

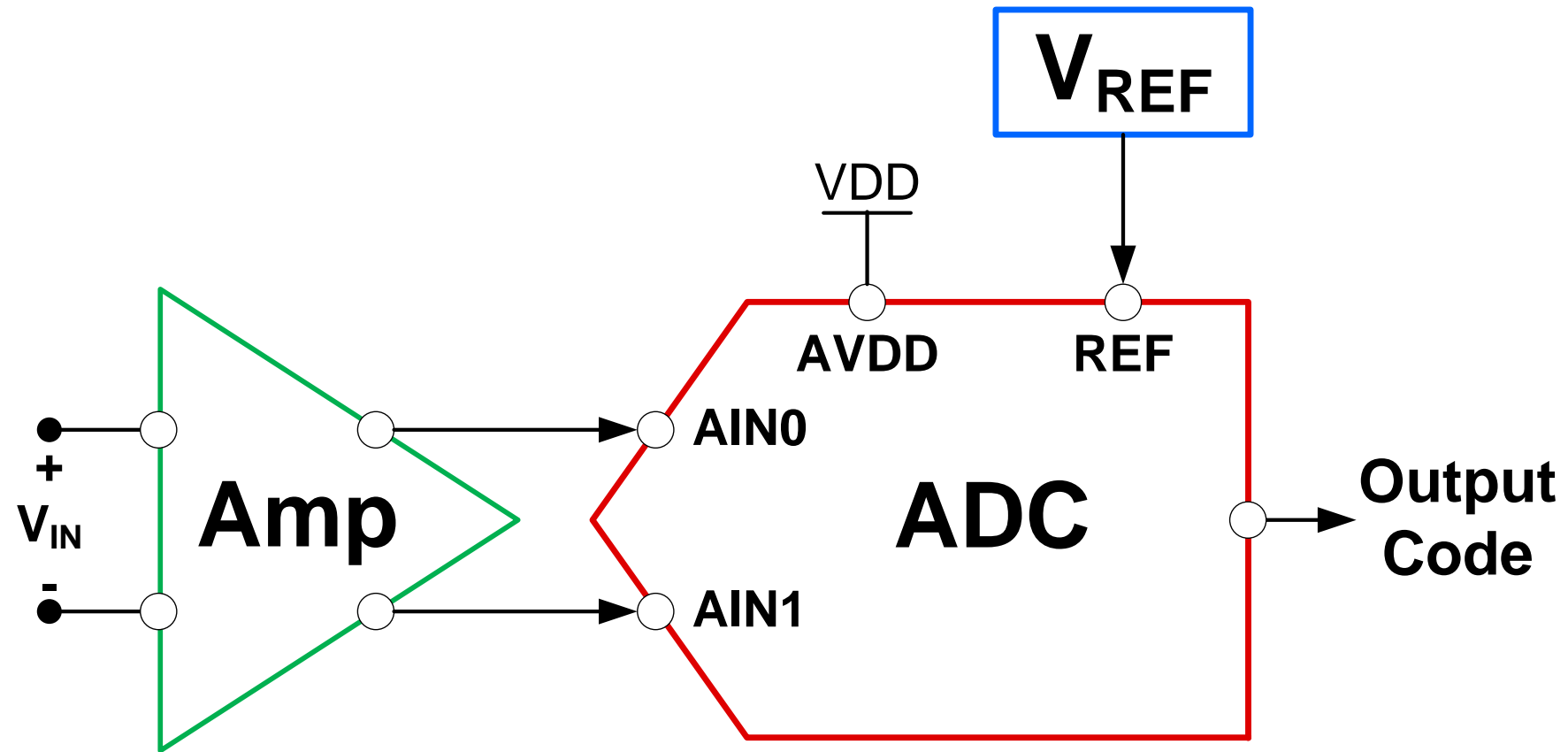
How reference noise affects signal chain performance

