Analyzing and calculating noise bandwidth in ADC systems – multi-stage filters

TIPL 4801

TI Precision Labs – ADCs

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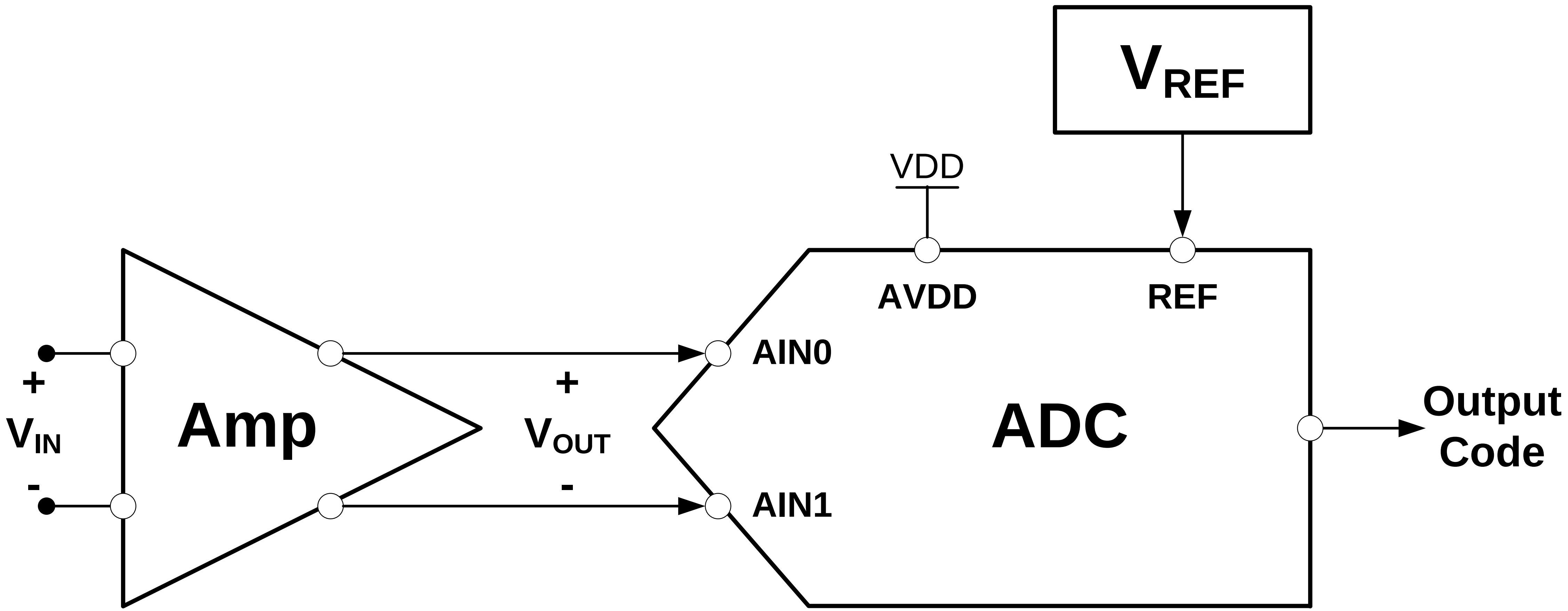
Basic data acquisition system noise calculation

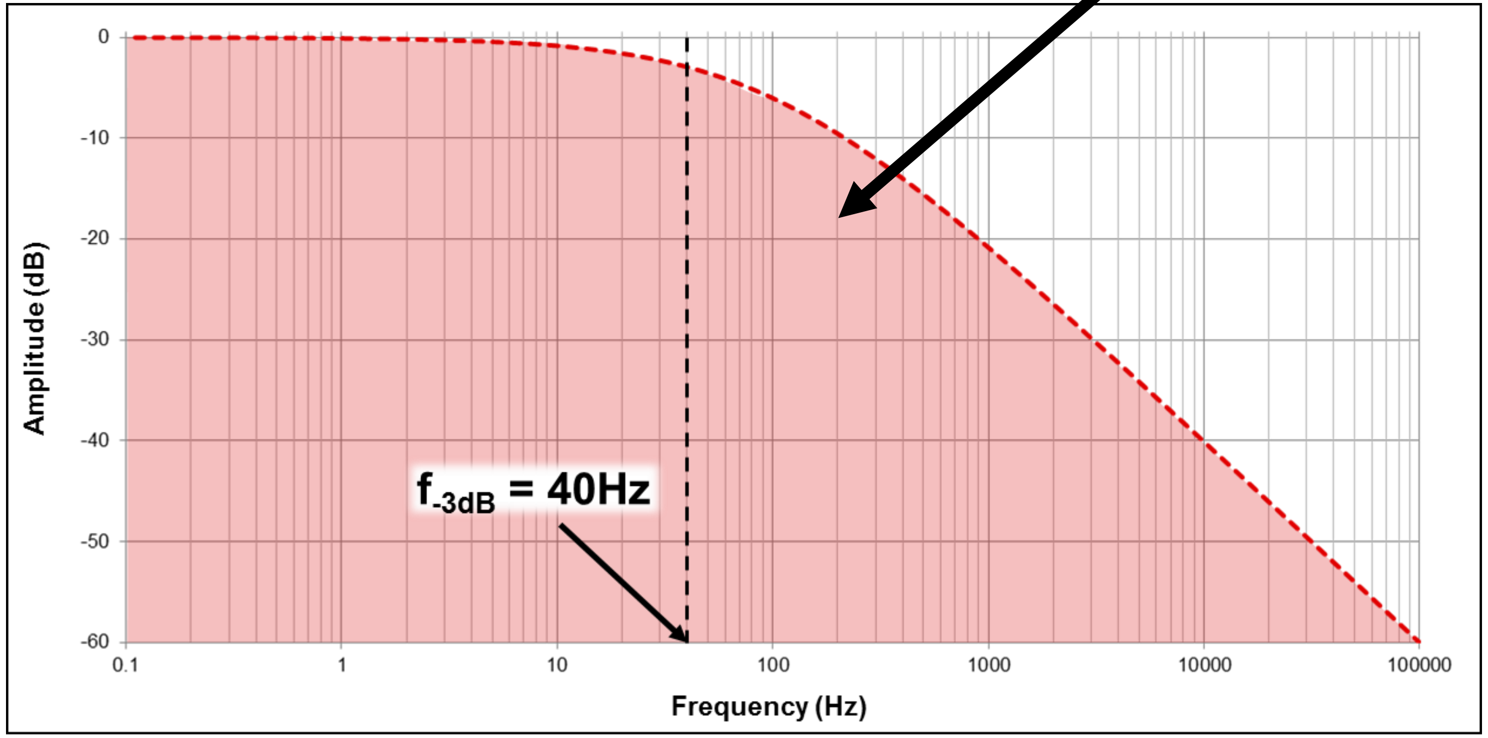


$$V_{N,Total} = \sqrt{V_{N,AMP}{}^2 + V_{N,ADC}{}^2 + V_{N,REF}{}^2}$$

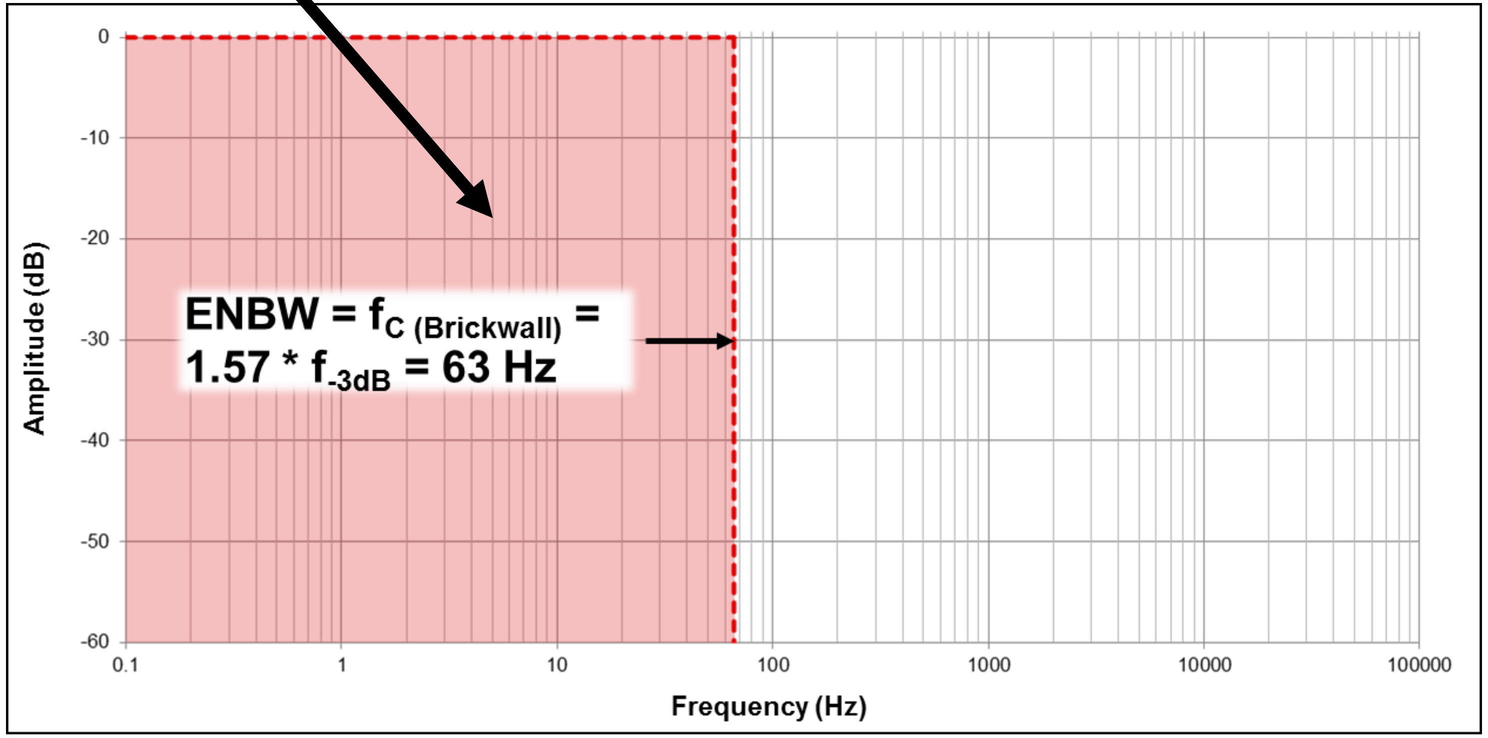
$$ex.\ V_{N,AMP} = V_{Noise\ Density\ (NSD)} * \sqrt{Bandwidth}, \qquad V_{NSD} = \frac{V_{Noise}}{\sqrt{Hz}}$$

What is effective noise bandwidth?

These filters have equal noise power



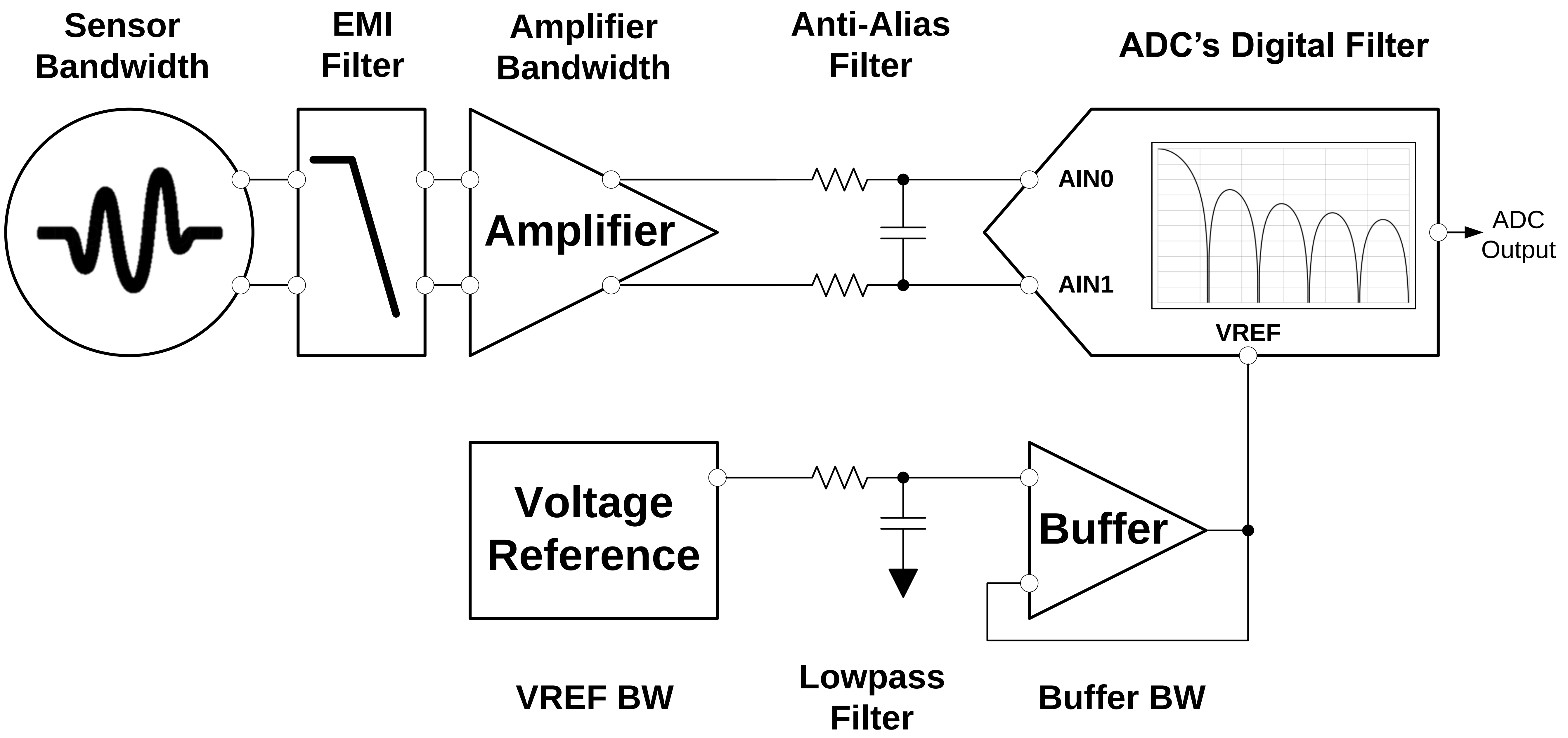
Low Pass Filter



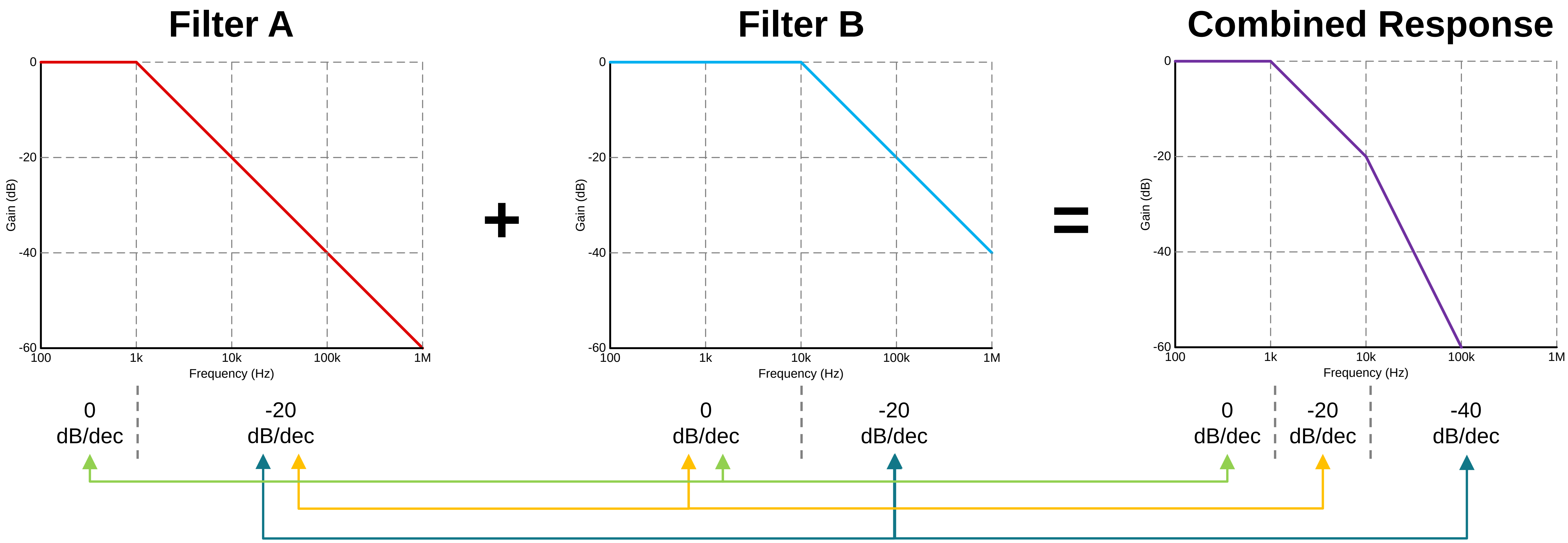
Equivalent Brickwall Filter

For more information, watch the Precision Labs video on amplifier noise

Filtering in a typical signal chain



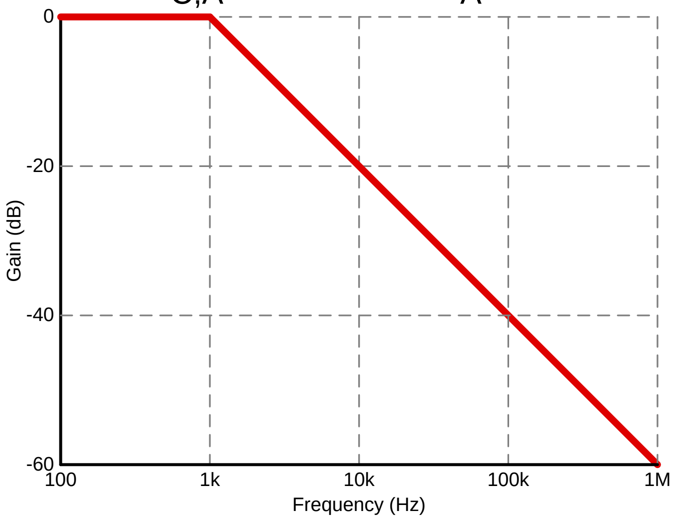
Combining filters



- Combine filters by adding decibel response point-by-point
- Adding frequency responses is transitive: **A + B = B + A**
  → **position does not matter**

