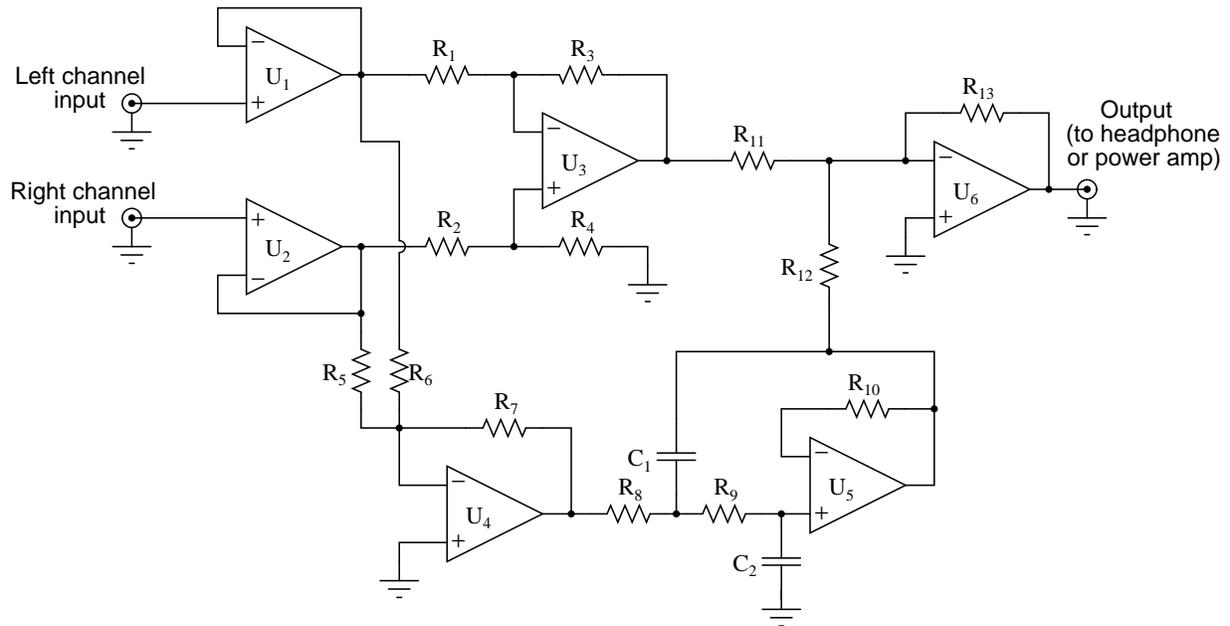
You might think that these three opamps would be sufficient to make a vocal eliminator circuit, but there is one more necessary feature. Not only is the vocal track common to both left and right channels, but so is most of the bass (low-frequency) tones. Thus, the first three opamps (U_1 , U_2 , and U_3) eliminate both vocal *and* bass signals from getting to the output, which is not what we want.

Explain how the other three opamps (U_4 , U_5 , and U_6) work to restore bass tones to the output so they are not lost along with the vocal track.

[file 02576](#)

Question 30

This vocal eliminator circuit used to work just fine, but then one day it seemed to lose a lot of its bass. It still did its job of eliminating the vocal track, but instead of hearing the full range of musical tones it only reproduced the high frequencies, while the low frequency tones were lost:



Identify the following fault possibilities:

One resistor failure (either open or shorted) that could cause this to happen:

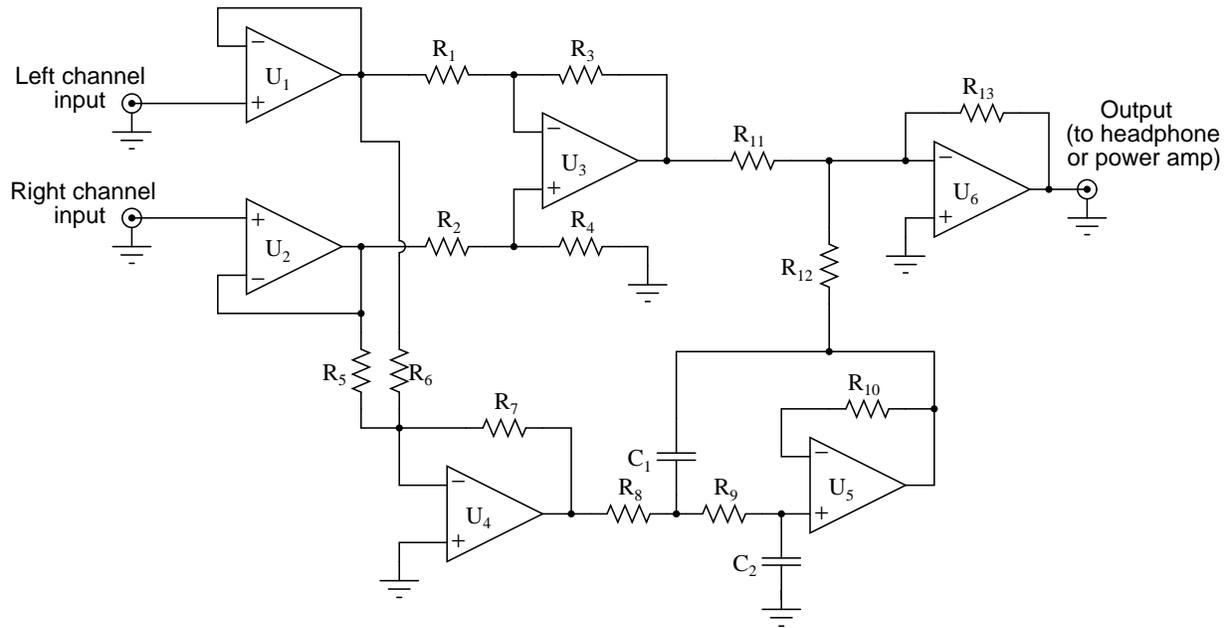
One capacitor failure (either open or shorted) that could cause this to happen:

One opamp failure that could cause this to happen:

For each of these proposed faults, explain *why* the bass tones would be lost.
[file 03796](#)

Question 31

This vocal eliminator circuit used to work just fine, but then one day it stopped eliminating the vocal track. The tone of the music sounded a bit heavy on the bass, and the vocal track was there when it shouldn't have been there:



Identify the following fault possibilities:

One resistor failure (either open or shorted) that could cause this to happen:

One opamp failure that could cause this to happen:

For each of these proposed faults, explain *why* the bass tones would be lost.

file 03797

Don't just sit there! Build something!!

Learning to mathematically analyze circuits requires much study and practice. Typically, students practice by working through lots of sample problems and checking their answers against those provided by the textbook or the instructor. While this is good, there is a much better way.

You will learn much more by actually *building and analyzing real circuits*, letting your test equipment provide the "answers" instead of a book or another person. For successful circuit-building exercises, follow these steps:

1. Carefully measure and record all component values prior to circuit construction.
2. Draw the schematic diagram for the circuit to be analyzed.
3. Carefully build this circuit on a breadboard or other convenient medium.
4. Check the accuracy of the circuit's construction, following each wire to each connection point, and verifying these elements one-by-one on the diagram.
5. Mathematically analyze the circuit, solving for all voltage and current values.
6. Carefully measure all voltages and currents, to verify the accuracy of your analysis.
7. If there are any substantial errors (greater than a few percent), carefully check your circuit's construction against the diagram, then carefully re-calculate the values and re-measure.

Avoid using the model 741 op-amp, unless you want to challenge your circuit design skills. There are more versatile op-amp models commonly available for the beginner. I recommend the LM324 for DC and low-frequency AC circuits, and the TL082 for AC projects involving audio or higher frequencies.

As usual, avoid very high and very low resistor values, to avoid measurement errors caused by meter "loading". I recommend resistor values between 1 k Ω and 100 k Ω .

One way you can save time and reduce the possibility of error is to begin with a very simple circuit and incrementally add components to increase its complexity after each analysis, rather than building a whole new circuit for each practice problem. Another time-saving technique is to re-use the same components in a variety of different circuit configurations. This way, you won't have to measure any component's value more than once.

[file 00705](#)

Answers

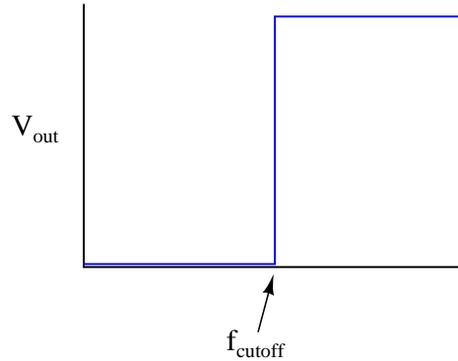
Answer 1

- Capacitor as it "appears" to a low frequency signal: *high* impedance.
- Capacitor as it "appears" to a high frequency signal: *low* impedance.