TI Precision Labs – ADCs

Created by Chris Hall & Bryan Lizon

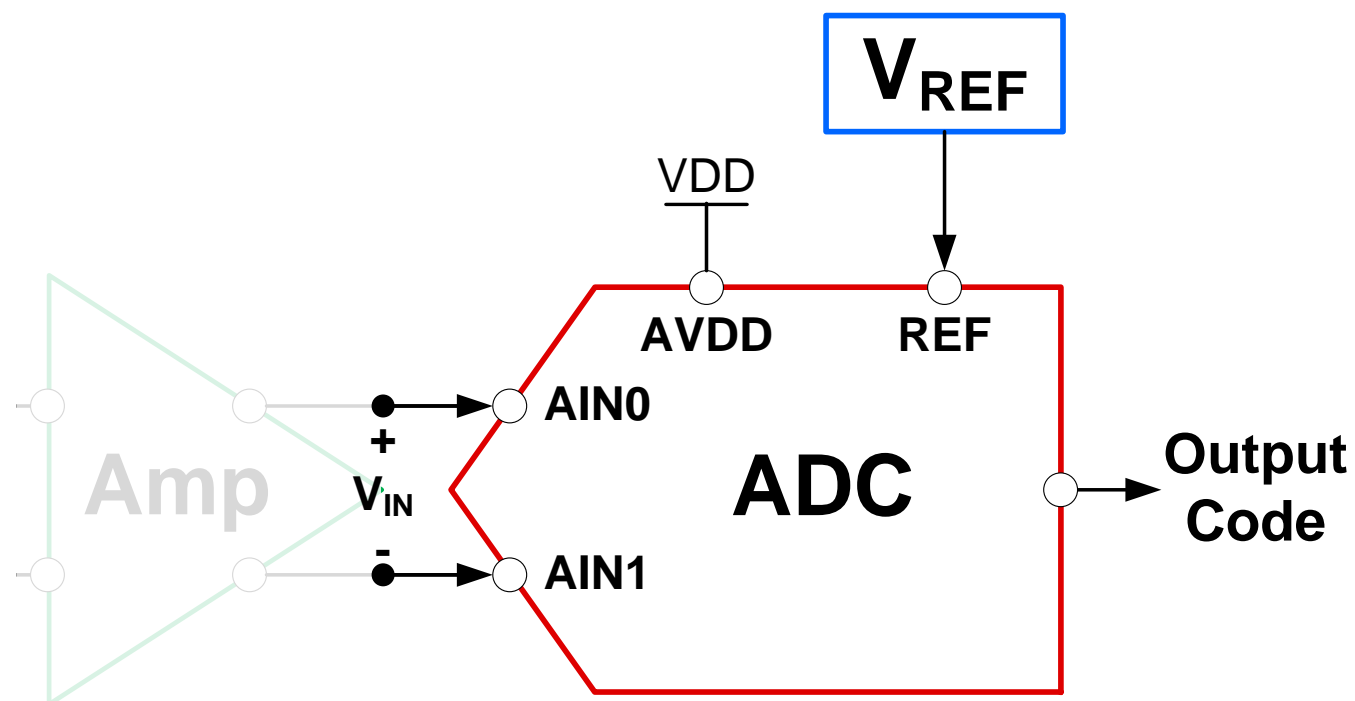
Presented by Alex Smith

Total system noise



$$\text{Total noise} = \sqrt{V_{N,ADC(RTI)}^2 + V_{N,AMP(RTI)}^2 + V_{N,REF(RTI)}^2}$$

Calculating system (ADC + VREF) noise

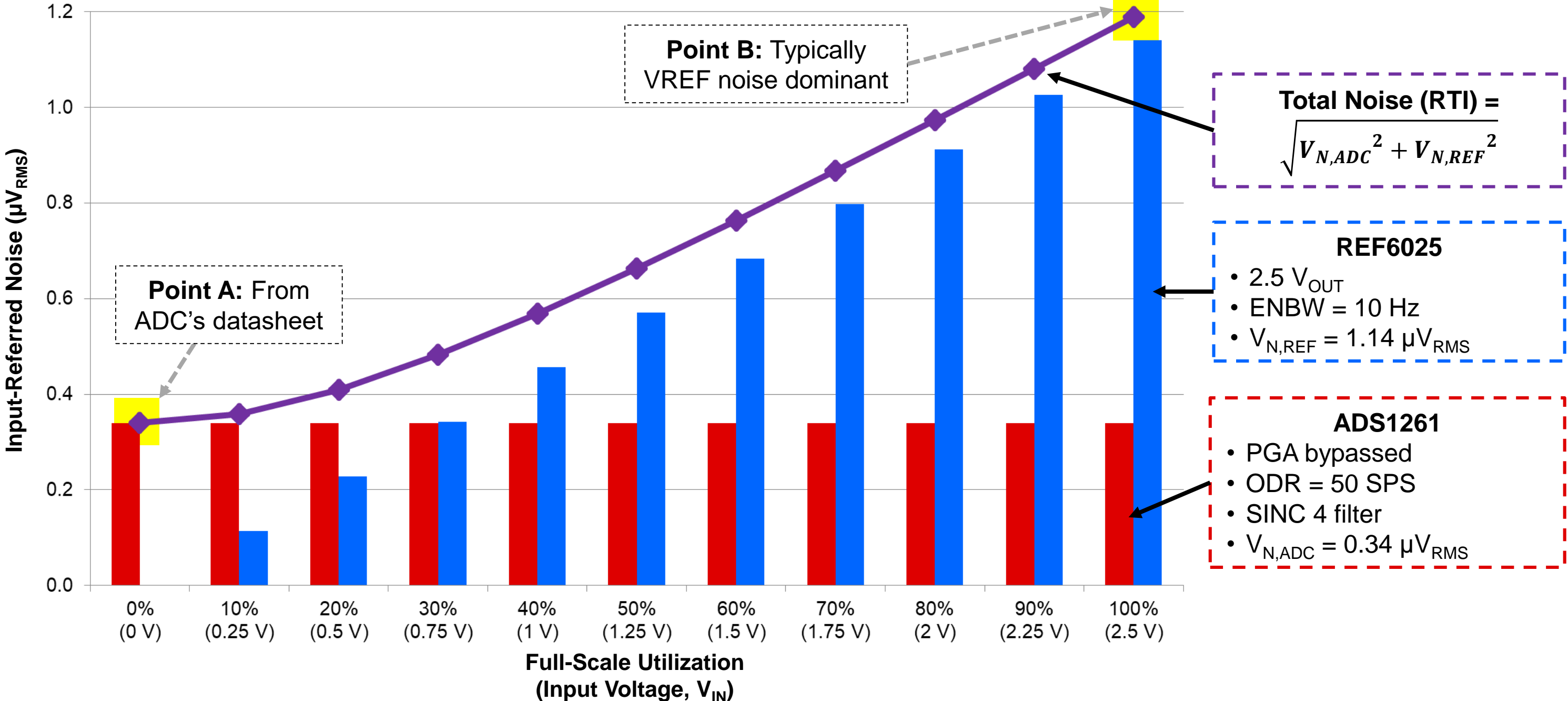


$$V_{N,REF(RTI)} = \frac{V_{IN(RMS)}}{V_{REF}} \cdot V_{N,REF(RMS)}$$

$$V_{N,ADC(RTI)} = \text{ADC noise from datasheet}$$

$$\text{Total noise} = \sqrt{V_{N,ADC(RTI)}^2 + V_{N,REF(RTI)}^2}$$

Plotting system noise across V_{IN} (gain = 1)