Multi-stage filter frequency response approximations

$f_{C,A}$ = 1 kHz, N_A = 1



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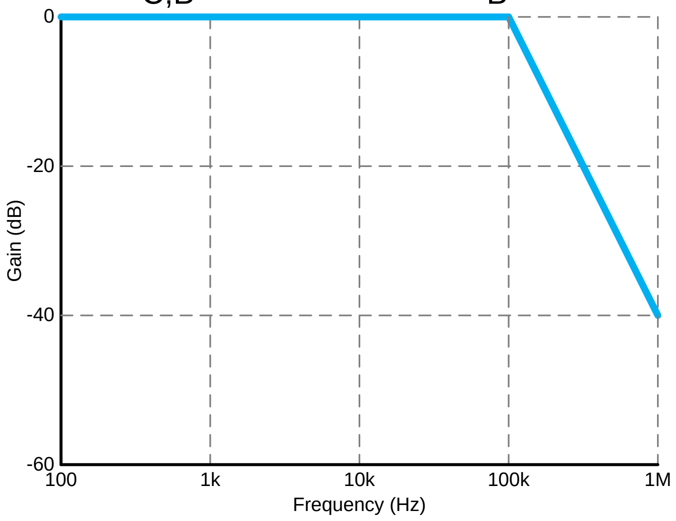
$f_{C,B}$ = 100 kHz, N_B = 2



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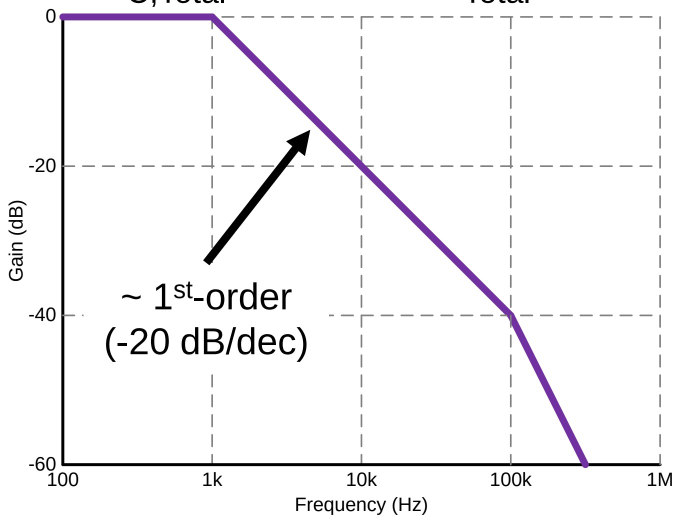
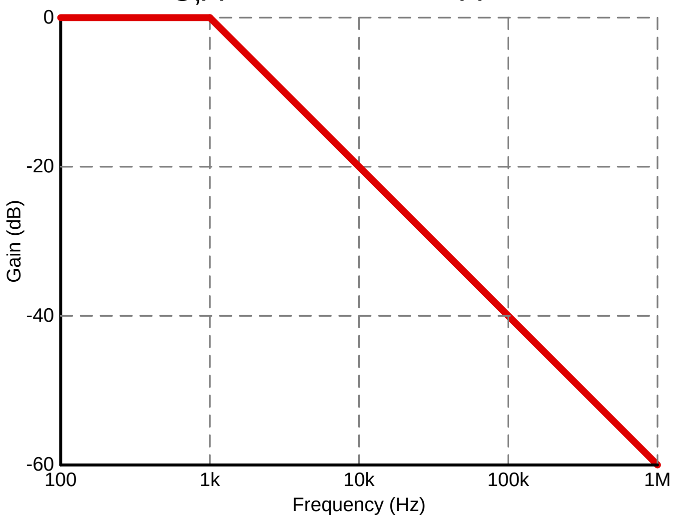
$f_{C,Total}$ ≈ 1 kHz, N_{Total} = 1



If $10*f_{C,A} \leq f_{C,B}$,
then $f_{C,Total} \approx f_{C,A}$
&
$N_{Total} \approx N_A$

$f_{C,A}$ = 1 kHz, N_A = 1



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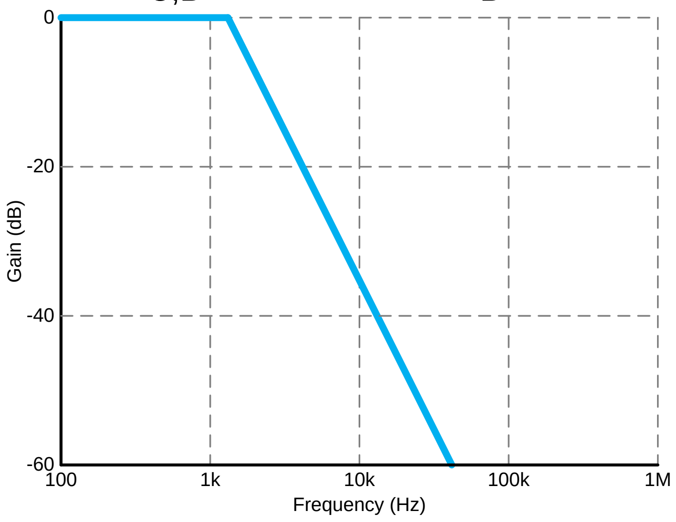
$f_{C,B}$ = 1.1 kHz, N_B = 2



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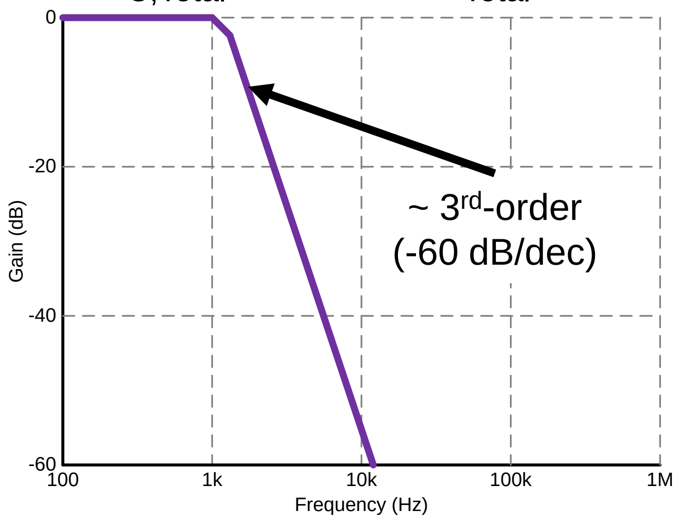
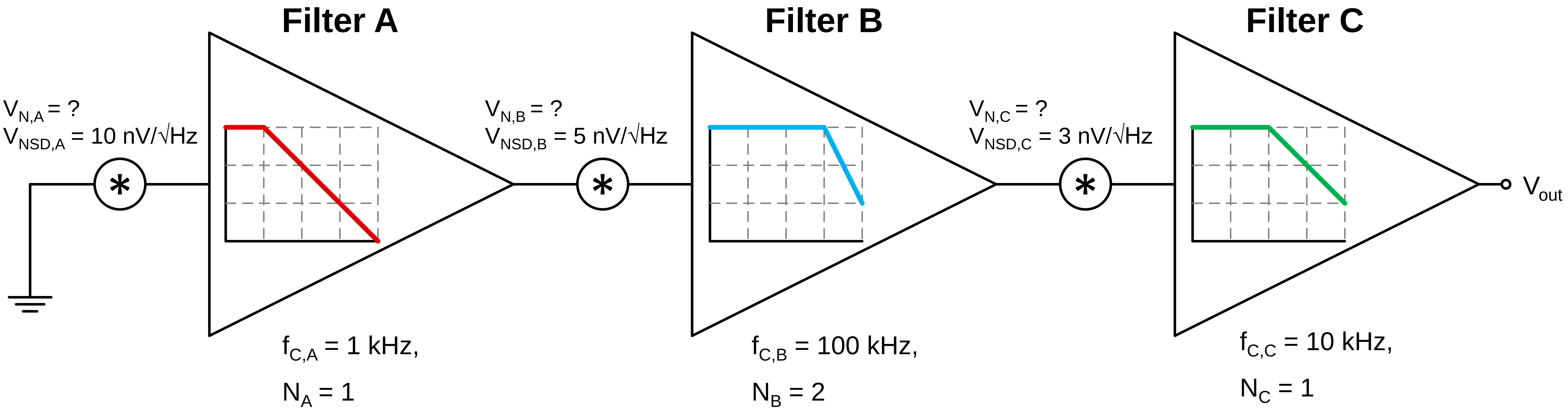
$f_{C,Total}$ ≈ 1 kHz, N_{Total} = 3



If $f_{C,A} \approx f_{C,B}$, then
$f_{C,Total} \approx f_{C,A} \approx f_{C,B}$
&
$N_{Total} \approx N_A + N_B$

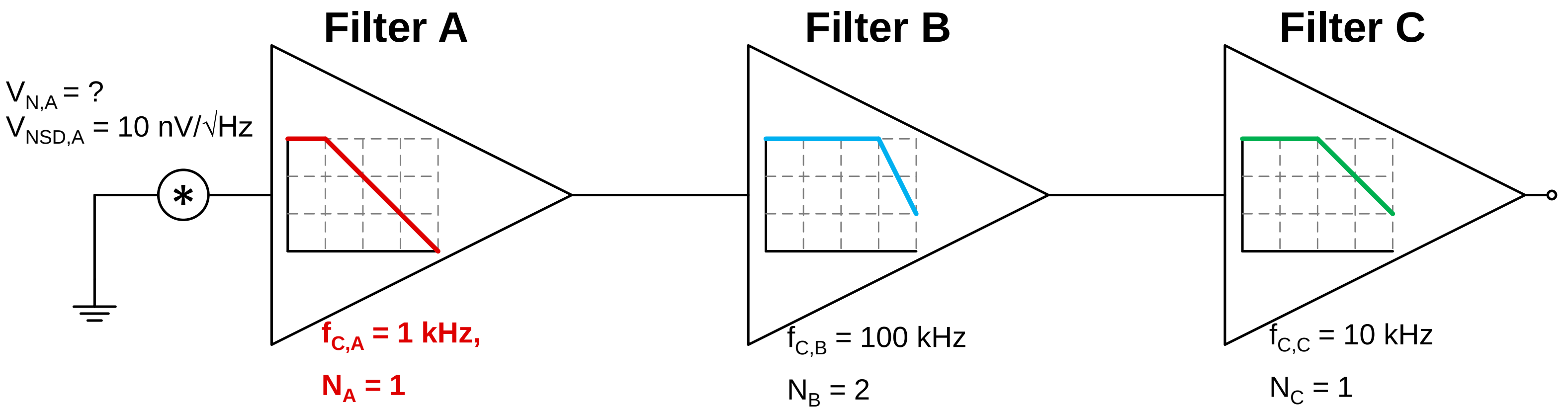
Noise analysis using multi-stage filters



$$V_{N(out)} = \sqrt{\left(V_{N,A(out)}\right)^2 + \left(V_{N,B(out)}\right)^2 + \left(V_{N,C(out)}\right)^2} \quad , \quad V_{N,x(out)} = V_{NSD,x} * \sqrt{BW_x}$$

→ Determine the BW seen by each source to calculate noise

Determining BW and noise seen by each source



- $V_{N,A}$ sees the combined BW of Filters A, B, and C
- Since $f_{C,A} << f_{C,C} << f_{C,B}$, then **$f_{Total1} \approx f_A$ & $N_{Total1} = 1$**

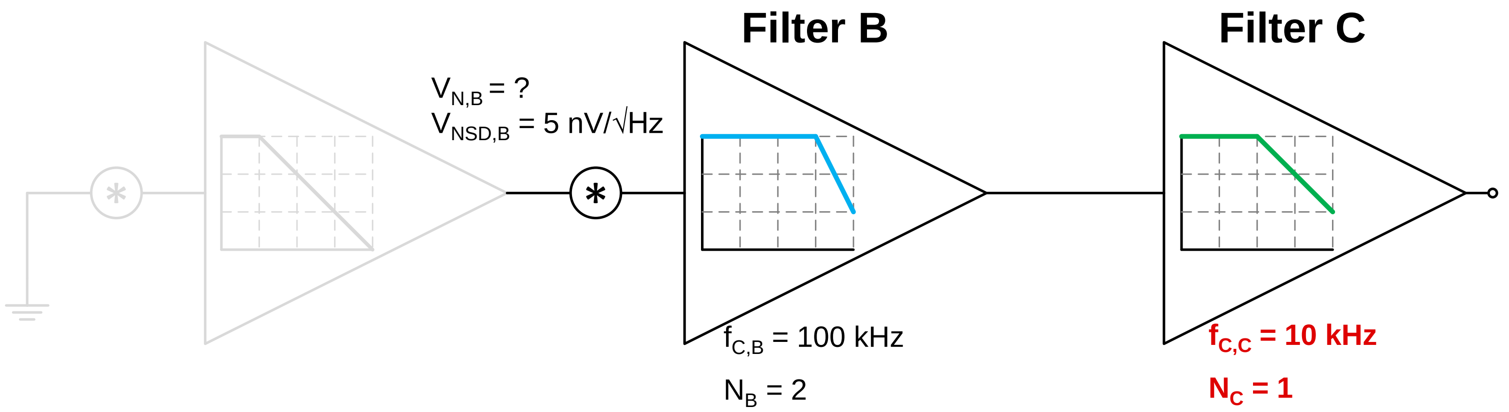
Calculation Steps for $V_{N,A}$

$$BW_A = 1.57 * f_{C,A} = 1.57\ kHz$$

$$V_{N,A(out)} = V_{NSD,A} * \sqrt{BW_A}$$

$$= 10 \frac{nV}{\sqrt{Hz}} * \sqrt{1.57\ kHz}$$

$$= \mathbf{0.4\ \mu V_{RMS}}$$



- $V_{N,B}$ sees the combined BW of Filters B and C
- Since $f_{C,C} << f_{C,B}$, then **$f_{Total2} \approx f_C$ & $N_{Total2} = 1$**

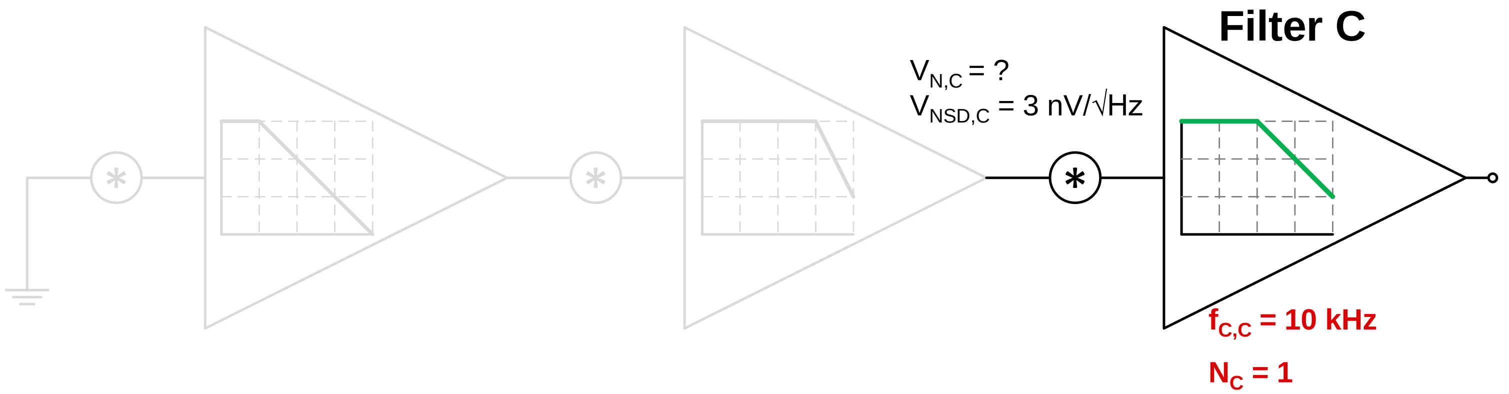
Calculation Steps for $V_{N,B}$

$$BW_B = 1.57 * f_{C,C} = 15.7\ kHz$$

$$V_{N,B(out)} = V_{NSD,B} * \sqrt{BW_B}$$

$$= 5 \frac{nV}{\sqrt{Hz}} * \sqrt{15.7\ kHz}$$

$$= \mathbf{0.63\ \mu V_{RMS}}$$



- $V_{N,C}$ only sees Filter C
- So, **$f_{Total3} \approx f_C$ & $N_{Total3} = 1$**

Calculation Steps for $V_{N,C}$

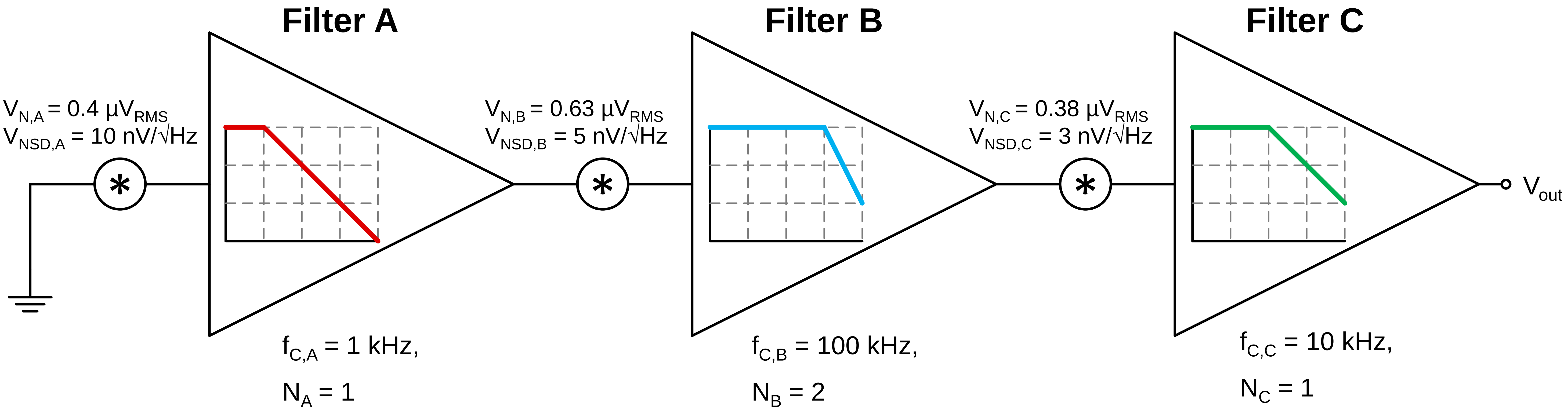
$$BW_C = 1.57 * f_{C,C} = 15.7\ kHz$$

$$V_{N,C(out)} = V_{NSD,C} * \sqrt{BW_C}$$

$$= 3 \frac{nV}{\sqrt{Hz}} * \sqrt{15.7\ kHz}$$

$$= \mathbf{0.38\ \mu V_{RMS}}$$

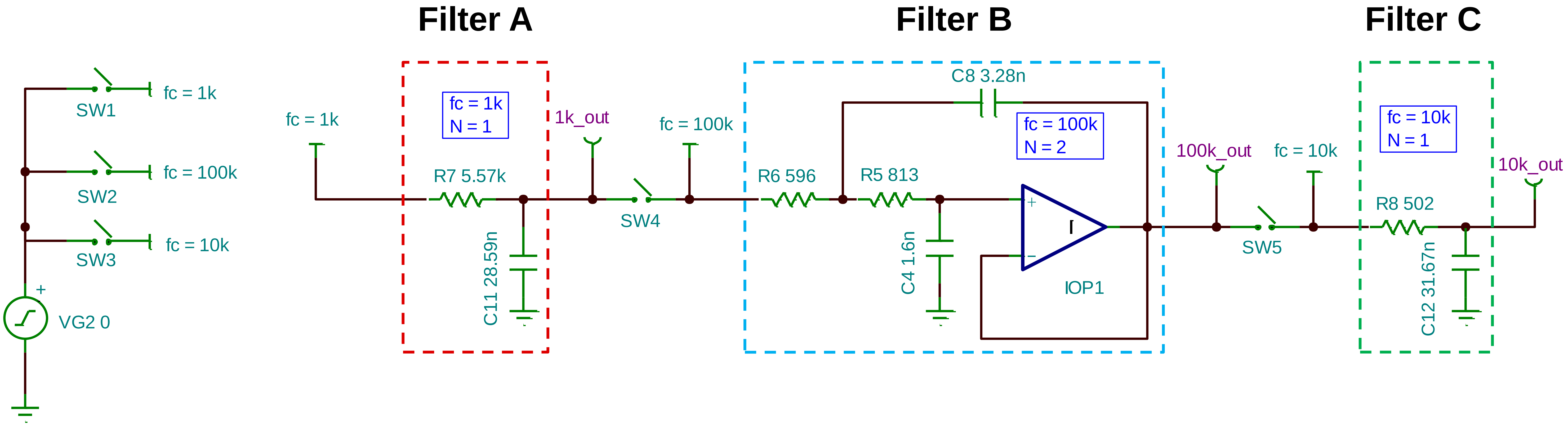
Total noise



$$V_{N(out)} = \sqrt{\left(V_{N,A(out)}\right)^2 + \left(V_{N,B(out)}\right)^2 + \left(V_{N,C(out)}\right)^2}$$

$$V_{N(out)} = \sqrt{(0.4)^2 + (0.63)^2 + (0.38)^2} = \mathbf{0.84\ \mu V_{RMS}}$$