- Inductor as it "appears" to a low frequency signal: *low* impedance.
- Inductor as it "appears" to a high frequency signal: *high* impedance.

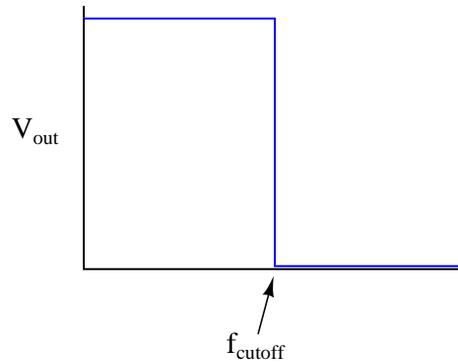
Challenge question: what does a capacitor "appear" as to a *DC* signal?

Answer 2



Follow-up question: a theoretical filter with this kind of idealized response is sometimes referred to as a "brick wall" filter. Explain why this name is appropriate.

Answer 3



Follow-up question: a theoretical filter with this kind of idealized response is sometimes referred to as a "brick wall" filter. Explain why this name is appropriate.

Answer 4

This is a *low-pass* filter.

$$f_{cutoff} = 723.4 \text{ Hz}$$

Answer 5

This is a *high-pass* filter circuit, with a cutoff frequency of:

$$f_{-3dB} = \frac{1}{2\pi RC}$$

Answer 6

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

Answer 7

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

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

Answer 8

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

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

Answer 9

This is a low-pass filter circuit.

$$f_{-3dB} = 7.95 \text{ kHz}$$

Follow-up question: explain what the purpose of the 9.1 k Ω feedback resistor is, since all we're using the opamp for is a voltage buffer anyway (which theoretically does not require resistance in the feedback loop). Furthermore, explain how the Superposition theorem is used to determine the optimum value of this feedback resistance.

Answer 10

This is a high-pass filter circuit.

$$f_{-3dB} = 482.3 \text{ Hz}$$

Follow-up question: the feedback resistor network comprised of the 52 k Ω and 91 k Ω resistors not only provides a gain of 1.75 (4.86 dB), but these values were also intentionally chosen to compensate for the effects of DC bias current through the opamp input terminals. You will notice that the *parallel* combination of 52 k Ω and 91 k Ω is approximately equal to 33 k Ω . Explain why this is significant with reference to the Superposition theorem.

Answer 11

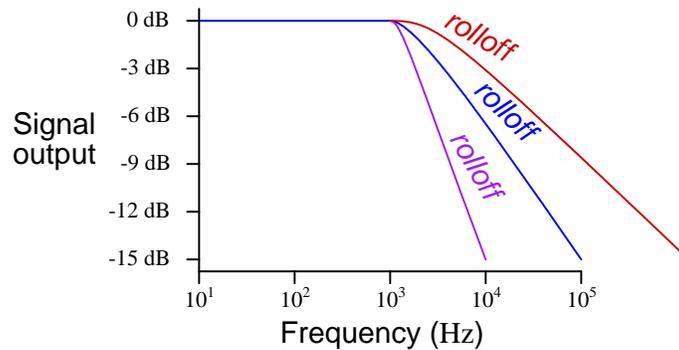
- Resistor R_1 fails open: *Filter circuit stops filtering, passes all frequencies.*
- Capacitor C_1 fails open: *No signal output at all from the circuit.*
- Solder bridge (short) across resistor R_1 : *No signal output at all from the circuit.*
- Solder bridge (short) across capacitor C_1 : *Filter circuit stops filtering, passes all frequencies.*
- Resistor R_2 fails open: *Voltage gain of circuit decreases to value of 1 (0 dB).*
- Resistor R_3 fails open: *Filter circuit outputs square wave at all frequencies.*

Answer 12

- Resistor R_1 fails open: *No signal output at all from the circuit.*
- Capacitor C_1 fails open: *Filter circuit stops filtering, passes all frequencies.*
- Solder bridge (short) across resistor R_1 : *Filter circuit stops filtering, passes all frequencies.*
- Solder bridge (short) across capacitor C_1 : *No signal output at all from the circuit.*
- Resistor R_2 fails open: *Voltage gain of circuit decreases to value of 1 (0 dB).*
- Resistor R_3 fails open: *Filter circuit outputs square wave at all frequencies.*