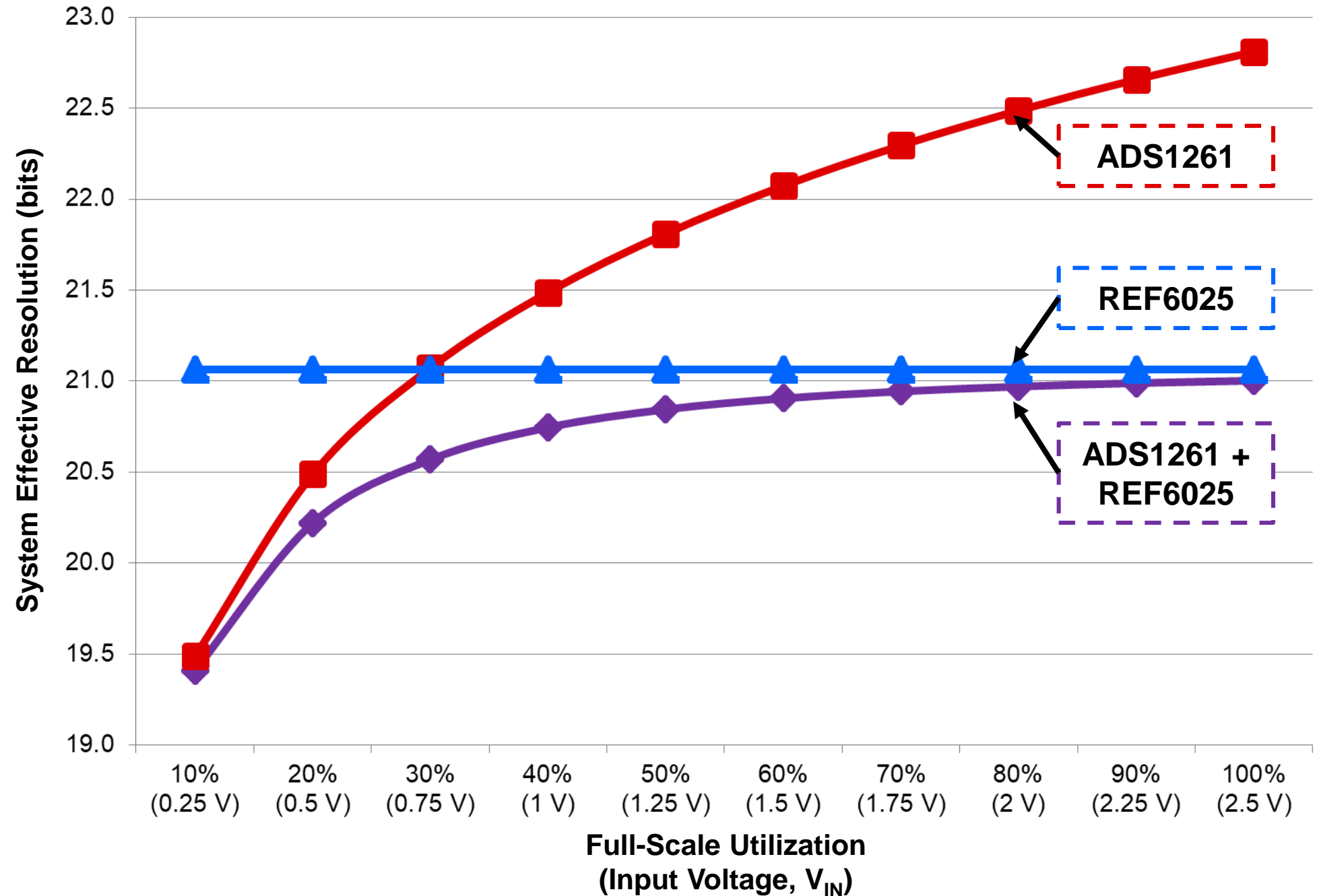


System effective resolution (dynamic range)

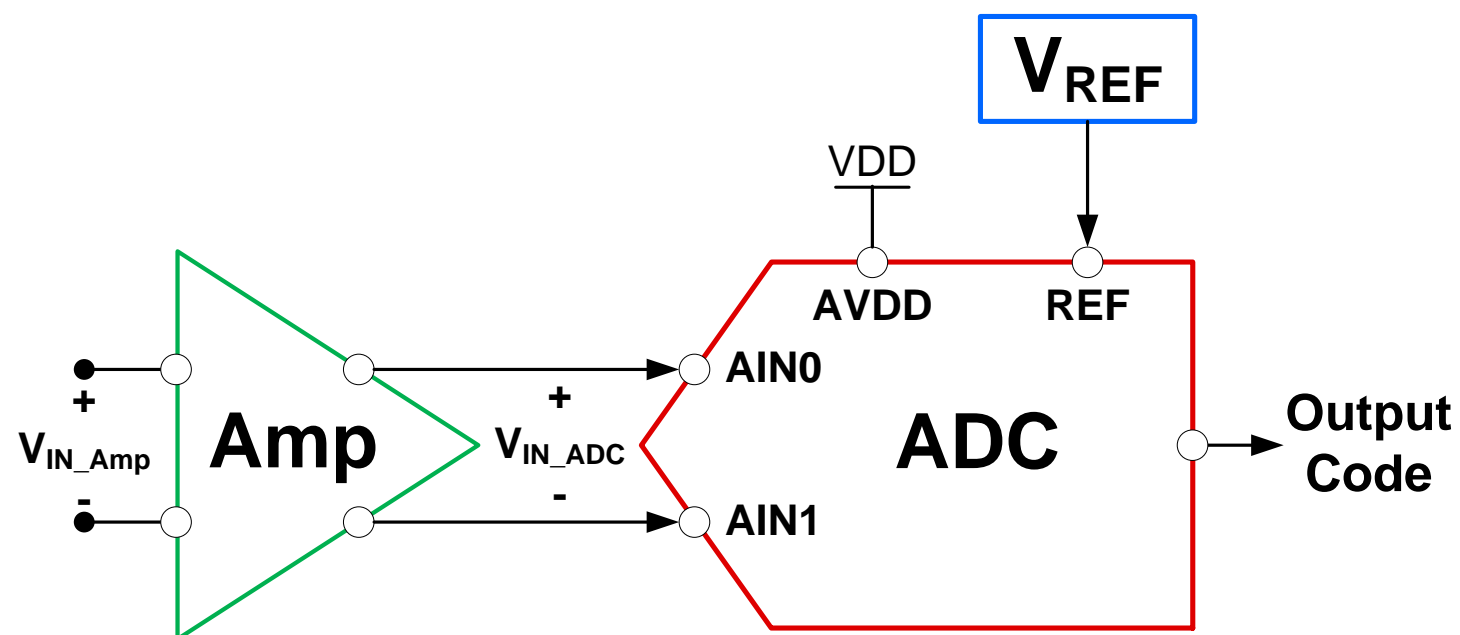
$$\text{Effective resolution} = \log_2 \left(\frac{V_{IN}}{V_{N,RTI}} \right)$$