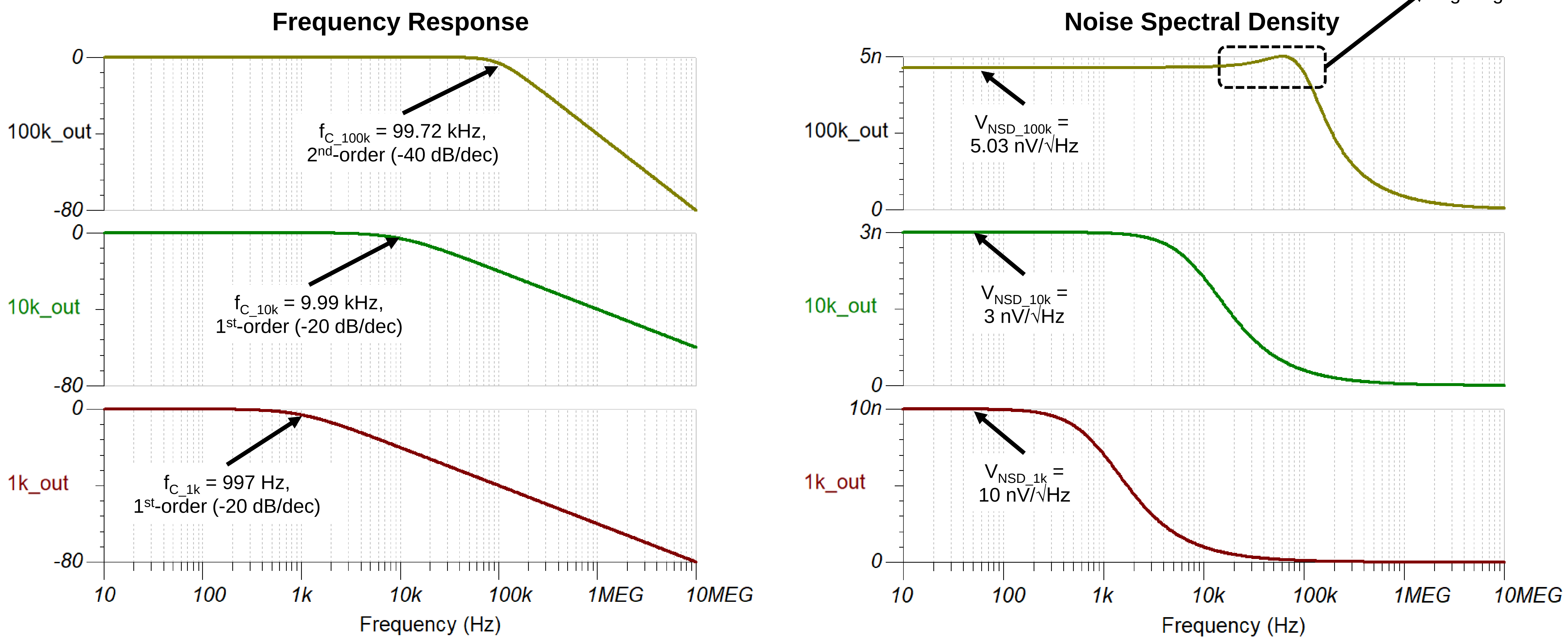
Simulating the filter system



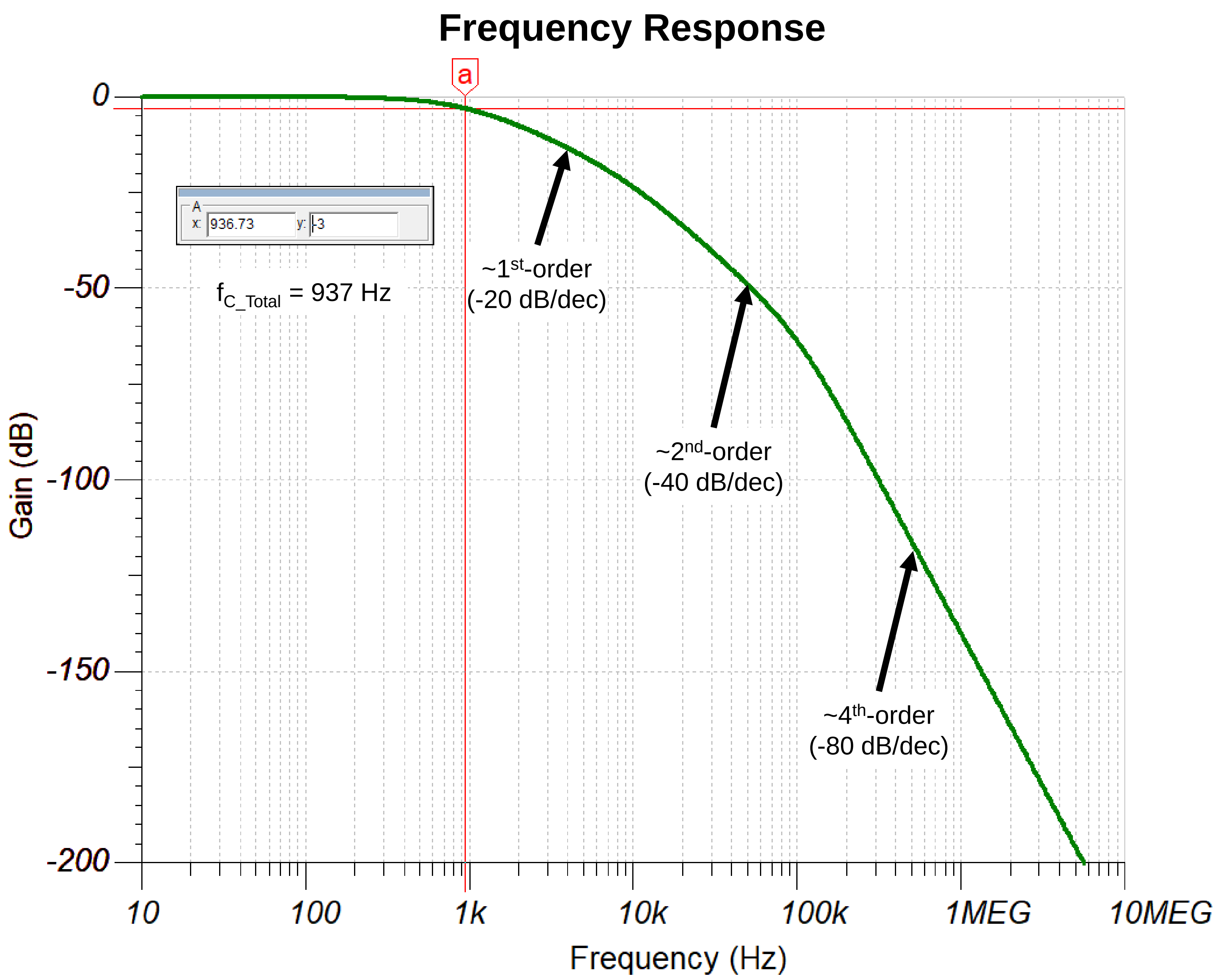
Important circuit notes:

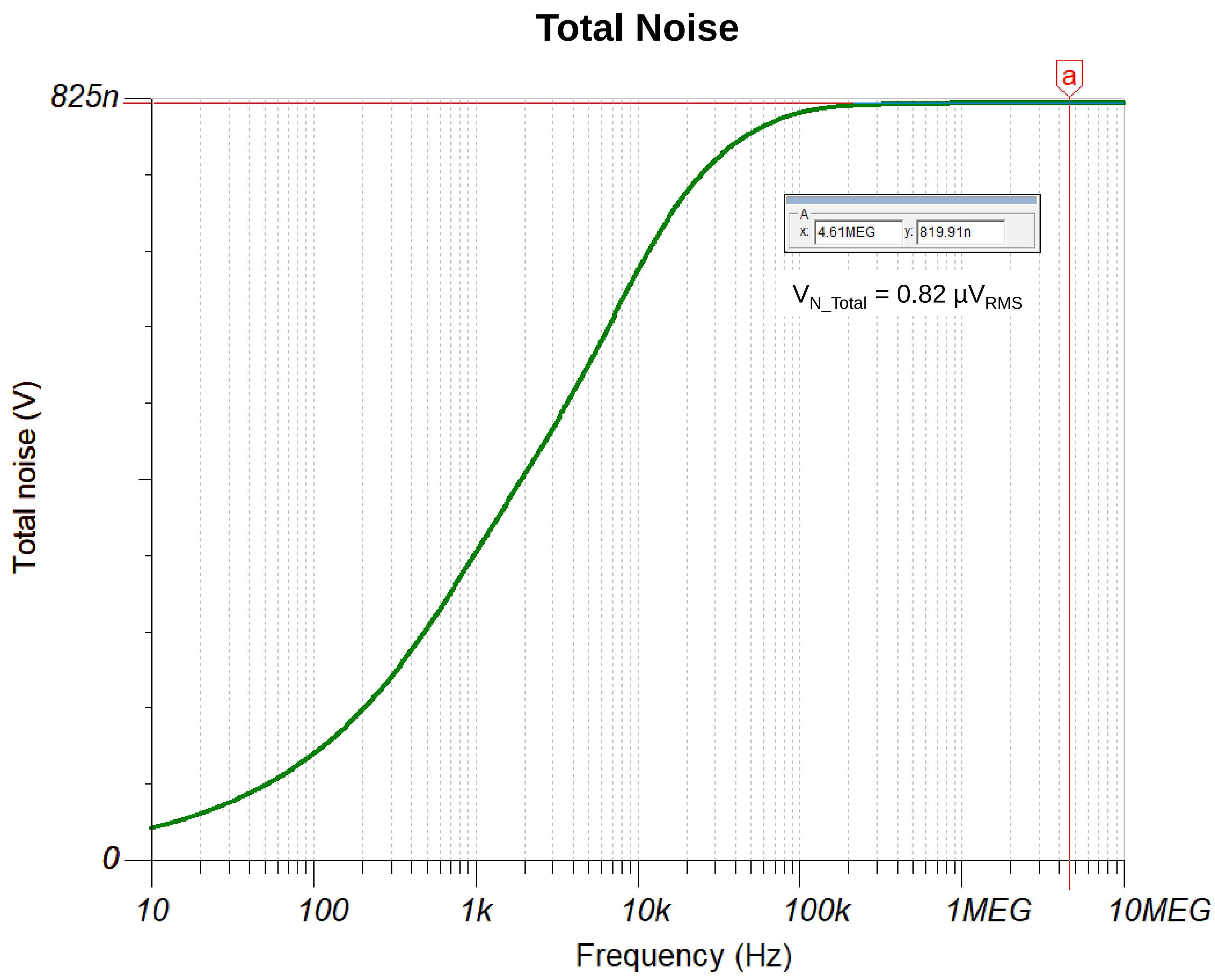
- Second-order Butterworth filter designed using TI's Filter Design Tool
- Ideal op amp used to keep noise analysis simple – more on next slide
- Switches enable simulation of each component and entire system
  - ex. Close SW3 to simulate only Filter C

Simulated results for discrete filters

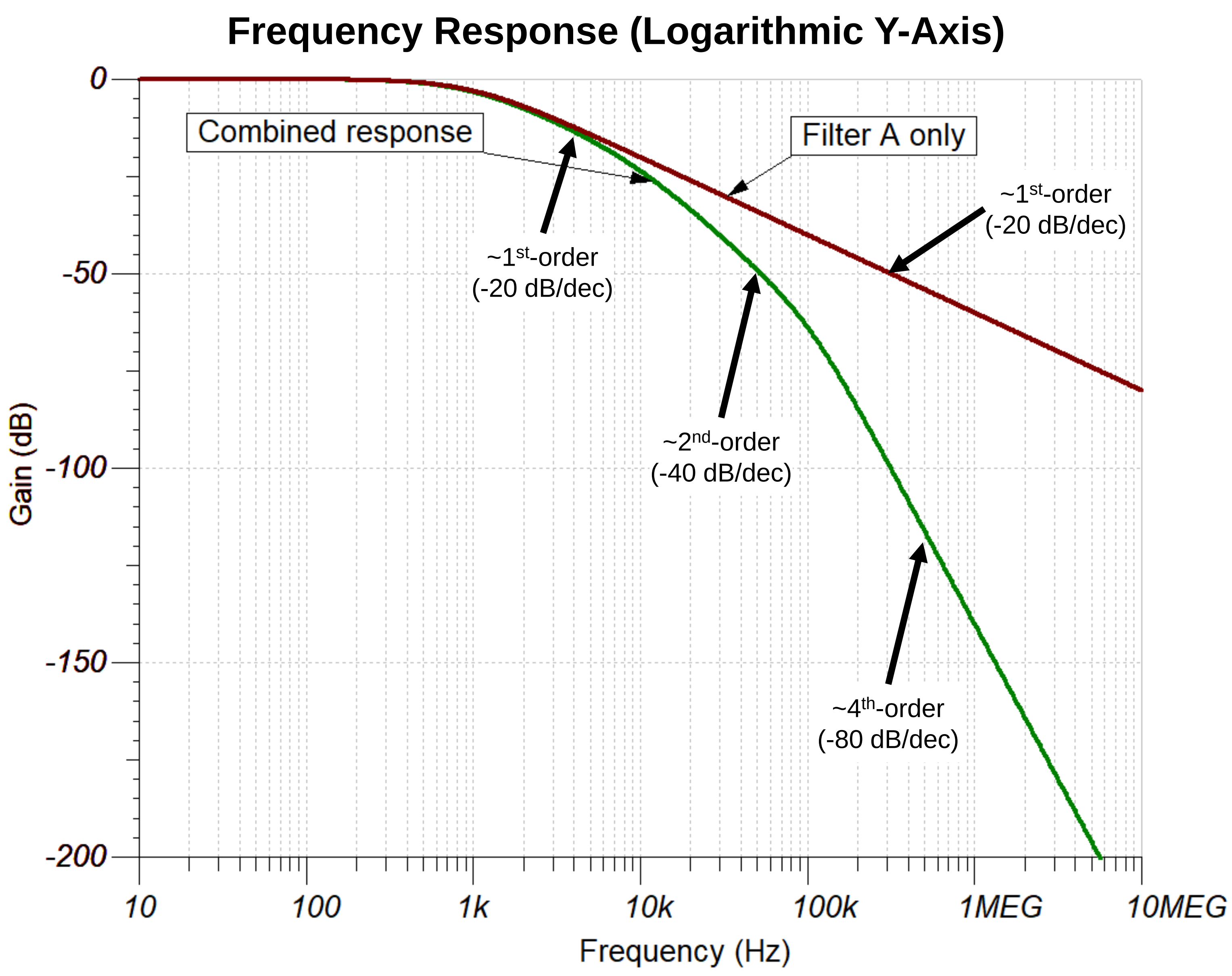


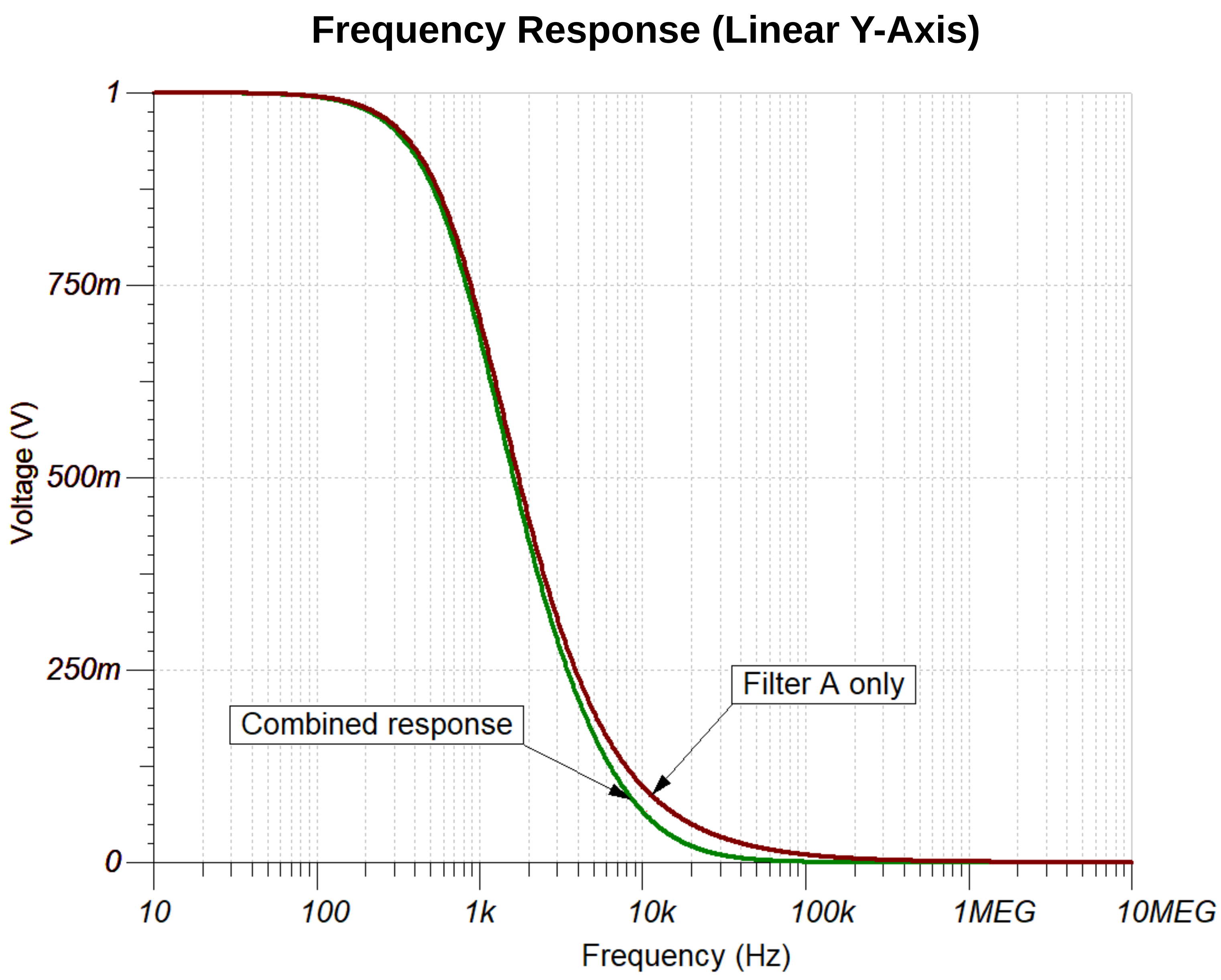
Simulated results for combined filter system