Answer 13

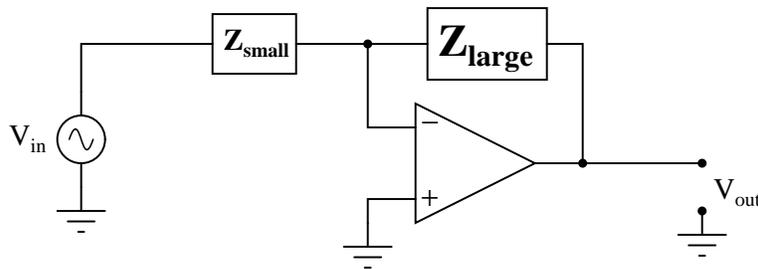
"Rolloff" refers to the *slope* of the Bode plot in the attenuating range of the filter circuit, usually expressed in units of decibels per octave (dB/octave) or decibels per decade (dB/decade):



Answer 14

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

Answer 15



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

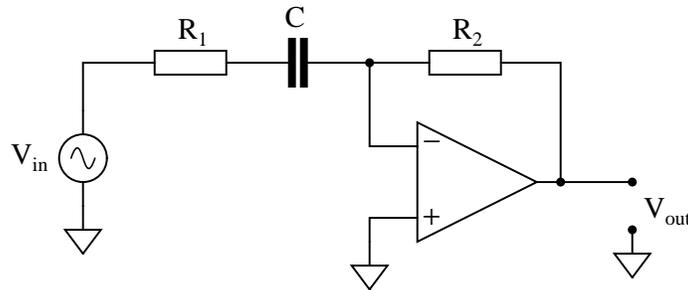
Answer 16

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

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

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

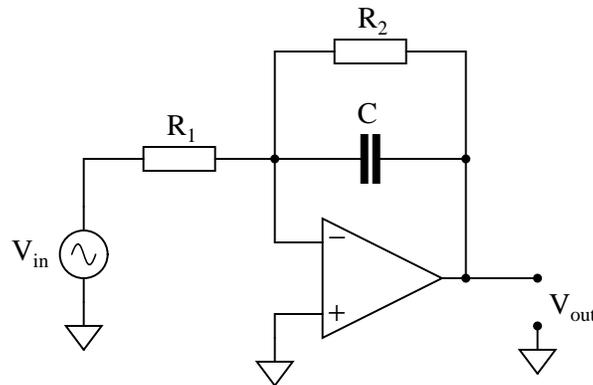
Challenge question #2: explain why this type of circuit is usually equipped with a low-value resistor (R_1) in series with the input capacitor:



Answer 17

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

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

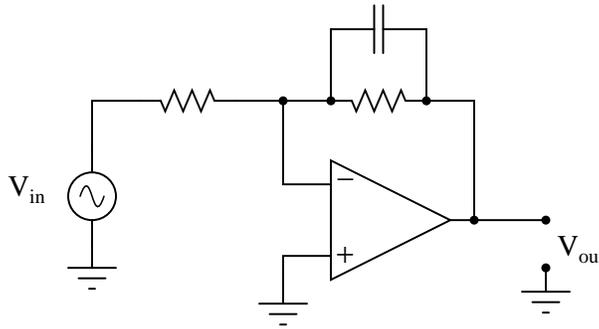


Answer 18

- Resistor R_1 fails open: *Output signal is always a square wave.*
- Capacitor C_1 fails open: *No output signal at all.*
- Solder bridge (short) across resistor R_1 : *No output signal at all.*
- Solder bridge (short) across capacitor C_1 : *Output signal is always a square wave.*

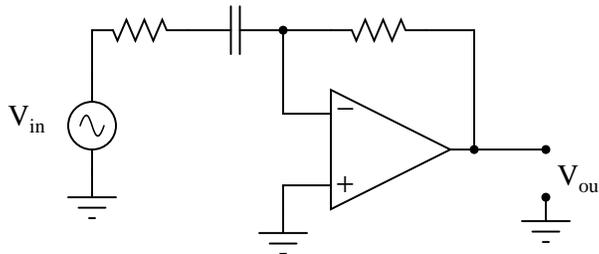
Answer 19

These are both low pass filters. The circuit with the shunt capacitor is the more practical one, because its voltage gain remains finite for all possible input signal frequencies:



Answer 20

These are both high pass filters. The circuit with the series capacitor is the more practical one, because its voltage gain remains finite for all possible input signal frequencies:



Answer 21

This is a band pass filter circuit.