- ADC**
- **Noise** = constant w.r.t. V_{IN}
 - **Effective resolution** = changes w.r.t. V_{IN}

- VREF**
- **Noise** = scales linearly w.r.t. V_{IN}
 - **Effective resolution** = constant w.r.t. V_{IN}



Calculating system (amp + ADC + VREF) noise



$V_{N,AMP} (RTI)$ = from datasheet

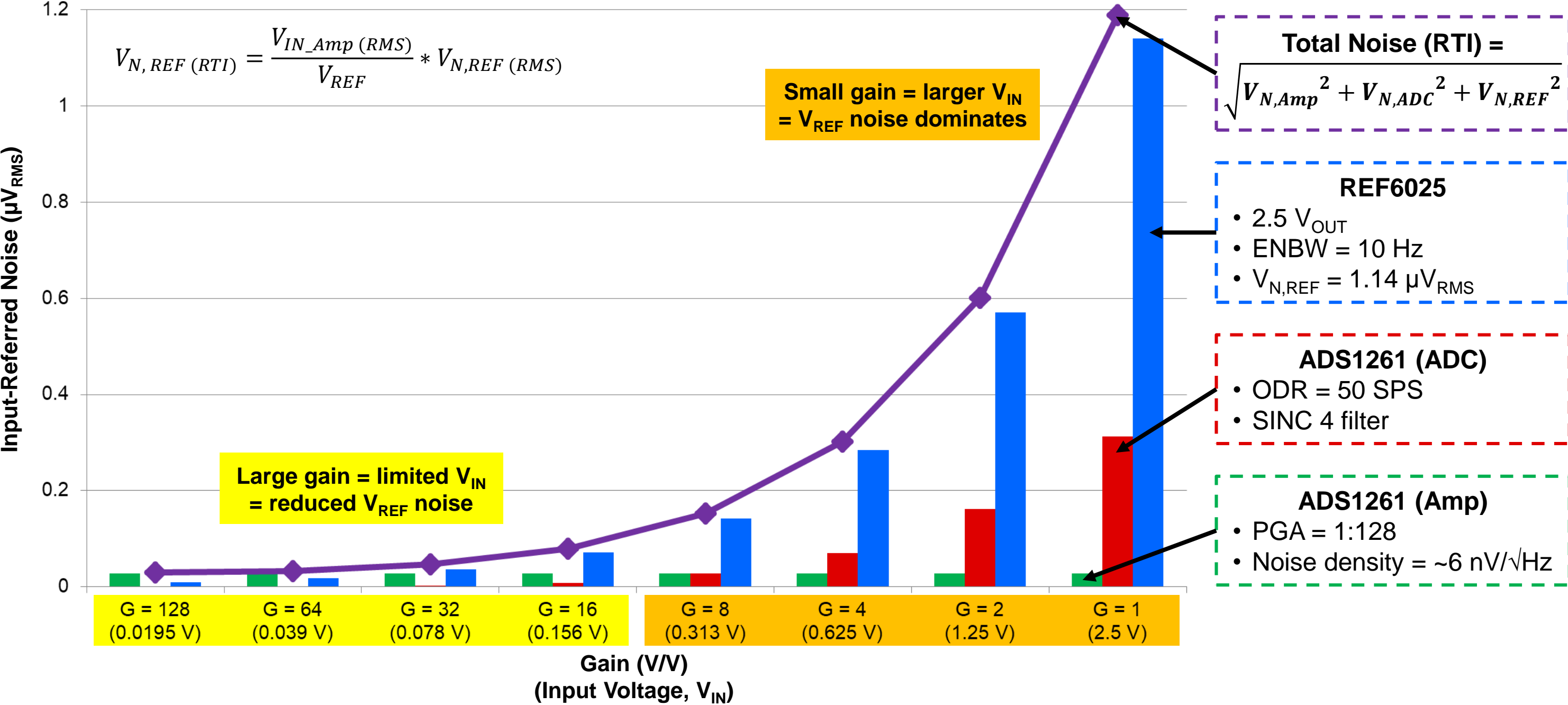
$$V_{N,ADC} (RTI) = \frac{V_{N,ADC} (datasheet)}{Gain}$$