Verifying the approximations

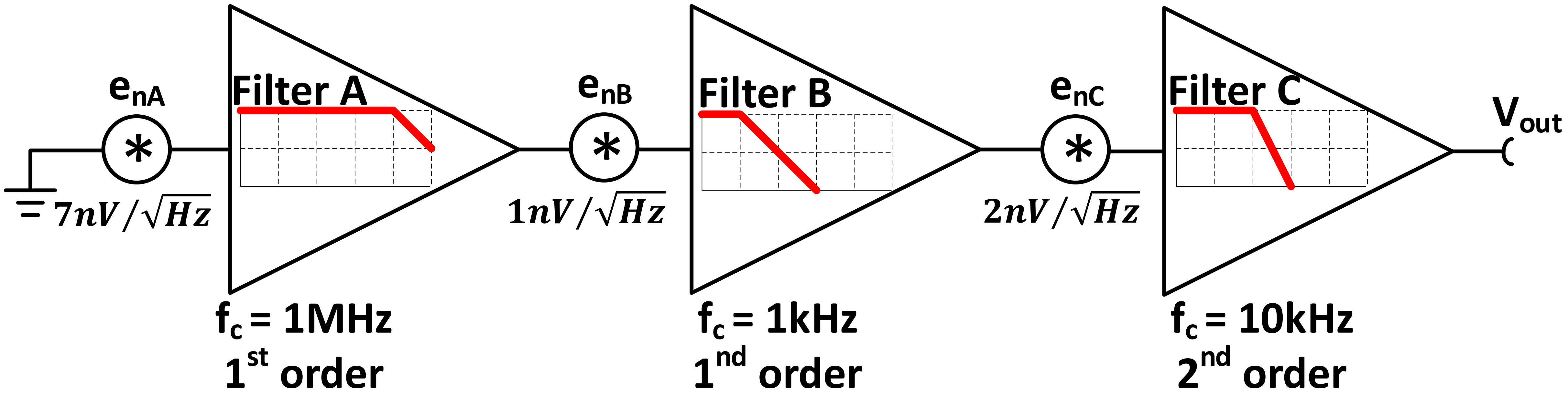




Thanks for your time! Please try the quiz.

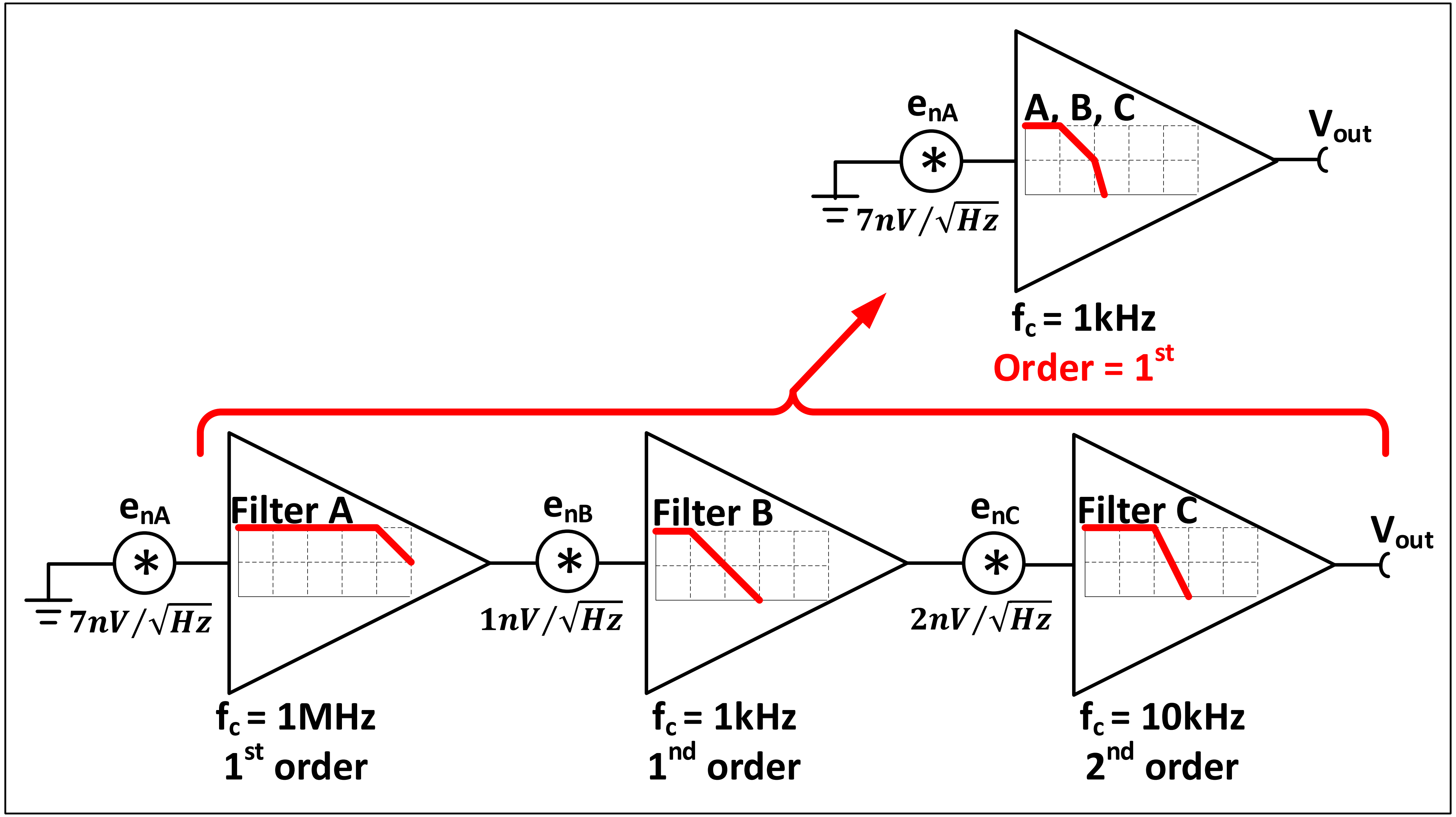
Quiz: Noise bandwidth in ADC systems

1. For the circuit below, what is the effective cutoff frequency seen by signal source e_{nA} to the output Vout?
   a. 1kHz
   b. 10kHz
   c. 100kHz
   d. 1MHz



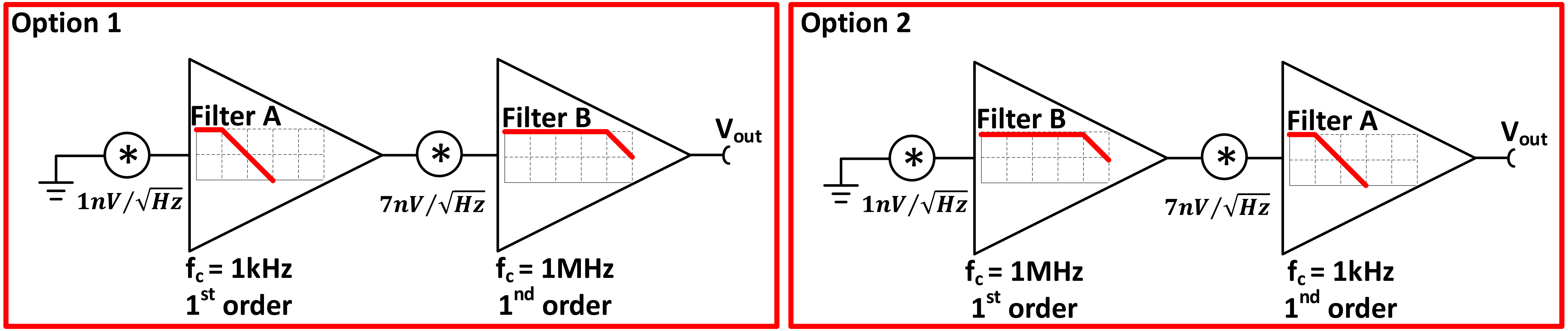
Quiz: Noise bandwidth in ADC systems

2. Combining filter stages A, B, and C below form a 1kHz filter. What is the order of this filter?
   - a. 1st order
   - b. 2nd order
   - c. 3rd order
   - d. 4th order



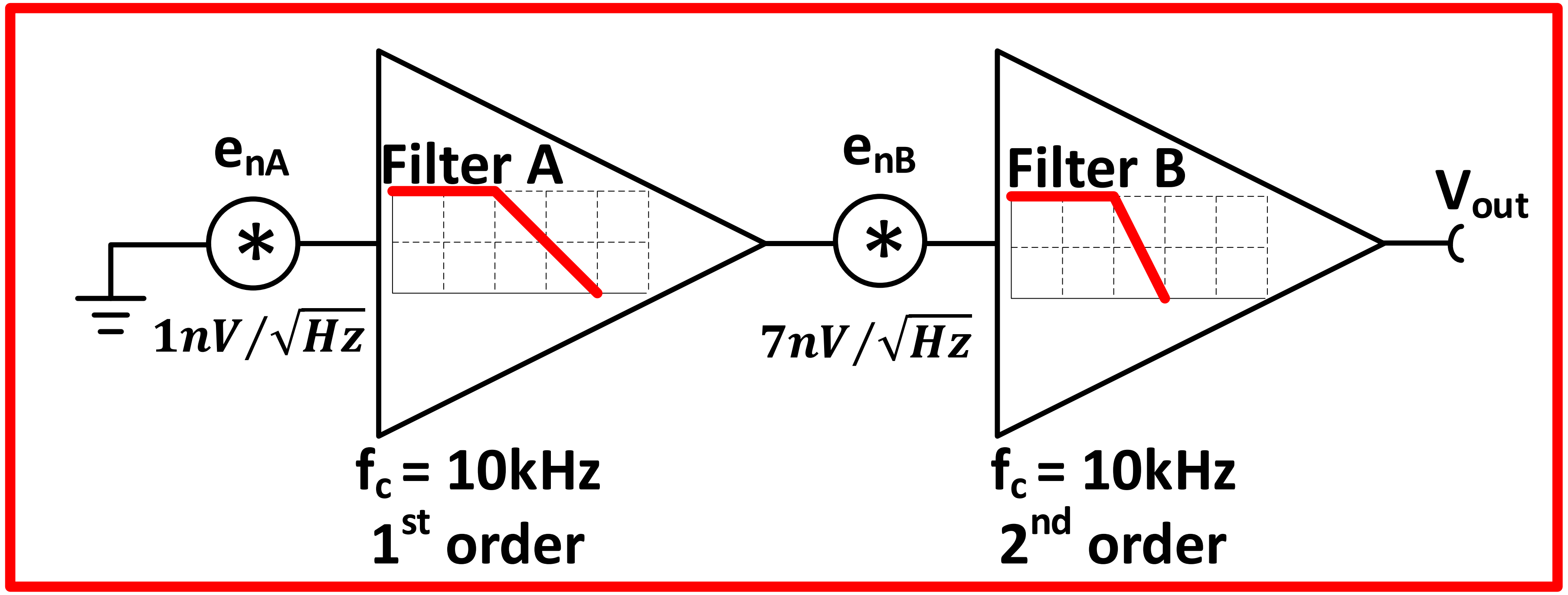
Quiz: Noise bandwidth in ADC systems

3. The two circuits below are identical except that the position of filter A and B are swapped. Which circuit will have the lowest noise total noise? Note that both noise sources are included in the analysis.
   a. They are both the same from a noise perspective
   b. Option 1 is better
   c. Option 2 is better



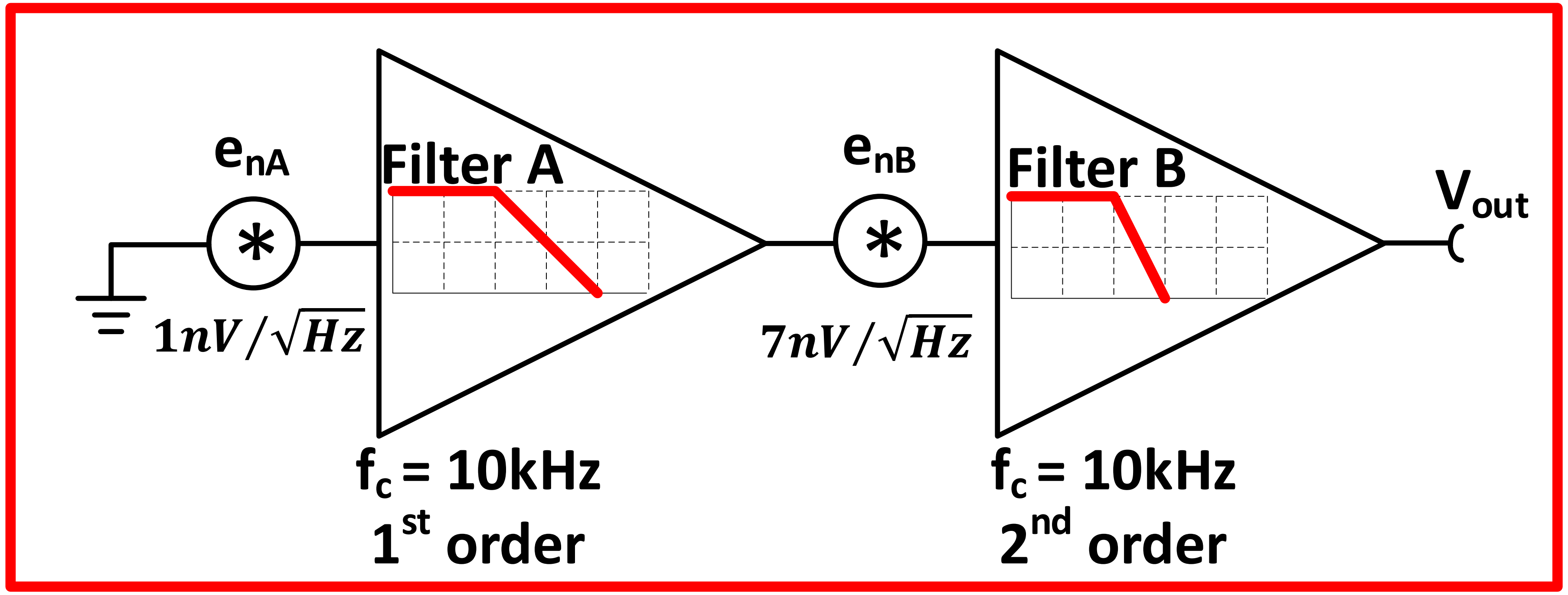
Quiz: Noise bandwidth in ADC systems

4. For the circuit below, what is the effective cutoff frequency seen by signal source e_{nA} to the output Vout?
   a. 1kHz
   b. 5kHz
   c. 10kHz
   d. 20kHz



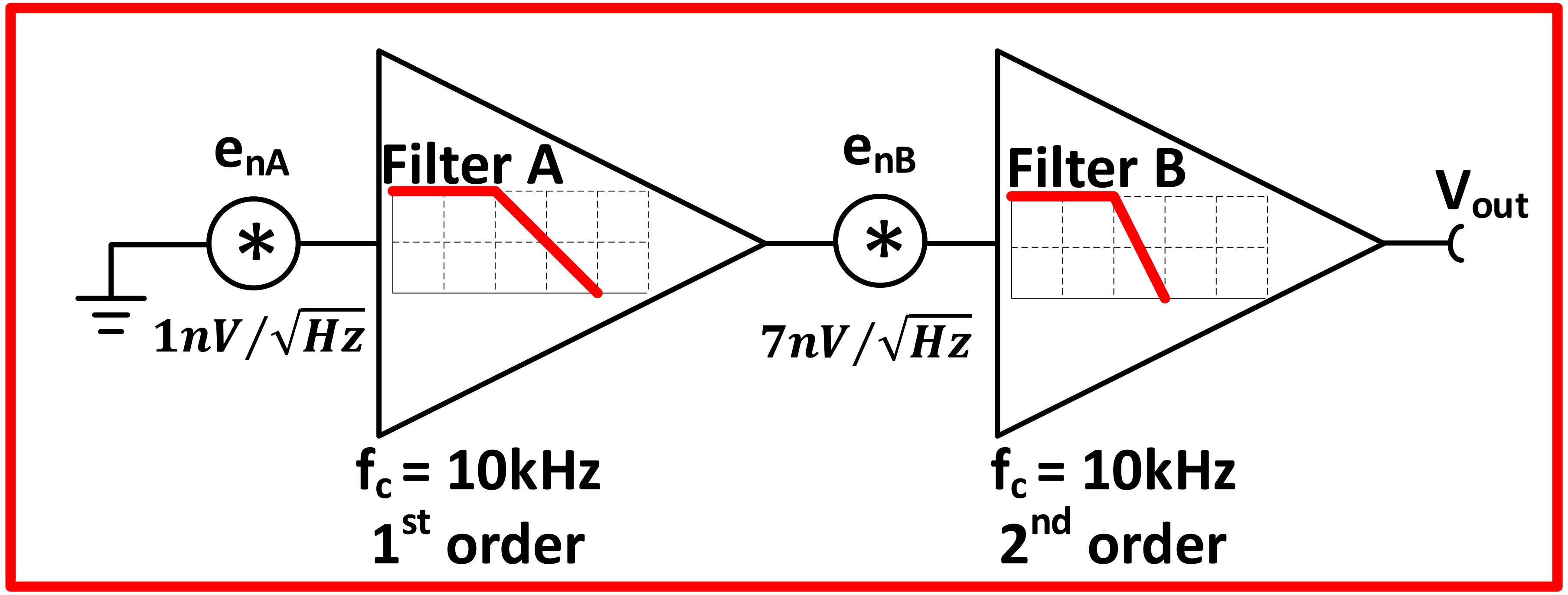
Quiz: Noise bandwidth in ADC systems

5. Combining filter stages A, B, and C below form a 10kHz filter. What is the order of this filter?
   a. 1st order
   b. 2nd order
   c. 3rd order
   d. 4th order