Answer 22

This is a band stop filter circuit.

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

Answer 23

- Resistor R_1 fails open: *No output signal at all.*
- Resistor R_2 fails open: *Output saturates (either positive or negative) when there is any DC voltage input to the circuit.*
- Capacitor C_1 fails open: *No filtering action at all, merely operates as a fixed-gain amplifier.*
- Solder bridge (short) across resistor R_1 : *Output signal is always a square wave.*
- Solder bridge (short) across resistor R_2 : *No output signal at all.*
- Solder bridge (short) across capacitor C_1 : *No output signal at all.*

Answer 24

- Resistor R_1 fails open: *No output signal at all.*
- Resistor R_2 fails open: *Output signal is always a square wave.*
- Capacitor C_1 fails open: *No output signal at all.*
- Solder bridge (short) across resistor R_1 : *Output signal is a square wave at high frequencies (too much high-frequency gain).*
- Solder bridge (short) across resistor R_2 : *No output signal at all.*
- Solder bridge (short) across capacitor C_1 : *No filtering action at all, merely operates as a fixed-gain amplifier.*

Answer 25

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

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

Answer 26

Bear in mind that this is just one possible set of component values:

- $C = 3.3 \text{ nF}$
- $R = 9.744 \text{ k}\Omega$
- $\frac{R}{2} = 4.872 \text{ k}\Omega$

Follow-up question: how would you suggest we obtain the precise resistance values necessary to build this circuit?

Answer 27

Bear in mind that this is just one possible set of component values:

- $C = 0.0047 \text{ }\mu\text{F}$
- $2C = 0.0094 \text{ }\mu\text{F}$
- $R = 5.701 \text{ k}\Omega$
- $2R = 11.402 \text{ k}\Omega$

Follow-up question: while $0.0047 \text{ }\mu\text{F}$ is a common capacitor size, $0.0094 \text{ }\mu\text{F}$ is not. Explain how you could obtain this precise value of capacitance needed to build this circuit.

Answer 28

The first filter shown is a band-stop, while the second filter shown is a band-pass.

Answer 29

I'll let you figure out the function of opamps U_4 , U_5 , and U_6 on your own!

Answer 30

Please note that the following list is not exhaustive. That is, other component faults may be possible!

One resistor failure (either open or shorted) that could cause this to happen: R_8 *failed open*.

One capacitor failure (either open or shorted) that could cause this to happen: C_2 *failed shorted*.

One opamp failure that could cause this to happen: U_4 *failed*.

Answer 31

Please note that the following list is not exhaustive. That is, other component faults may be possible!

One resistor failure (either open or shorted) that could cause this to happen: R_2 *failed open*.

One opamp failure that could cause this to happen: U_2 *failed*.

Answer 32

Let the electrons themselves give you the answers to your own "practice problems"!

Notes 1

Ask your students how they arrived at their answers for these qualitative assessments. If they found difficulty understanding the relationship of frequency to impedance for reactive components, I suggest you work through the reactance equations qualitatively with them. In other words, evaluate each of the reactance formulae ($X_L = 2\pi fL$ and $X_C = \frac{1}{2\pi fC}$) in terms of f increasing and decreasing, to understand how each of these components reacts to low- and high-frequency signals.

Notes 2

The plot given in the answer, of course, is for an ideal high-pass filter, where all frequencies below f_{cutoff} are blocked and all frequencies above f_{cutoff} are passed. In reality, filter circuits never attain this ideal "square-edge" response. Discuss possible applications of such a filter with your students.

Challenge them to draw the Bode plots for ideal *band-pass* and *band-stop* filters as well. Exercises such as this really help to clarify the purpose of filter circuits. Otherwise, there is a tendency to lose perspective of what real filter circuits, with their correspondingly complex Bode plots and mathematical analyses, are supposed to do.