Deriving an equation for $V_{N,REF} (RTI)$

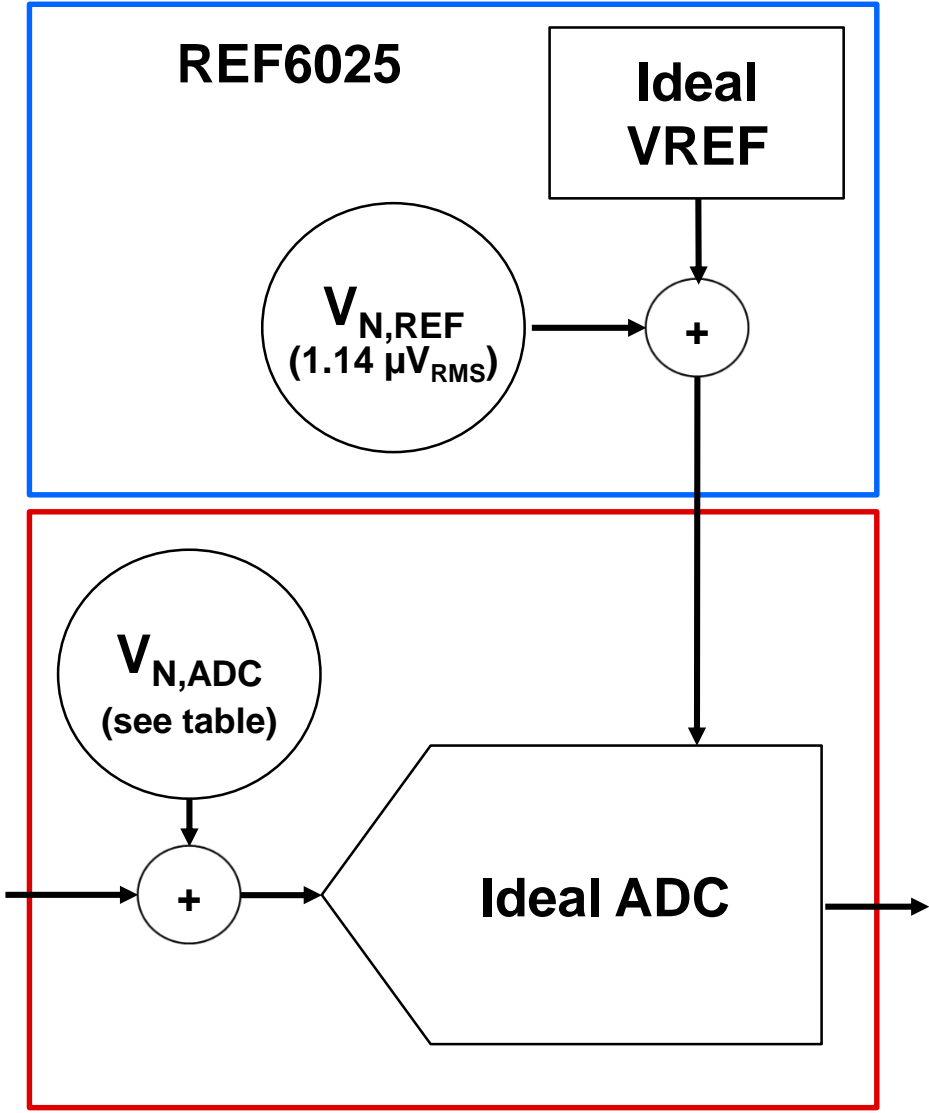
	Comment	Equation
Step #1	VREF noise equation	$\frac{V_{IN_ADC} (RMS)}{V_{REF}} * V_{N,REF} (RMS)$
Step #2	Refer to input = divide by gain	$\frac{V_{IN_ADC} (RMS)}{V_{REF} * Gain} * V_{N,REF} (RMS)$
Step #3	Substitute V_{IN_ADC} for $V_{IN_AMP} * Gain$	$\frac{V_{IN_Amp} (RMS) * Gain}{V_{REF} * Gain} * V_{N,REF} (RMS)$
Step #4	Final equation	$\frac{V_{IN_Amp} (RMS)}{V_{REF}} * V_{N,REF} (RMS)$

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

Plotting system noise across gain ($V_{IN} = 100\% \text{ FS}$)



Lower- vs higher-resolution ADCs: references



Parameter	Conditions	Units	ADC Resolution (bits)							
			8	10	12	14	16	20	24	32
ADC noise	G=1, 50 SPS, $V_{REF} = 2.5 V$	μV_{RMS}	19,531	4,883	1,221	305	76	11.2	0.53	0.18
LSB size	FSR = $2 \cdot V_{REF}$	μV	19,531	4,883	1,221	305	76	4.76	0.29	0.001
VREF noise	BW = 10 Hz	μV_{RMS}	1.14							
Total noise	$V_{IN} = 100\% FS$	μV_{RMS}	19,531	4,883	1,221	305	76	11.3	1.3	1.2
Increase in noise	n/a	%	0%	0%	0%	0%	0.01%	0.9%	148%	589%

For lower-resolution ADCs, reference noise has **virtually no impact** on total noise

For higher-resolution ADCs, reference noise has a **large impact** on total noise

Key takeaways

Input closer to full-scale = system is in low gain with high utilization, ensure that ADC + VREF noise are comparable