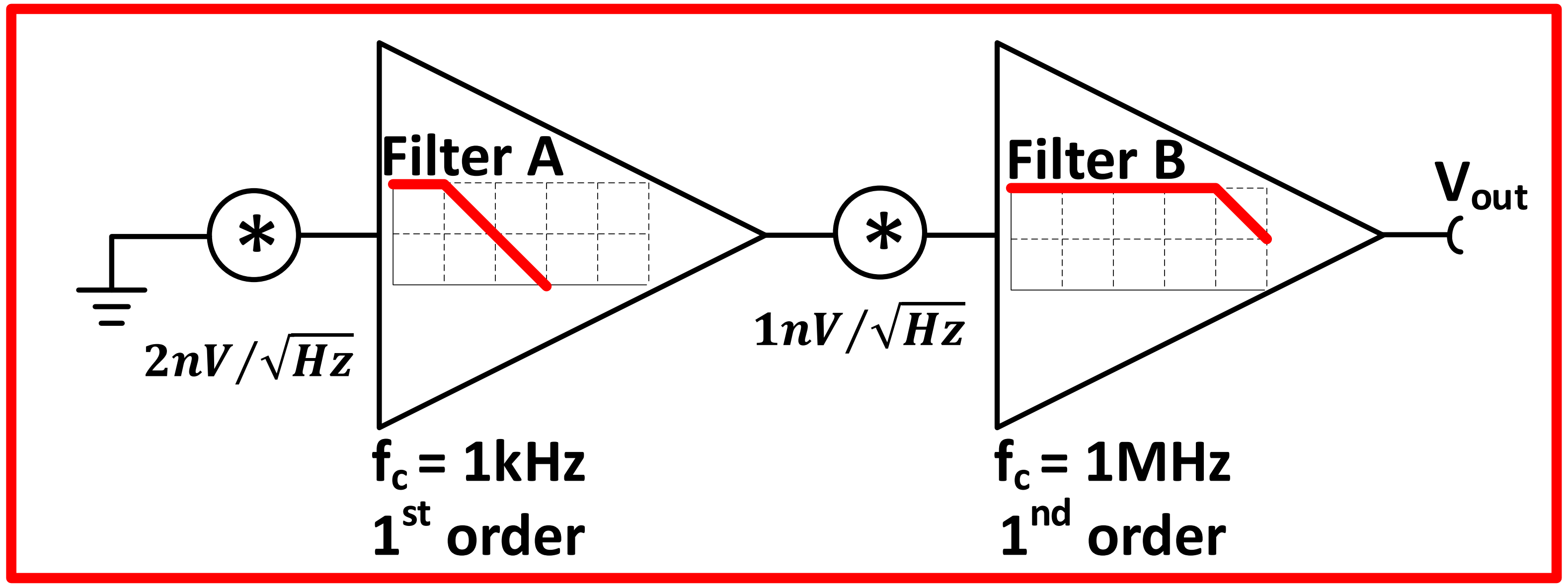
Quiz: Noise bandwidth in ADC systems

5. Combining filter stages A, B, and C below form a 10kHz filter. What is the order of this filter?
   a. 1st order
   b. 2nd order
   c. 3rd order
   d. 4th order



Quiz: Noise bandwidth in ADC systems

6. Find the total integrated noise for the circuit below. Include the effects of both noise sources.
   a. 0.079µV rms
   b. 0.159µV rms
   c. 0.825µV rms
   d. 1.26µV rms
   e. 2.15µV rms



$$f_{c\_A} := 1\ kHz \qquad e_{nA} := 2\ \frac{nV}{\sqrt{Hz}}$$

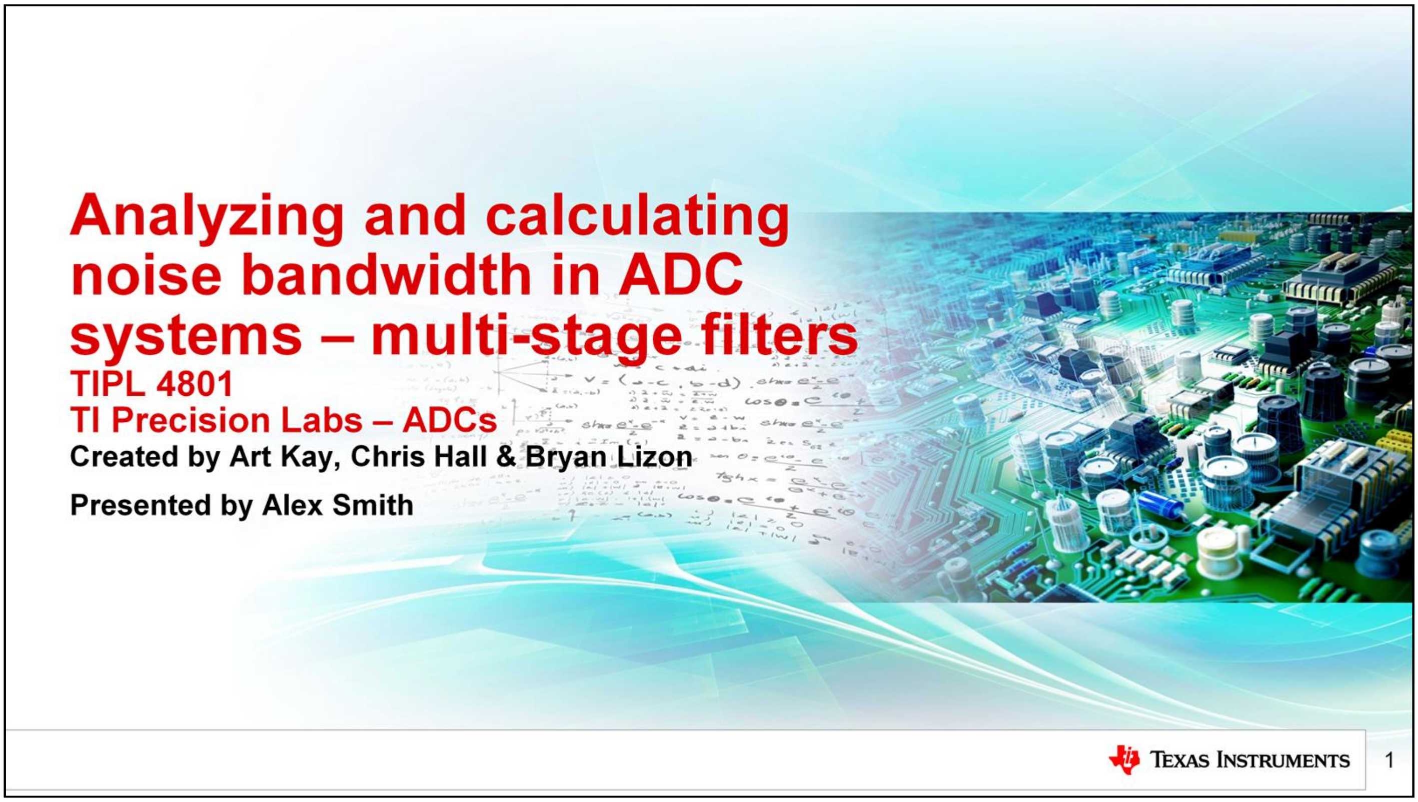
$$V_{outA} := 2\ \frac{nV}{\sqrt{Hz}} \cdot \sqrt{1.57 \cdot 1\ kHz} = 0.079\ \mu V$$

$$f_{c\_B} := 1\ MHz \qquad e_{nA} := 1\ \frac{nV}{\sqrt{Hz}}$$

$$V_{outB} := 1\ \frac{nV}{\sqrt{Hz}} \cdot \sqrt{1.57 \cdot 1\ MHz} = 1.253\ \mu V$$

$$V_{out\_Total} := \sqrt{V_{outA}^{\ 2} + V_{outB}^{\ 2}} = 1.255\ \mu V$$

Thanks for your time!

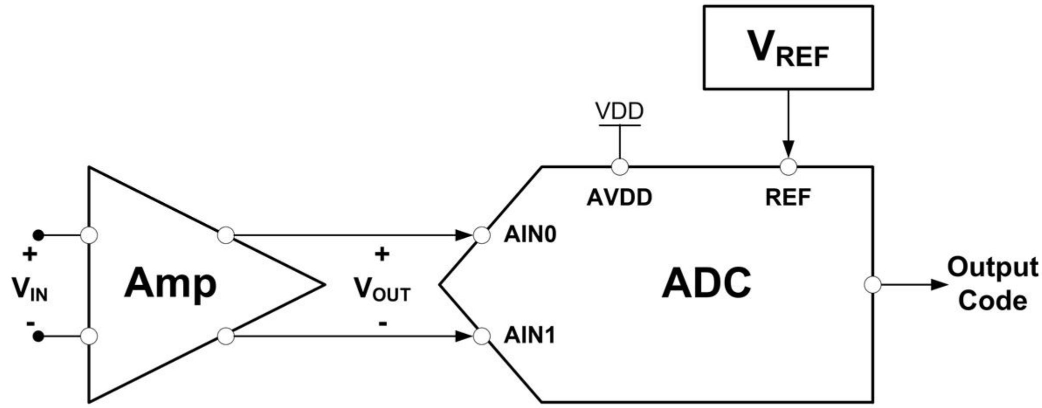


Hello, and welcome to the TI Precision Lab that introduces the concept of effective noise bandwidth in a signal chain. In this module, we will discuss what effective noise bandwidth is, where it comes from in your system, and how to calculate and simulate the combined frequency response and noise density of multi-stage filters.

In a subsequent presentation on effective noise bandwidth, we will analyze a delta-sigma ADC's digital filter frequency response, and its combined affect with a first-order lowpass filter, to better understand how to calculate total system noise.

The goal for these effective noise bandwidth Precision Labs modules will be to apply the knowledge from these examples to help determine the total noise in your next signal chain design.

Basic data acquisition system noise calculation



$$V_{N,Total} = \sqrt{V_{N,AMP}{}^2 + V_{N,ADC}{}^2 + V_{N,REF}{}^2}$$

$$ex.\ V_{N,AMP} = V_{Noise\ Density\ (NSD)} * \sqrt{Bandwidth}, \qquad V_{NSD} = \frac{V_{Noise}}{\sqrt{Hz}}$$

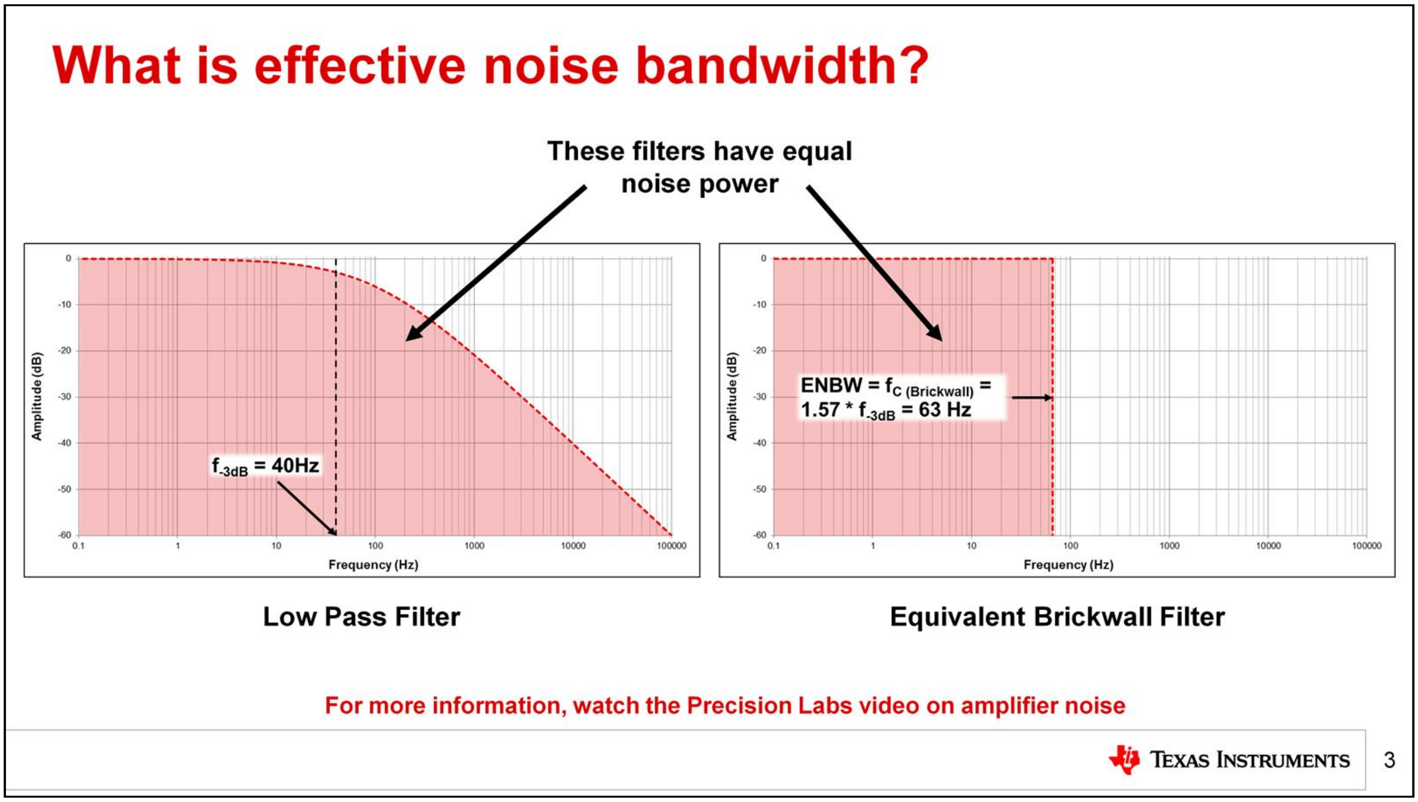
TEXAS INSTRUMENTS 2

To begin, let's revisit the simple data acquisition system used as the basis for the analysis throughout the ADC noise presentations. We previously made the claim that these three components, the ADC, amplifier and voltage reference, generally contribute the most noise in your signal chain. In order to calculate the total noise of this system, you would take the root sum square of each component's individual noise contribution using the equation shown here. But how do you calculate the amount of noise each component contributes? And can you just read noise values directly from each component's datasheet?

Unfortunately this is not always possible. Sometimes noise is given over a specific frequency range, such as 0.1 to 10 Hz, which may not cover your system's requirements. Or, as shown in the amplifier noise equation at the bottom of the screen, noise can be specified as a spectral density instead of an RMS or peak to peak value. Noise spectral density generalizes the relationship between noise power and frequency and has the units of noise per root Hertz. Therefore, you need to know the system bandwidth in order to calculate the amplifier's noise contribution in this example. However, the amount of noise filtering applied to each component is often different, as multiple filtering stages combine to act on an individual component. Moreover, the input signal and reference input paths can behave differently, depending on the filtering applied. In either case, you must calculate an effective noise bandwidth for each component in the signal path to determine its noise contribution.

As stated on the previous slide, the focus of this presentation will be on understanding the concept of noise bandwidth and how filters combine to act on one or more noise sources in your system. Therefore, you will not need a detailed understanding of ADC, amplifier or voltage reference noise to continue. However, you can view the Precision Labs modules on these topics if you want to learn more.

Let's now quickly review what effective noise bandwidth is.

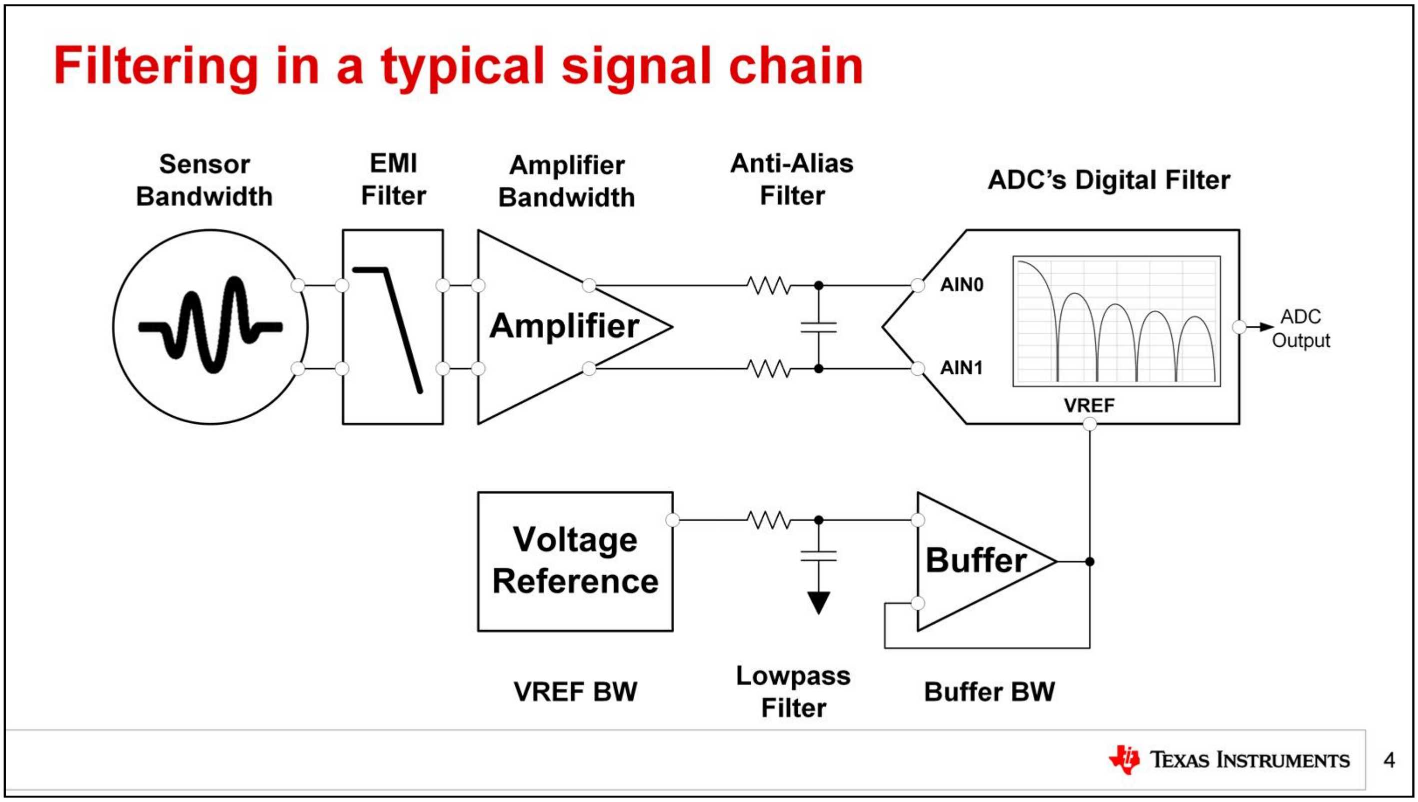


Effective noise bandwidth is a mathematical approximation that helps simplify the calculations that determine how much noise each component passes into a signal chain. The effective noise bandwidth of any component or system is the cutoff frequency of an ideal, brickwall filter whose noise power is approximately equivalent to the noise power of the original filter. The "brickwall" approximation accounts for non-ideal filters allowing frequencies beyond the cutoff pass into the rest of the system. Using this method provides a much more accurate result when calculating the total amount of noise that is able to pass through the filter.