Notes 3

The plot given in the answer, of course, is for an ideal low-pass filter, where all frequencies below f_{cutoff} are passed and all frequencies above f_{cutoff} are blocked. In reality, filter circuits never attain this ideal "square-edge" response. Discuss possible applications of such a filter with your students.

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Notes 4

Be sure to ask students where they found the cutoff frequency formula for this filter circuit.

When students calculate the impedance of the resistor and the capacitor at the cutoff frequency, they should notice something unique. Ask your students why these values are what they are at the cutoff frequency. Is this just a coincidence, or does this tell us more about how the "cutoff frequency" is defined for an RC circuit?

Notes 5

Nothing fancy here, just a review of passive RC filter circuitry.

Notes 6

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

Notes 7

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

Notes 8

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

Notes 9

Ask your students to explain how they arrived at their answers: what formulae did they use, and how did they determine the type of the filter circuit that this is? Ask them if there was any information given in the diagram irrelevant to either determination.

Notes 10

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Notes 11

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.

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Notes 13

Point students' attention to the scale used on this particular Bode plot. This is called a *log-log* scale, where neither vertical nor horizontal axis is linearly marked. This scaling allows a very wide range of conditions to be shown on a relatively small plot, and is very common in filter circuit analysis.

Notes 14

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

Notes 15

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

Notes 16

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

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

Notes 17

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

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Notes 19

Discuss with your students their methods of determining filter type. How did they approach this problem, to see what type of filter both these circuits were?

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

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Notes 21

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

Notes 22

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

Notes 23

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Notes 25

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

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

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

Notes 26

In order for students to solve for R , they must algebraically manipulate the cutoff frequency formula. Ask them why we might choose a standard value for capacitance and then calculate a non-standard value for resistance. Why not the other way around (first choose R , then calculate C)?

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An interesting concept at work here is the inversion of a function by placement inside the feedback loop of a negative-feedback opamp circuit. What is a band-stop filter all by itself forces the opamp to be a band-pass if placed within the negative feedback signal path. Discuss this very important concept with your students, as this is most definitely not the only application for it!

Notes 29

Not only does this circuit illustrate a neat application of opamps, but it also showcases modular operational circuit design, where each opamp (and its supporting passive components) performs exactly one task.

Notes 30

Ask your students to explain how they identified their proposed faults, and also how they were able to identify component that *must* still be working properly.

Notes 31

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It has been my experience that students require much practice with circuit analysis to become proficient. To this end, instructors usually provide their students with lots of practice problems to work through, and provide answers for students to check their work against. While this approach makes students proficient in circuit theory, it fails to fully educate them.

Students don't just need mathematical practice. They also need real, hands-on practice building circuits and using test equipment. So, I suggest the following alternative approach: students should *build* their own "practice problems" with real components, and try to mathematically predict the various voltage and current values. This way, the mathematical theory "comes alive," and students gain practical proficiency they wouldn't gain merely by solving equations.

Another reason for following this method of practice is to teach students *scientific method*: the process of testing a hypothesis (in this case, mathematical predictions) by performing a real experiment. Students will also develop real troubleshooting skills as they occasionally make circuit construction errors.

Spend a few moments of time with your class to review some of the "rules" for building circuits before they begin. Discuss these issues with your students in the same Socratic manner you would normally discuss the worksheet questions, rather than simply telling them what they should and should not do. I never cease to be amazed at how poorly students grasp instructions when presented in a typical lecture (instructor monologue) format!

A note to those instructors who may complain about the "wasted" time required to have students build real circuits instead of just mathematically analyzing theoretical circuits:

What is the purpose of students taking your course?

If your students will be working with real circuits, then they should learn on real circuits whenever possible. If your goal is to educate theoretical physicists, then stick with abstract analysis, by all means! But most of us plan for our students to do something in the real world with the education we give them. The "wasted" time spent building real circuits will pay huge dividends when it comes time for them to apply their knowledge to practical problems.

Furthermore, having students build their own practice problems teaches them how to perform *primary research*, thus empowering them to continue their electrical/electronics education autonomously.

In most sciences, realistic experiments are much more difficult and expensive to set up than electrical circuits. Nuclear physics, biology, geology, and chemistry professors would just love to be able to have their students apply advanced mathematics to real experiments posing no safety hazard and costing less than a textbook. They can't, but you can. Exploit the convenience inherent to your science, and *get those students of yours practicing their math on lots of real circuits!*