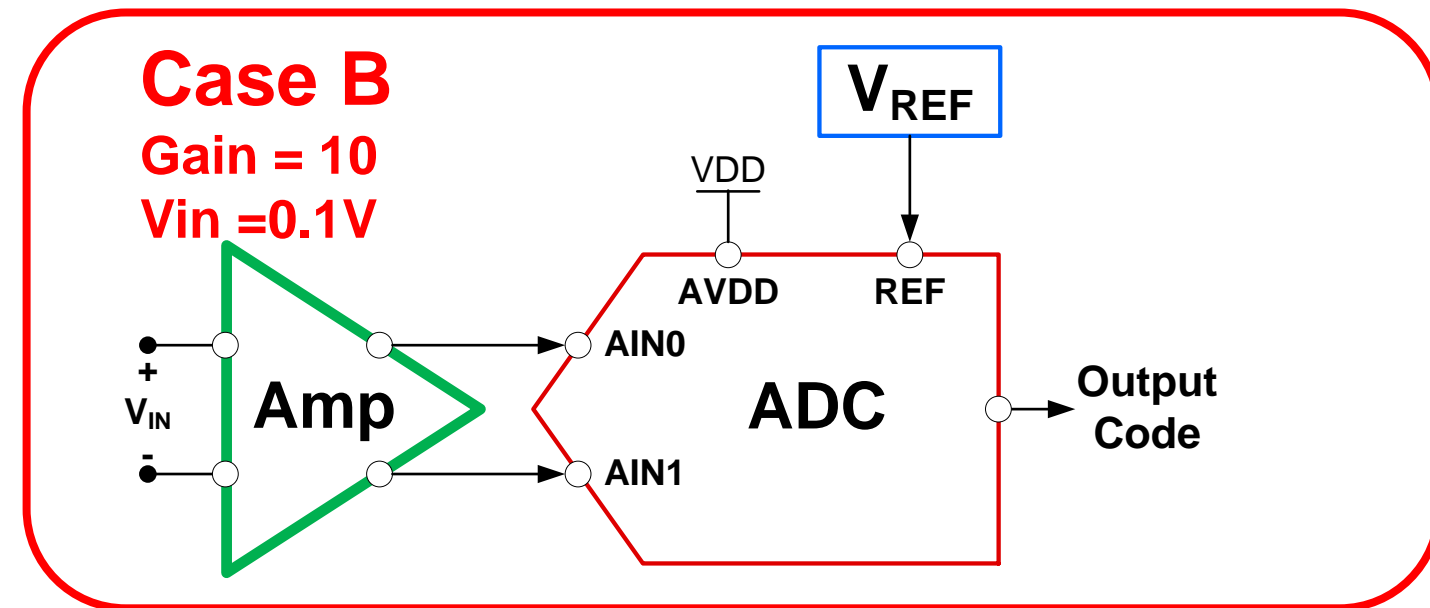
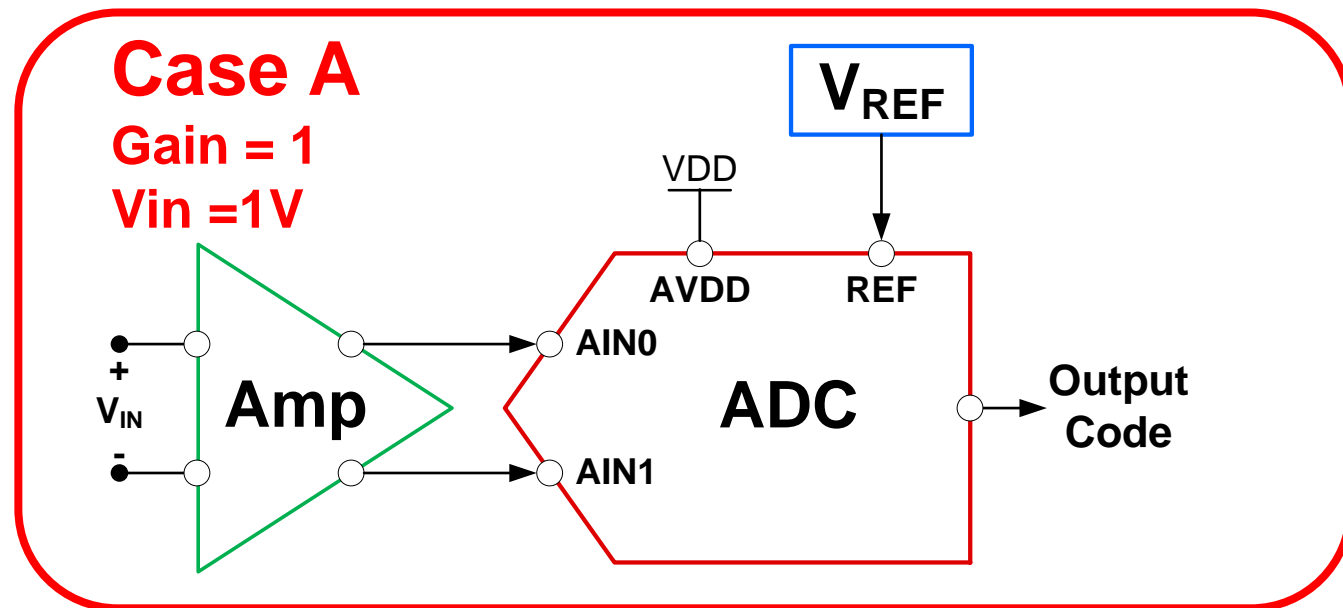
Small input signals = large gain reduces ADC noise and allowable full scale input, which indirectly limits VREF noise

Lower- vs higher-resolution ADCs = amp and VREF noise effects have a greater impact on higher-resolution ADCs, while quantization noise dominates in lower-resolution ADCs

Thanks for your time!
Please try the quiz.