For example, the 40 Hz lowpass filter shown on the left side of this slide has an effective noise bandwidth of 63 Hz, as shown in the plot on the right. The scaling factor of 1.57 is an approximation for determining a first-order lowpass filter's effective bandwidth from its cutoff frequency.

For more information about how this scaling factor is derived as well as calculating the cutoff frequency for different filter types, please review the Precision Labs modules on amplifier noise.

Let's now take these principles and apply them to an entire system.

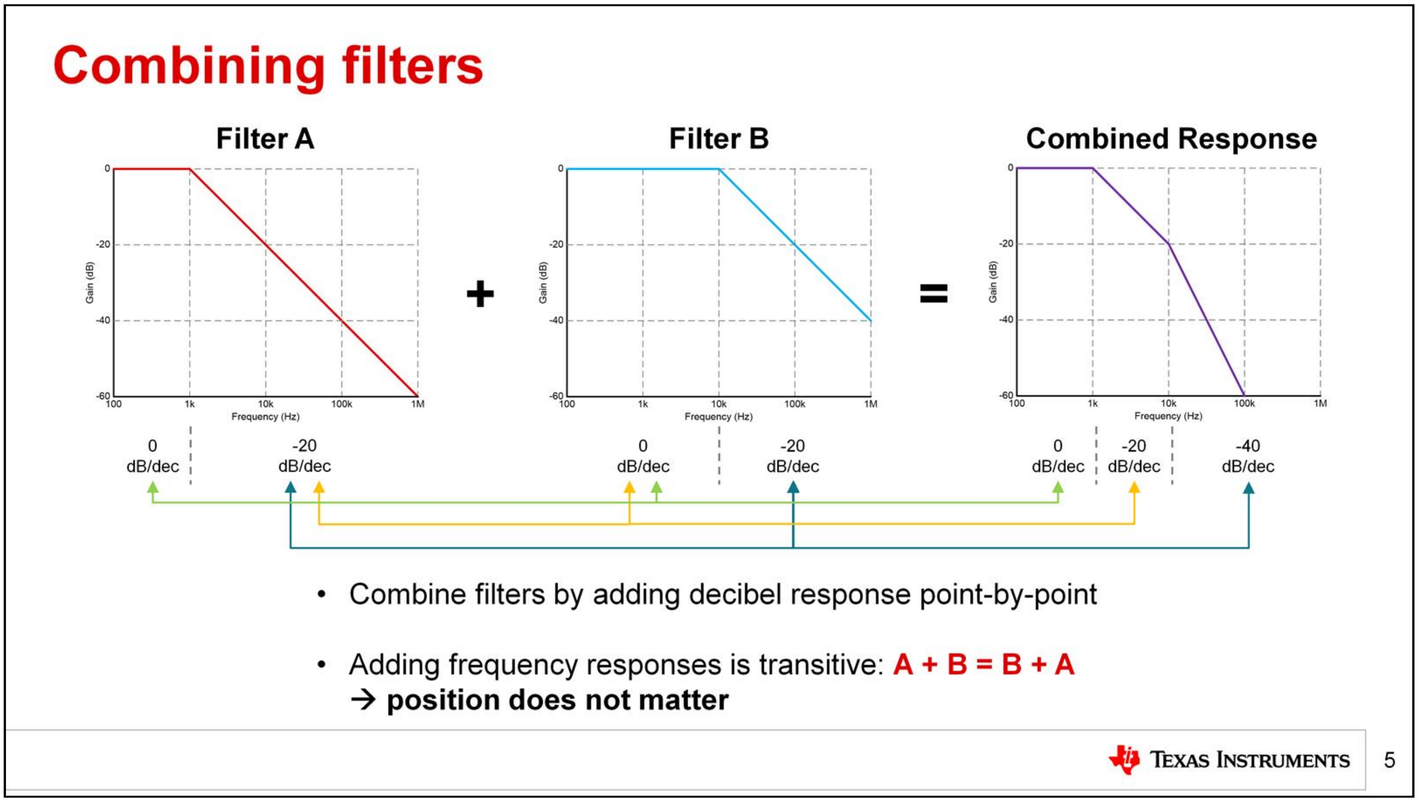


Here is a more complete view of a typical analog signal chain, showing two distinct input paths. Each stage in these paths has some definable bandwidth that acts as a filter

The signal chain filter path can include the bandwidth of the sensor being measured; the cutoff of any electromagnetic interference (EMI) filters; the bandwidth of any amplifiers in the signal chain; the cutoff frequency of the anti-aliasing filter; and finally, any digital filters integrated into an ADC. The second input path is from the voltage reference, which also has some definable bandwidth, and generally includes a lowpass filter at the output to limit how much voltage reference noise enters the system. A buffer might also be included to ensure proper settling and ADC performance for higher-speed data acquisition.

Not all filter types need to be included in every data acquisition system. For example, both wideband and low speed delta-sigma ADCs integrate a digital filter as part of their conversion architecture, whereas SAR converters typically do not. Additionally, all of these components contribute some noise to the circuit, as well as help filter noise from previous stages. As a result, it is possible that the ADC noise will have a different noise bandwidth compared to the amplifier, for example.

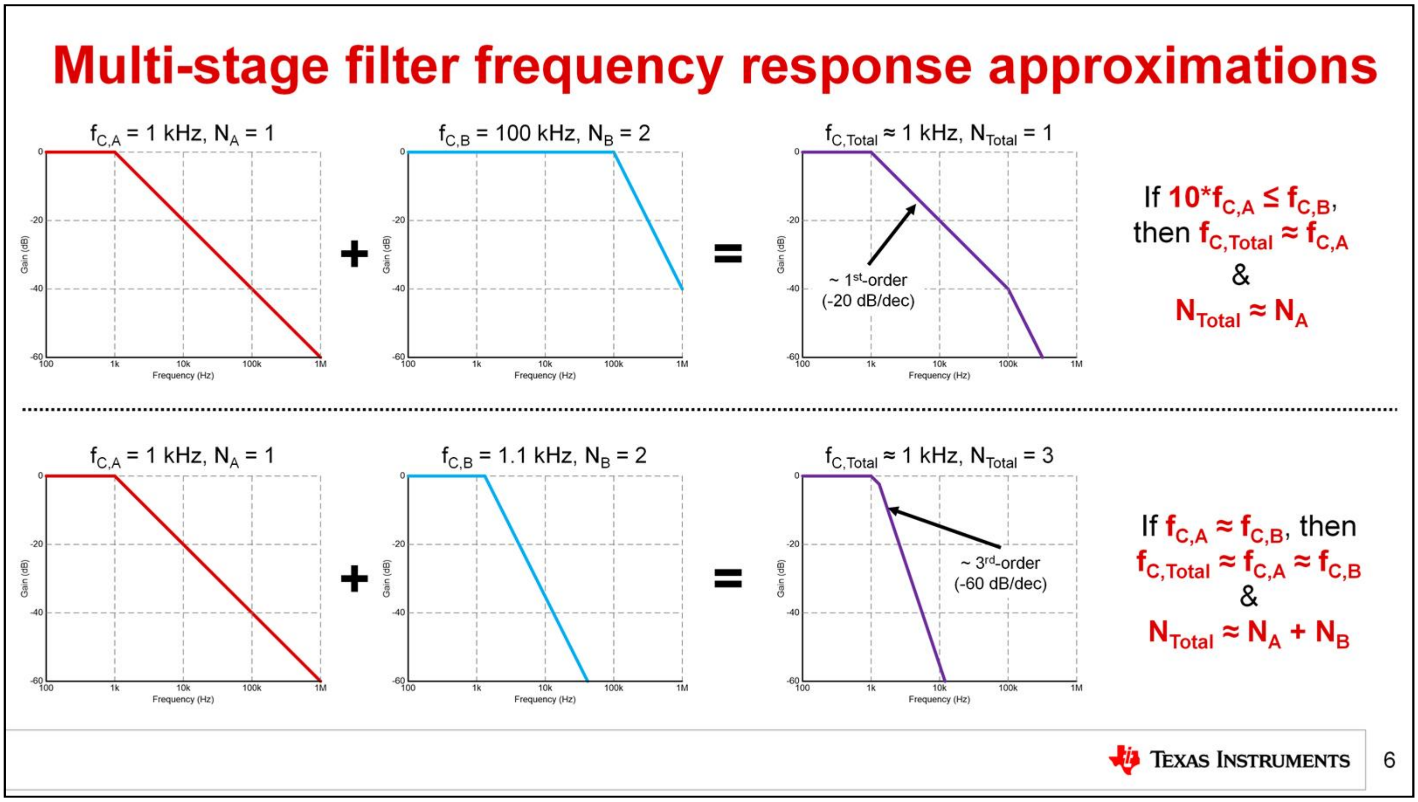
So how can you determine the effective noise bandwidth seen by each component in both the signal and reference paths shown here? And how does this help you calculate the noise performance of your system? To answer these questions, it is necessary to understand how to combine different filtering sources using frequency response plots.



Shown here are two arbitrary frequency response plots for Filter A in red and Filter B in blue. Filter A could represent the EMI filter shown on the previous slide, while Filter B could represent the anti-aliasing filter, for example.

To determine the cumulative affect of both filters, you can combine them by adding their decibel responses point-by-point. The purple plot on the right side of the screen represents this combined response. Note that the combined response looks like Filter A until approximately 10 kHz where it begins to roll off at -40 dB per decade. Also note that while only simple, first-order lowpass filters are shown here, combining filters of any type can be completed using this technique assuming that each plot is expressed in decibels. Moreover, this technique can be applied to more than two filters.

Also, since you are adding point-by-point, the position of Filter A compared to Filter B does not matter. If Filter B was actually the EMI filter and Filter A was the anti-aliasing filter shown in the signal chain on the previous slide, filtering seen by a noise source prior to the EMI filter would still be represented by the combined response shown here. This result is important as it allows you to approximate your system's effective bandwidth given various filter types, regardless of the position of those filters in your signal chain. We will explore some of these approximations on the next slide.

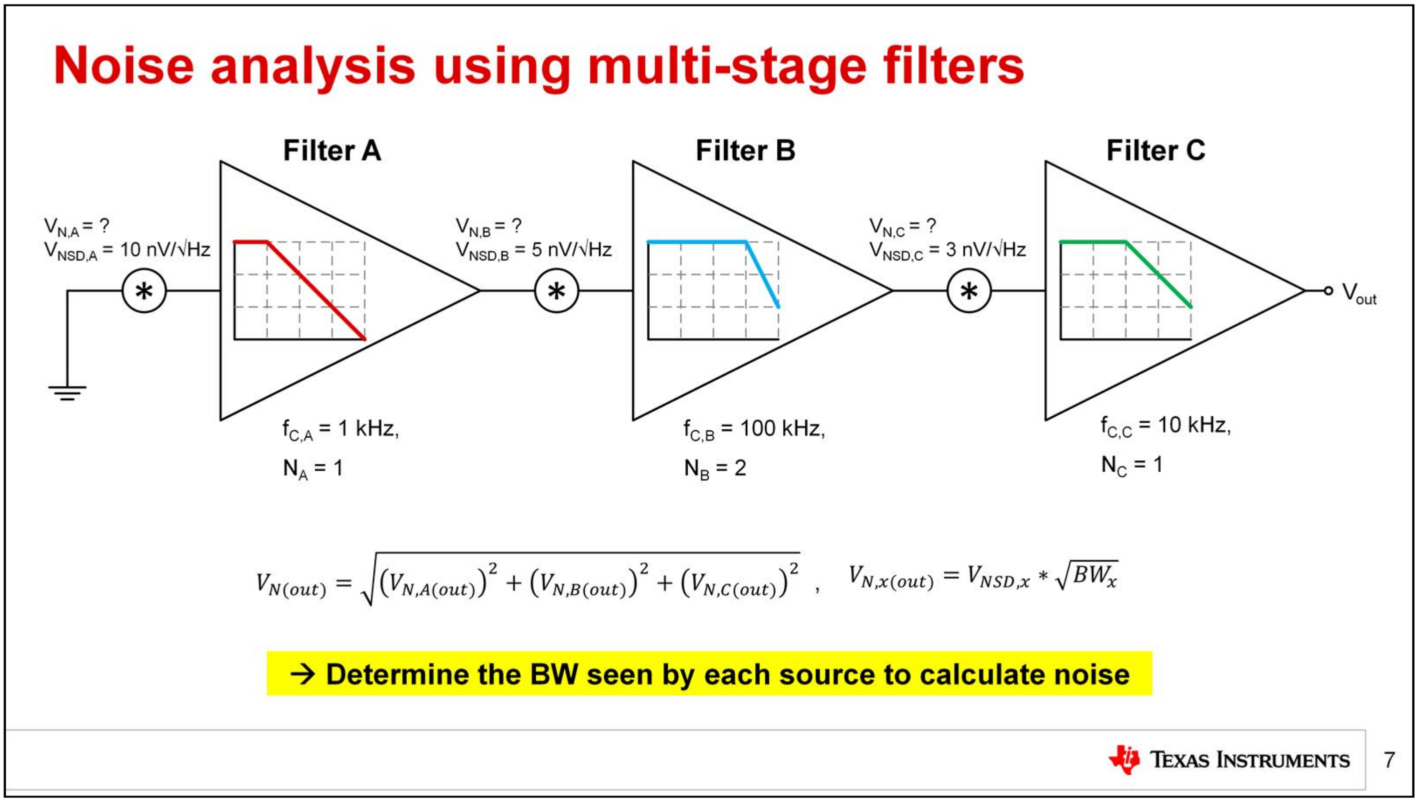


In general, you can approximate the combined frequency response of two or more filters as just the cutoff, f_C, and order, N, of the filter with the lower cutoff frequency. These approximations are valid when there is a difference of greater than or equal to one decade between filter cutoff frequencies, as the systems on this slide show.

For example, the top row of plots shows that Filter A in red has a cutoff frequency, f_{CA}, of 1 kHz and an order, N_A, equal to one, while Filter B in blue has a cutoff of 100 kHz, f_{CB}, and an order, N_B, equal to two. Using the point-by-point addition method introduced on the previous slide, the combined frequency response in purple is very similar to just Filter A's frequency response in terms of both cutoff frequency and filter order. You may note that the combined frequency response is affected by Filter B, though this does not occur until a gain of -40 dB and a frequency of 100 kHz. From a noise perspective, this means that Filter A has attenuated the bulk of the noise power before Filter B starts to affect the circuit, so using Filter A as an approximation for the total response is acceptable. Also, due to the transitive property of combining filter responses discussed on the previous slide, if Filter B came before Filter A in your signal chain, the combined response and the resulting approximation would be the same. Moreover, if Filter B had a much lower cutoff compared to the Filter A, the approximation still holds true, though Filter B's cutoff frequency and filter order would dominate in this case.

However, if this condition is not satisfied and the two filters had similar cutoff frequencies, you can no longer apply the approximations. Instead, you must add the frequency responses of all filters and use the resulting combined plot to apply to your noise source. This is shown in the bottom row of plots, where Filter A has a cutoff of 1 kHz and N_A equals one while Filter B has a cutoff of 1.1 kHz and N_B equals two. The resulting plot has a cutoff frequency that is approximately equal to 1 kHz with an effective filter rolloff of -60 dB per decade. This much steeper rolloff means that N_{Total} is equal to three, or just the sum of both filter orders.

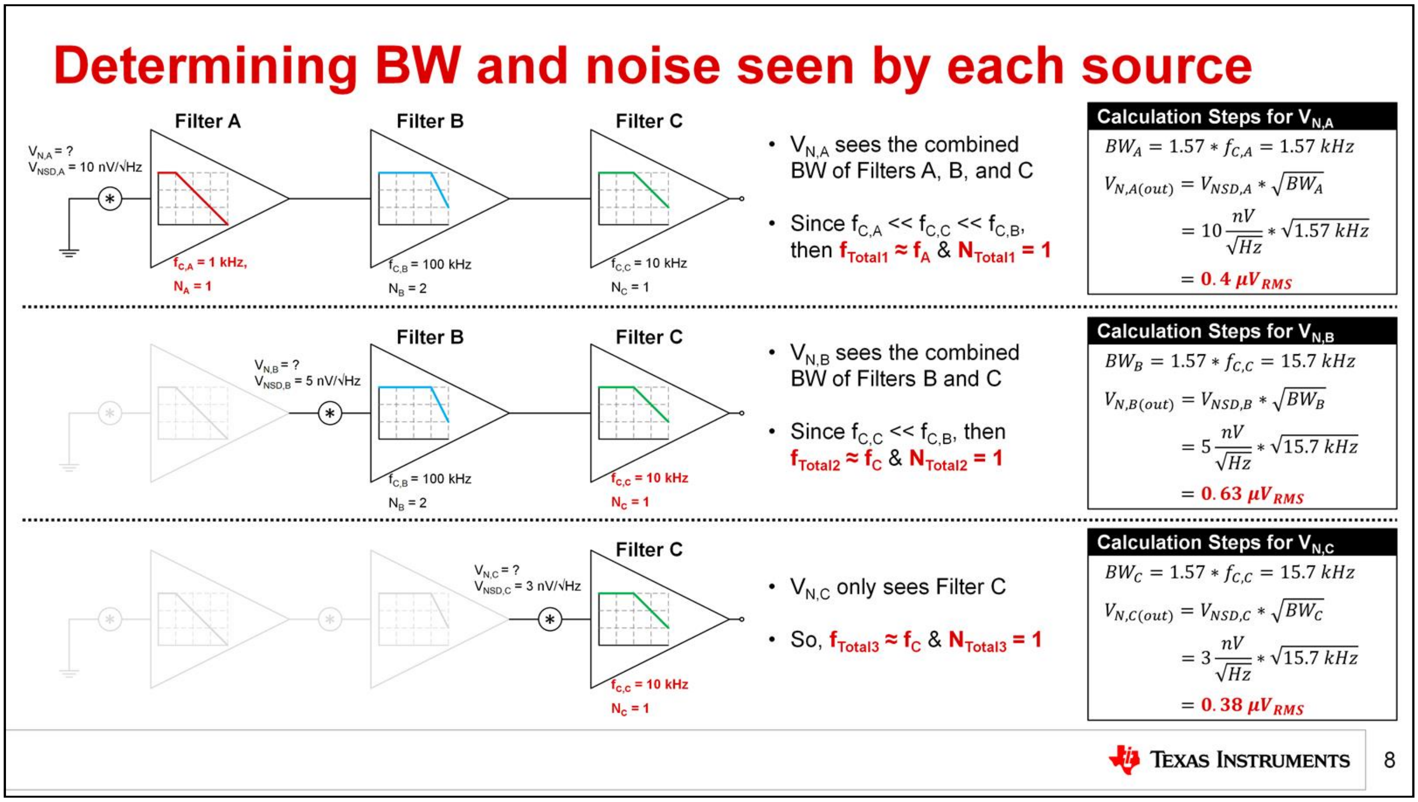
Now that you understand when and why these approximations are valid, as well as how to calculate the noise bandwidth of a lowpass filter, let's apply these principles to a design example.