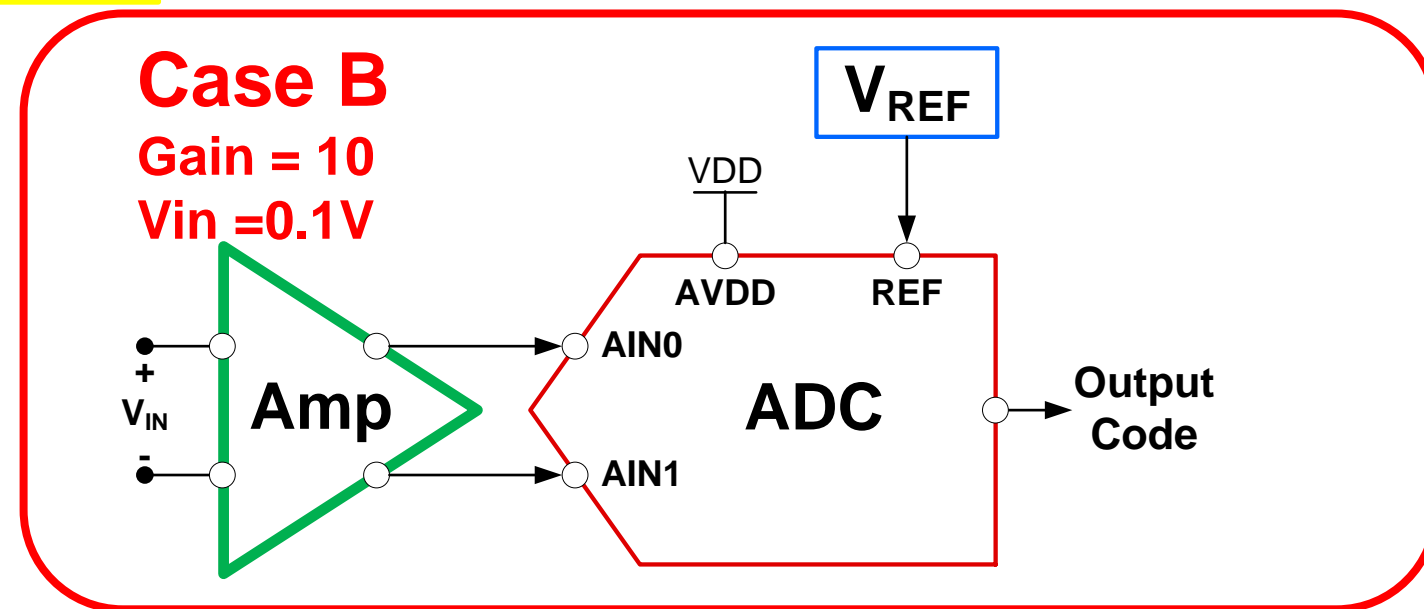
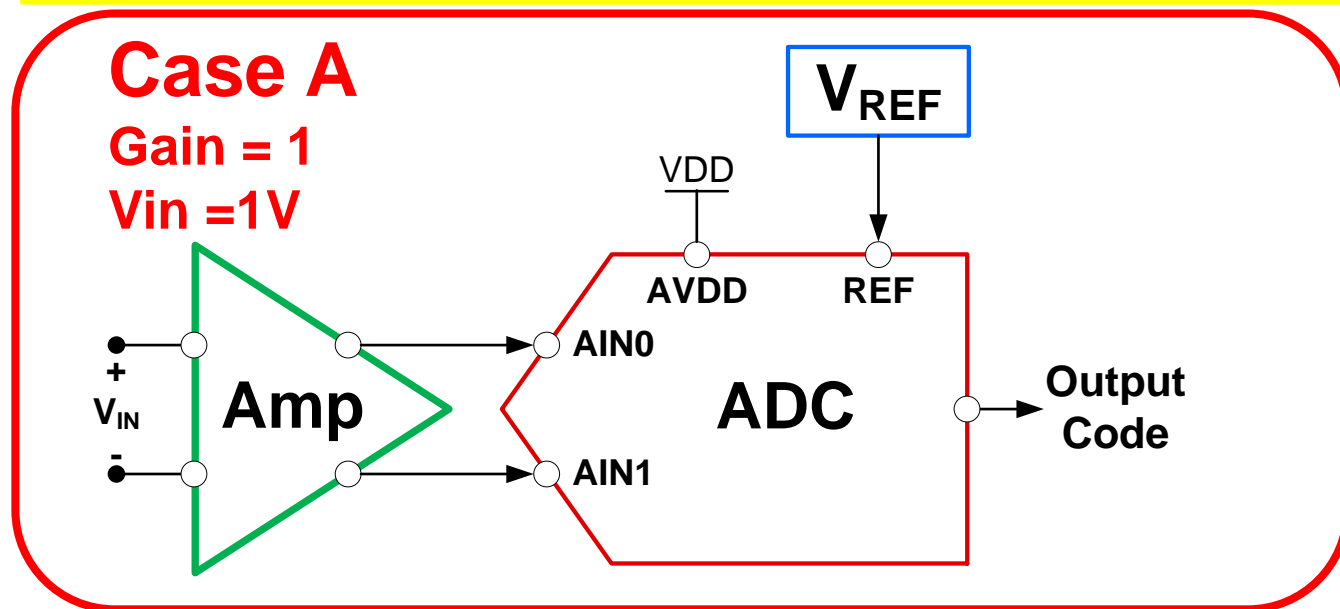
Quiz: How reference noise affects signal chain

- Referring to the figure below, assume both circuits are the same except for the gain and input signal. Which of the following are true? Select more than one answer if needed.
 - The ADC noise is minimized in case A
 - The ADC noise is minimized in case B
 - The reference noise is minimized in case A
 - The reference noise is minimized in case B