Shown here are three arbitrary filter responses and three arbitrary noise sources. These components could represent any part of the typical signal chain discussed earlier in this presentation, such as the EMI filter, the gain amplifier, and the anti-aliasing filter. Additionally, each noise source has a noise spectral density that represents real components used later in the simulation portion of this module.

Similar to the example at the beginning of this presentation, determine the total noise of this system by taking the root sum of squares of each stage's noise. To calculate the noise of each stage, you multiply the given noise spectral density by the square root of the system bandwidth seen by each source, as shown. You can use the principle of superposition as well as the techniques presented throughout this module to calculate the combined filter response seen by each source and the resulting bandwidth to calculate total noise.

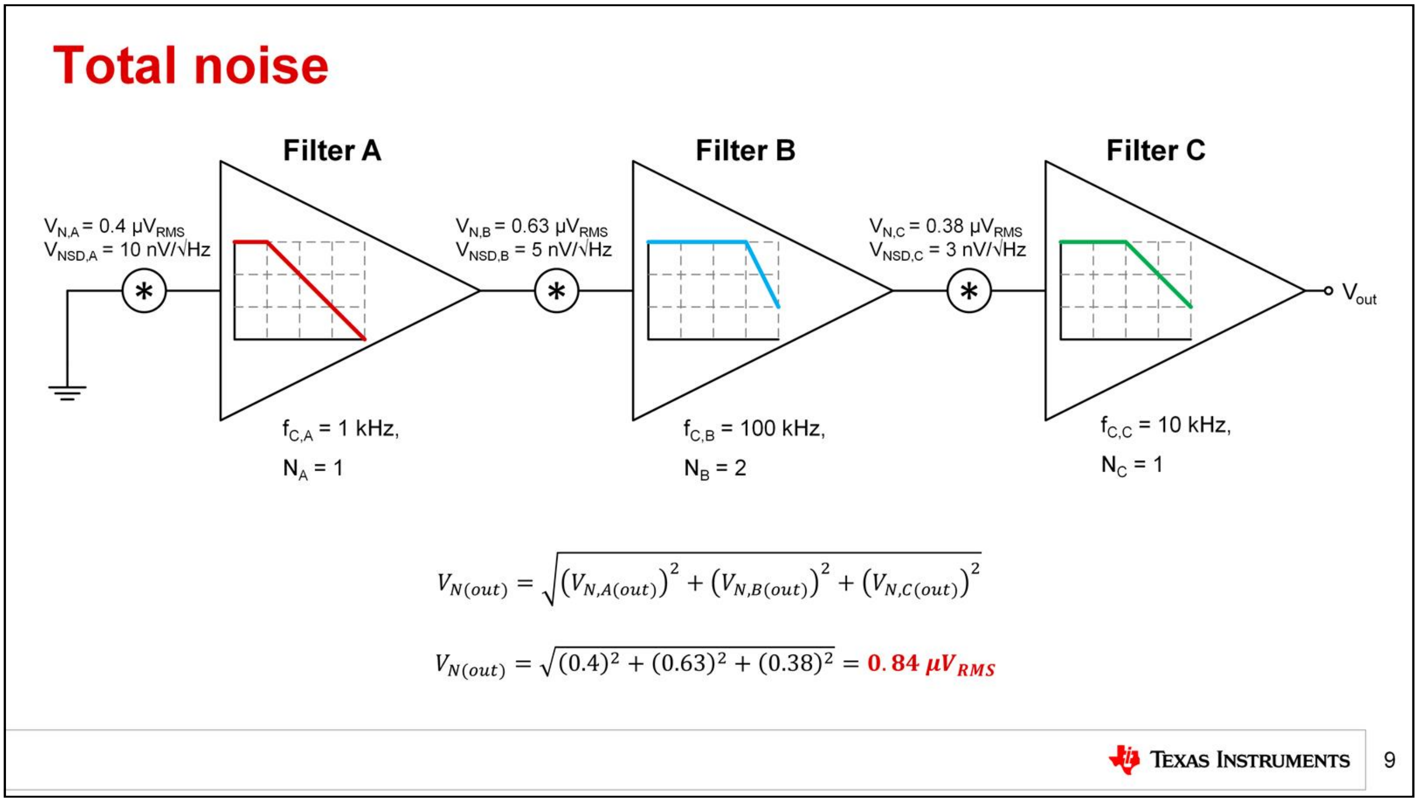
To begin, let’s look at the frequency response seen by each source.



On the top portion of this slide, noise source A sees all of the downstream filters, so you must calculate the combined response by adding each filter point-by-point. However, note that Filter A's cutoff frequency is at least one decade lower compared to either Filter B or Filter C, so you can approximate the combined frequency response as just Filter A's cutoff frequency and order. In this case, a first-order lowpass filter with a cutoff frequency of 1 kHz. Since Filter A is a first order lowpass filter, you can use the effective noise bandwidth equation shown at the beginning of this presentation to determine the bandwidth for this system. As shown, this bandwidth is calculated to be 1.57 kHz. Plugging this bandwidth value into the noise source A's equation yields an RMS voltage noise of 0.4 µV.

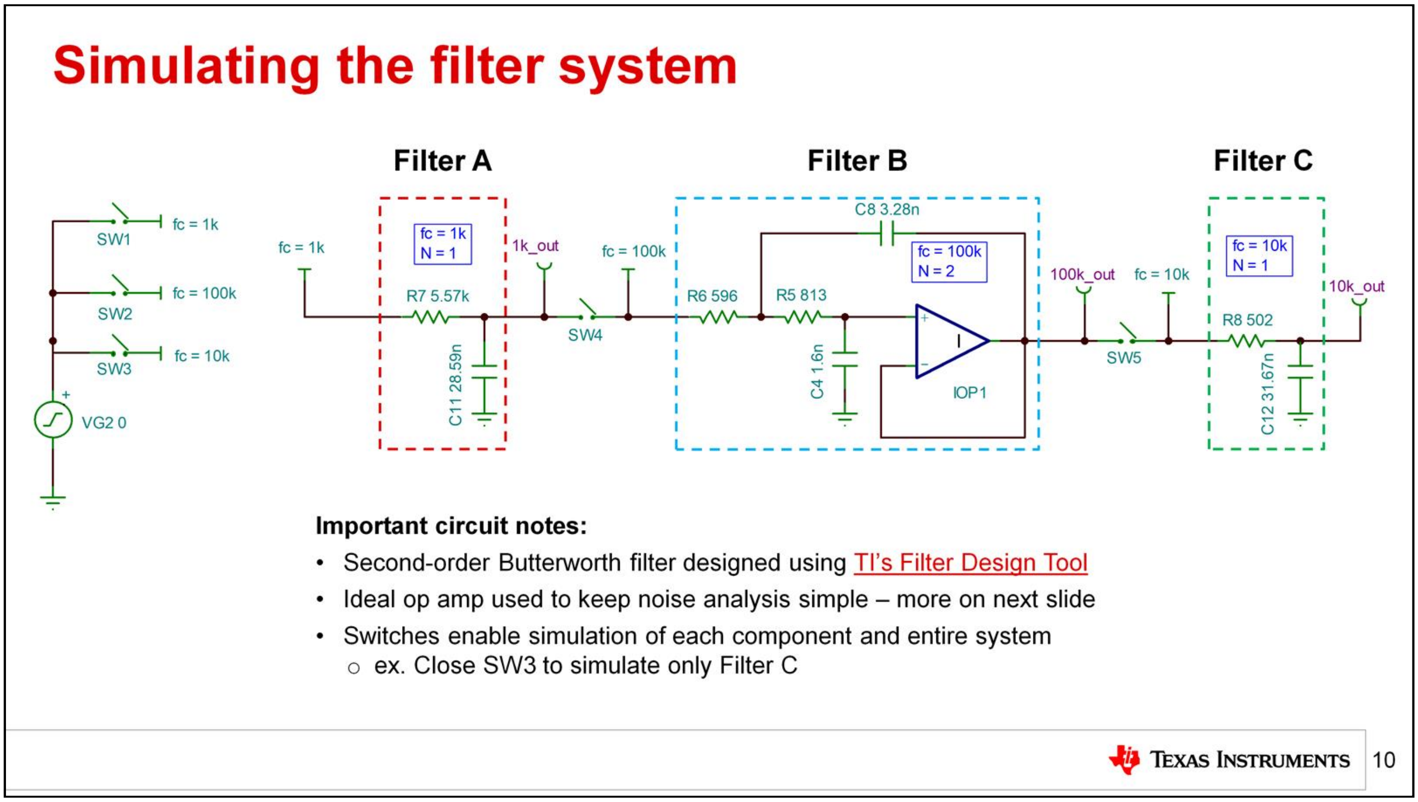
In the middle, noise source B sees the response from multiple filters just like noise source A. In this case, Filter B and Filter C. Also similar to the analysis for noise source A, noise source B has one filter that dominates the combined frequency response, though this time it is Filter C. Since Filter B's cutoff frequency is an order of magnitude greater than Filter C's, you can approximate the frequency response seen by noise source B as just Filter C: a first-order lowpass filter with a cutoff frequency of 10 kHz. Applying the same bandwidth approximation for a first order lowpass filter used for noise source A, the bandwidth seen by noise source B is 15.7 kHz. This results in an RMS noise voltage of 0.63 μV.

Finally, on the bottom of the slide, noise source C is very straightforward since it only sees the frequency response from Filter C. You can therefore use the 15.7 kHz bandwidth derived for Filter B to determine that noise source C adds an RMS voltage noise of 0.38 μV to the system. Now that you have determined the noise of each component, you can apply the root sum of squares to calculate the total noise.



Shown here is the original system used in this example with the voltage noise of each source identified. Taking the root sum of squares of the voltage noise for each component, the total voltage noise of this system is equal to 0.84 µV RMS.

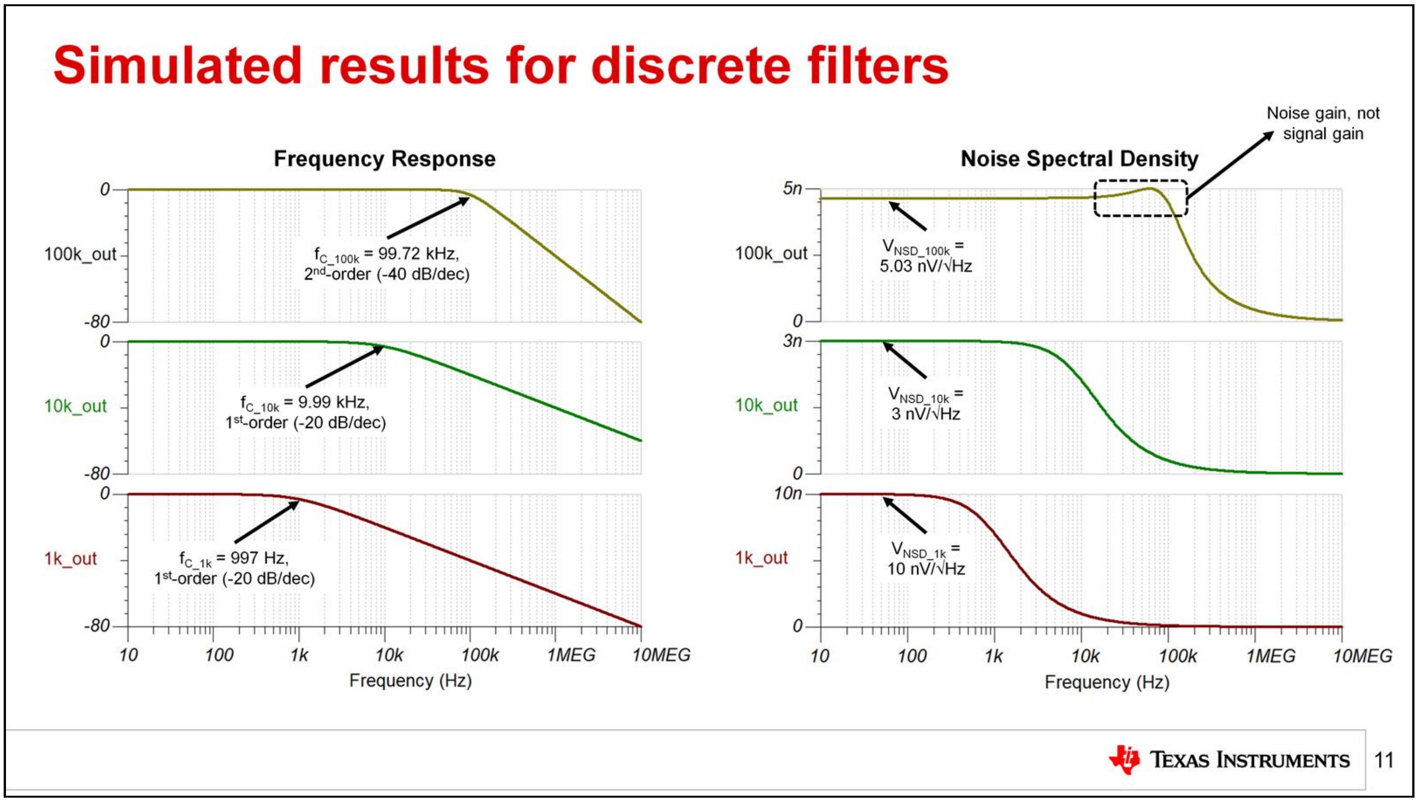
However, you might wonder how this compares to a simulated example using actual component values. Several assumptions were made regarding the filter order and bandwidth of each stage to reach the results shown on this slide, which begs the question, “how close are these approximations to the actual system noise?”



The schematic shown here is a real-world implementation of the filter system on the previous slide. Filter A and Filter C are simple first-order lowpass filters comprised of a resistor and a capacitor. Filter B is a second order lowpass Butterworth filter designed using Texas Instrument's online Filter Design Tool. You can access this tool to create your own filters at the link on the screen. An ideal amplifier was chosen for Filter B in lieu of using a real amplifier to keep the noise analysis simple. This choice will be explained in more detail on the next slide.

The switches at the output of the voltage source as well as the switches between the filters enable simulation of the entire system as well as each individual component. For example, to determine the voltage noise density for just Filter C, you would close switch 3 only. These switches are only included to make the analysis simpler, and would not need to be included in a real design.

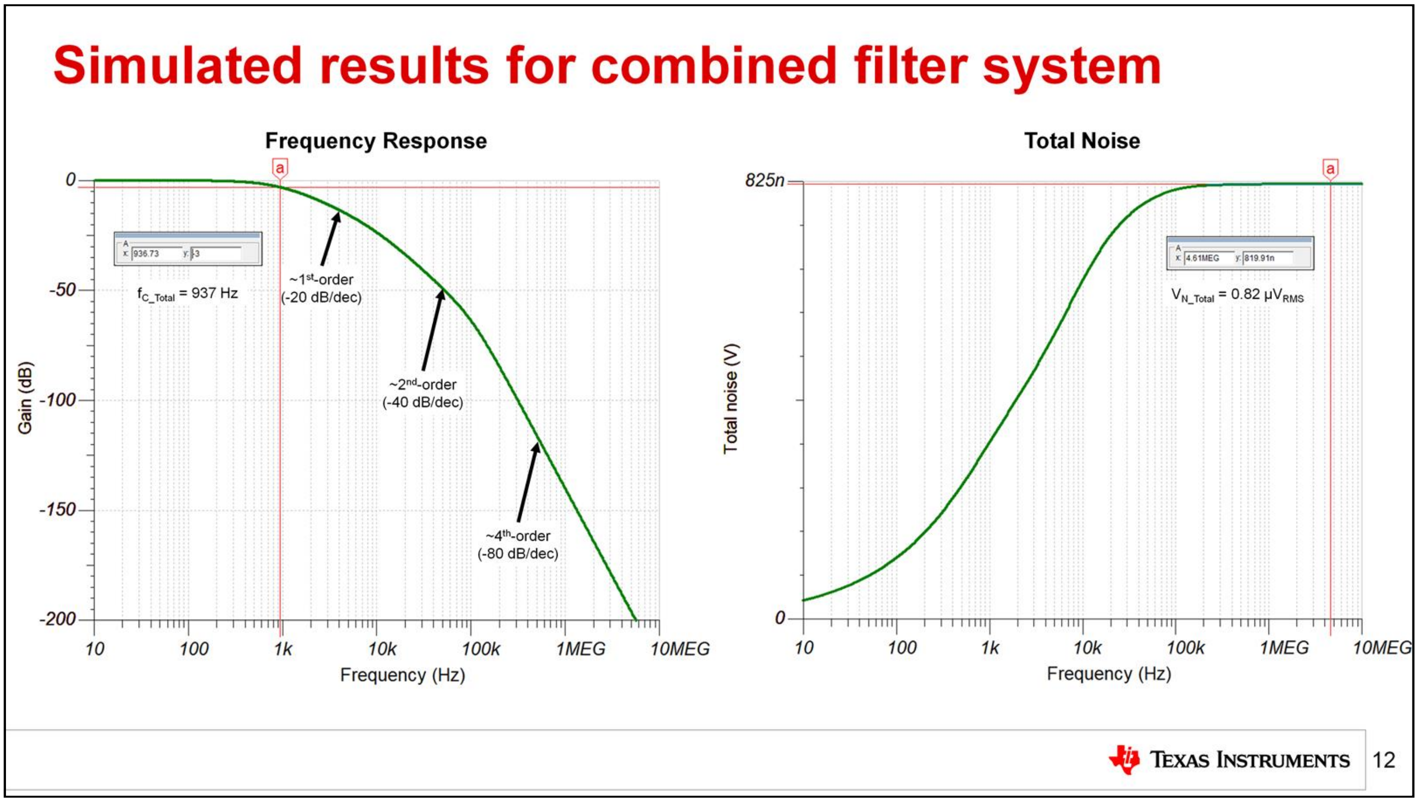
Now, let’s analyze the simulated results.



This slide shows six plots to confirm the performance of each filter. Note that for all the plots shown here, switches one through three on the schematic were closed, while switches four and five were left open. This enables each filter to be analyzed separately to determine their individual characteristics.

On the left, the three frequency response plots confirm the cutoff frequency and order for each filter. The figures on the right plot the noise spectral density for each filter. Note that the chosen component values yield noise spectral densities that match those used in the theoretical example. As stated on the previous slide, an ideal op-amp was chosen for the second-order filter because a real amplifier would add complexity to this system. You can see on the yellow plot on the top right that there is already a slight increase in noise spectral density around the cutoff frequency even when using the ideal op amp. This discrepancy results from impedance in the feedback path causing a noise gain, not a signal gain, that would be exacerbated by a real amplifier. In a real-world application, it would be necessary to account for these variables, but for the purposes of understanding the concepts in this module it can be ignored.

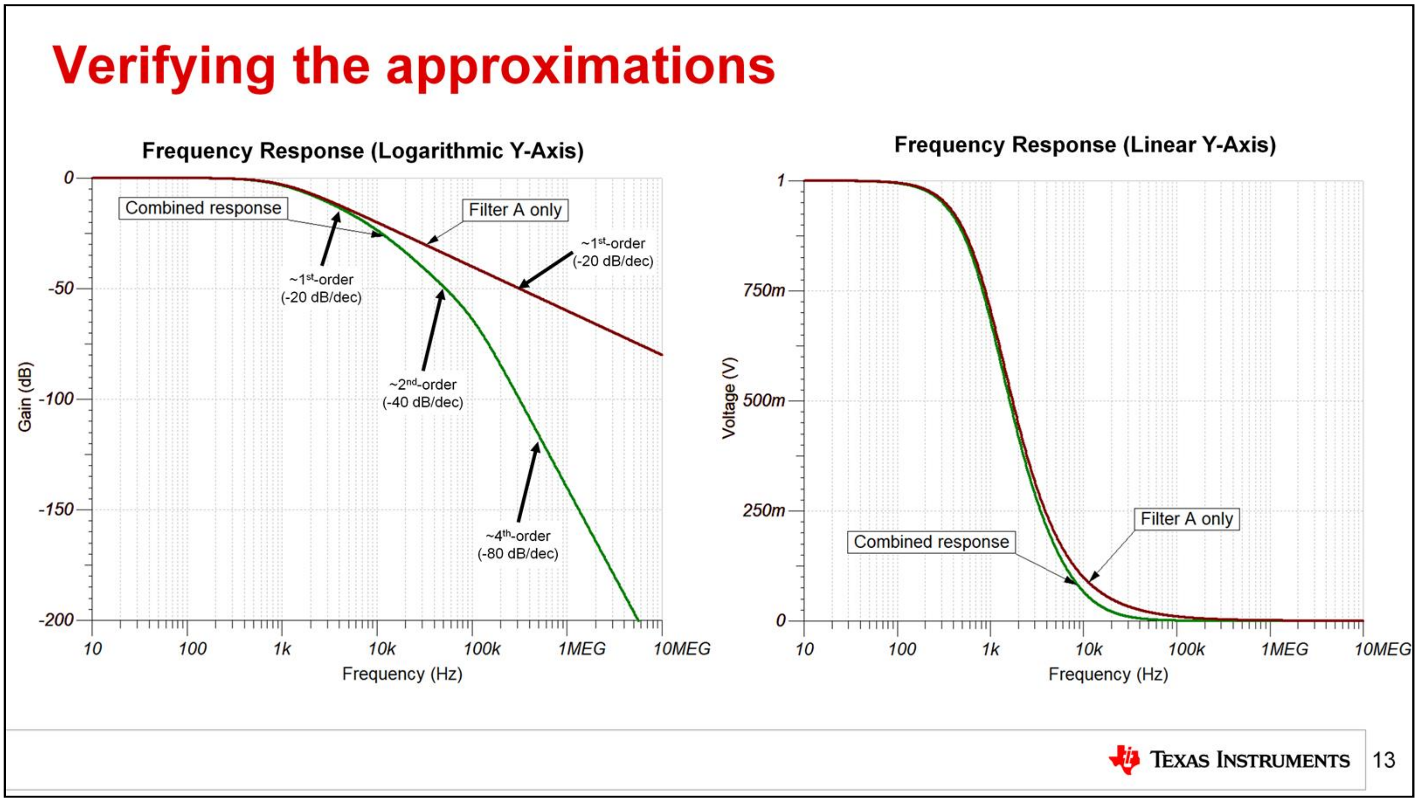
Now that we have confirmed the simulated filter parameters match the theoretical example, let’s look at the performance of the combined system and compare to the calculated results.



Here are the key plots for the simulation of the combined filter system. The frequency response plot on the left shows a system cutoff of 937 Hz, while the voltage noise plot on the right shows 0.82 µV of RMS voltage noise. Comparatively, the theoretical model predicted a filter cutoff of 1 kHz and 0.84 µV of RMS voltage noise, so the assumptions about which filter dominates in a multi-stage filter system proved to be valid with an error of only 20 nV.

This small discrepancy between the theoretical calculations and the simulated data results from the assumption that the system frequency response would depend solely on the filter with the lowest cutoff frequency. In reality, this was not completely accurate, such that the downstream filters actually did affect the cutoff frequency. Moreover, the shape of the frequency response curve suggests that approximating the combined filter as first-order was inaccurate. You can see that the combined filter starts to roll off at -20 dB per decade at -20 dB of gain and at -80 dB per decade at a gain of -120 dB, representing a fourth-order system.

So how is it possible that there is such a small error between predicted and simulated noise if the combined response is so dissimilar from a simple first-order lowpass filter?



In fact, you can see this issue more clearly by overlaying the first-order response from Filter A on the combined response, as shown in the plot on the left. Fortunately, this apparent issue actually results from the way these curves are displayed, not the behavior of the filters. Specifically, the logarithmic y-axis on the plot on the left exacerbates the difference between these two curves, making them seem more dissimilar than they actually are. If you were to use a linear y-axis instead, you would get the plot on the right. Note how the combined response and Filter A by itself look almost identical using a linear y-axis. Importantly, note that the vast majority of the noise power has been attenuated by 10 kHz in either case. This means the downstream filters have little to no effect on the overall response, even though the combined filter order changes from first to second to fourth.

Ultimately, these results prove that you can use the frequency response approximations and methods employed in this presentation to quickly and confidently analyze the noise of your next signal chain. You are also prepared to use simulation techniques to confirm the validity of these hand calculations, as well as account for any non-idealities similar to the ones seen with the second order lowpass active filter.

Check out the next video in this series to understand how to calculate the effective noise bandwidth for the digital filter commonly found in delta-sigma ADCs. This filter type presents a unique challenge that must be understood in order to calculate the total noise of a system using a delta-sigma ADC.

Thanks for your time!
Please try the quiz.

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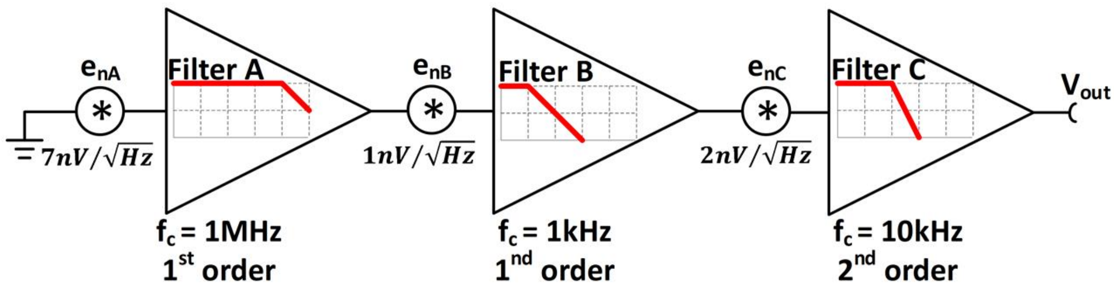
That concludes this video. Thank you for watching. Please try the quiz to check your understanding of this video's content.

Quiz: Noise bandwidth in ADC systems

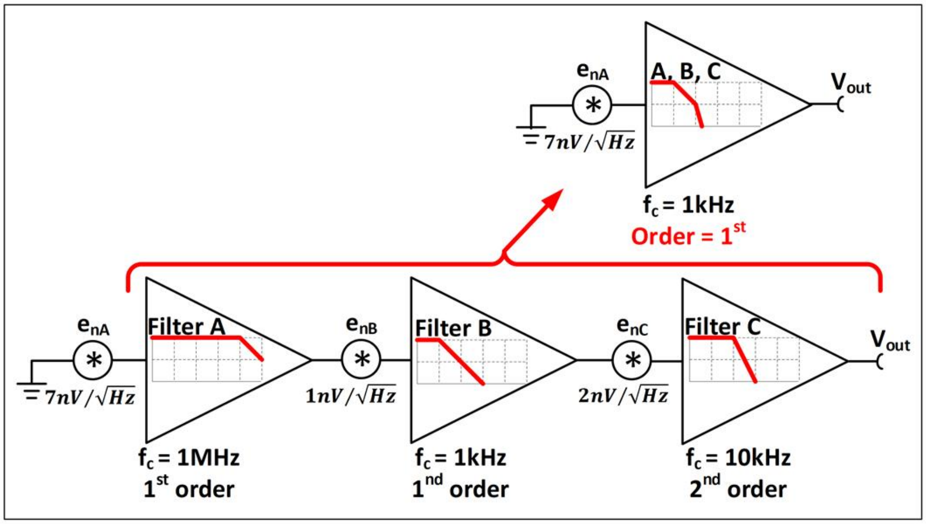
1. For the circuit below, what is the effective cutoff frequency seen by signal source e_{nA} to the output Vout?
   a. 1kHz
   b. 10kHz
   c. 100kHz
   d. 1MHz



The correct answer is “a”, 1kHz. When several filters are cascaded the cutoff frequency will be equal to the cutoff of the lowest filter.

Quiz: Noise bandwidth in ADC systems

2. Combining filter stages A, B, and C below form a 1kHz filter. What is the order of this filter?
   a. 1st order
   b. 2nd order
   c. 3rd order
   d. 4th order



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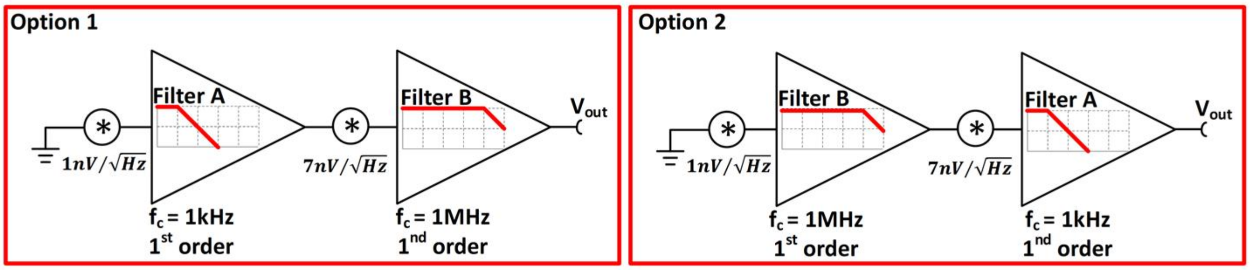
The correct answer is “a”, 1st order. When several filters are cascaded and the cutoff frequencies are significantly different, the order of the lowest cutoff filter will dominate. In this case the qualifier “significantly different” means the cutoff frequencies are apart by a one decade or more.

Quiz: Noise bandwidth in ADC systems

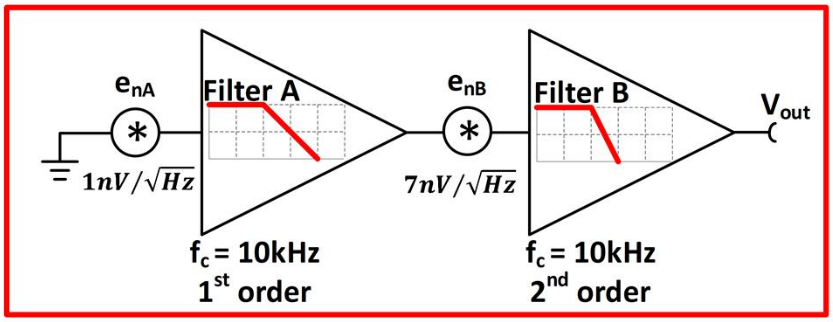
3. The two circuits below are identical except that the position of filter A and B are swapped. Which circuit will have the lowest noise total noise? Note that both noise sources are included in the analysis.
   a. They are both the same from a noise perspective
   b. Option 1 is better
   c. Option 2 is better



The correct answer is “c”, “option 2 is better”. If you look at option 1, you will notice that the 7nV/rtHz source is followed by a 1MHz filter. On the other hand, option 2 follows the 7nV/rtHz source with a 1kHz filter. Option 1, will allow more noise to reach the output so option 2 is better. Note that from the perspective of the input 1nV/rtHz source the filter sequence doesn’t matter so both options are equivalent from the input noise source perspective.

Quiz: Noise bandwidth in ADC systems

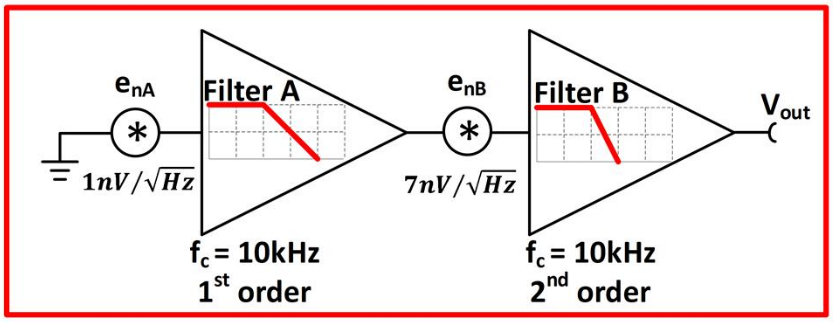
4. For the circuit below, what is the effective cutoff frequency seen by signal source e_{nA} to the output Vout?
   a. 1kHz
   b. 5kHz
   c. 10kHz
   d. 20kHz



The correct answer is “c” 10kHz. The general rule is that when two cutoff frequencies of two cascaded filters is the same the cutoff stays the same. In reality the cutoff will shift to a slightly lower frequency but there is no simple equation to predict the frequency. Typically this result is sufficient for a good rough estimate and the more precise result can be calculated using spice.

Quiz: Noise bandwidth in ADC systems

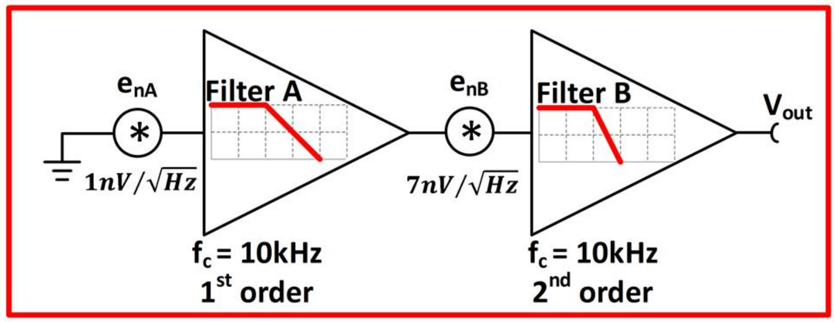
5. Combining filter stages A, B, and C below form a 10kHz filter. What is the order of this filter?
   a. 1st order
   b. 2nd order
   c. 3rd order
   d. 4th order



The correct answer is “c”, third order. The general rule here is that if two cascaded filters have approximately the same frequency the orders will add. Since the cutoff for these filters are both the same, the orders will add. So, the first order plus the second order yields a third order filter.

Quiz: Noise bandwidth in ADC systems

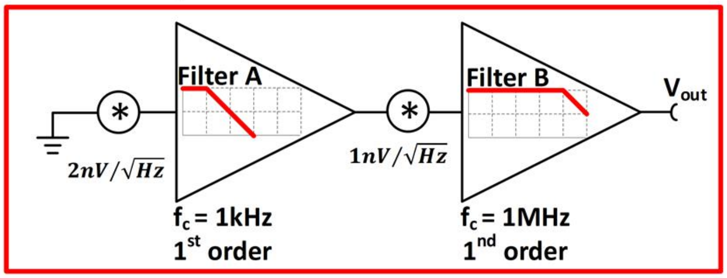
5. Combining filter stages A, B, and C below form a 10kHz filter. What is the order of this filter?
   a. 1st order
   b. 2nd order
   c. 3rd order
   d. 4th order



The correct answer is "c", third order. The general rule here is that if two cascaded filters have approximately the same frequency the orders will add. Since the cutoff for these filters are both the same, the orders will add. So, the first order plus the second order yields a third order filter.

Quiz: Noise bandwidth in ADC systems

6. Find the total integrated noise for the circuit below. Include the effects of both noise sources.
   a. 0.079µV rms
   b. 0.159µV rms
   c. 0.825µV rms
   d. 1.26µV rms
   e. 2.15µV rms



$$f_{c\_A} := 1\ kHz \qquad e_{nA} := 2\ \frac{nV}{\sqrt{Hz}}$$

$$V_{outA} := 2\ \frac{nV}{\sqrt{Hz}} \cdot \sqrt{1.57 \cdot 1\ kHz} = 0.079\ \mu V$$

$$f_{c\_B} := 1\ MHz \qquad e_{nA} := 1\ \frac{nV}{\sqrt{Hz}}$$

$$V_{outB} := 1\ \frac{nV}{\sqrt{Hz}} \cdot \sqrt{1.57 \cdot 1\ MHz} = 1.253\ \mu V$$

$$V_{out\_Total} := \sqrt{V_{outA}^{\ 2} + V_{outB}^{\ 2}} = 1.255\ \mu V$$

The correct answer is “d”, 1.26uV rms. The calculations for this problem are shown on the right. From filter “a” perspective the combined filter is a first order 1kHz filter. Using this information the total noise at the output from the 2nV/rtHz source is 0.079nV rms. The 1nV/rtHz noise source sees a 1MHz filter. The output noise for this source is 1.25uV rms. Combining both output noise values using the root sum of the square gives about 1.26uV rms.

Thanks for your time!