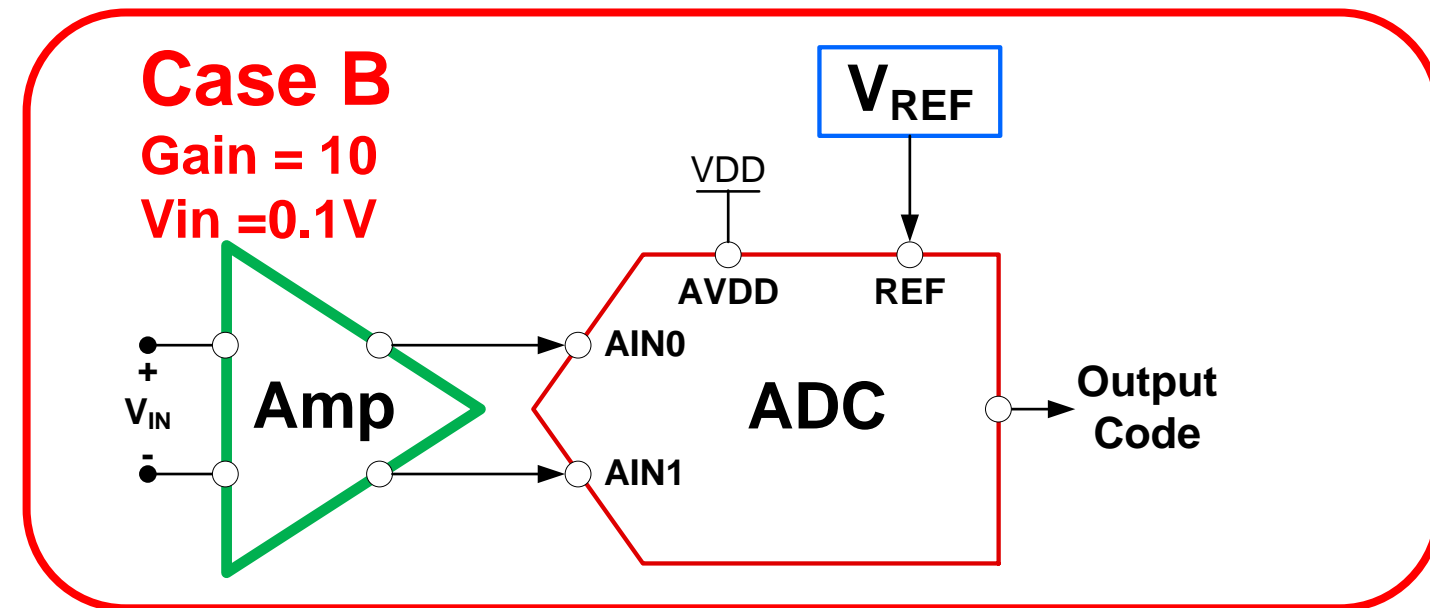
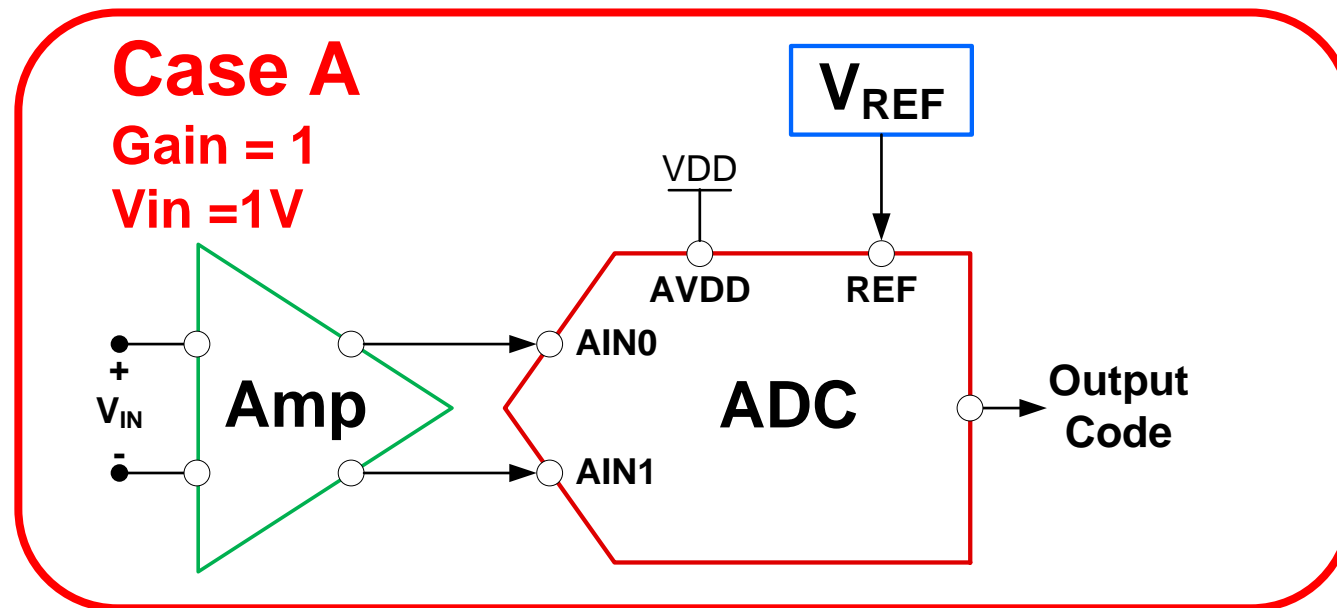
Quiz: How reference noise affects signal chain

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 - The reference noise is minimized in case A
 - The reference noise is minimized in case B



Quiz: How reference noise affects signal chain

2. Referring to the figure below, assume both circuits are the same except for the gain and input signal. Which of the following are true? Select more than one answer if needed.
- a. The amplifier noise referred to the input is the same in both cases
 - b. The amplifier noise referred to the input is smaller for case B
 - c. The amplifier noise referred to the output is larger for case A
 - d. The amplifier noise referred to the output is larger for case B



Quiz: How reference noise affects signal chain

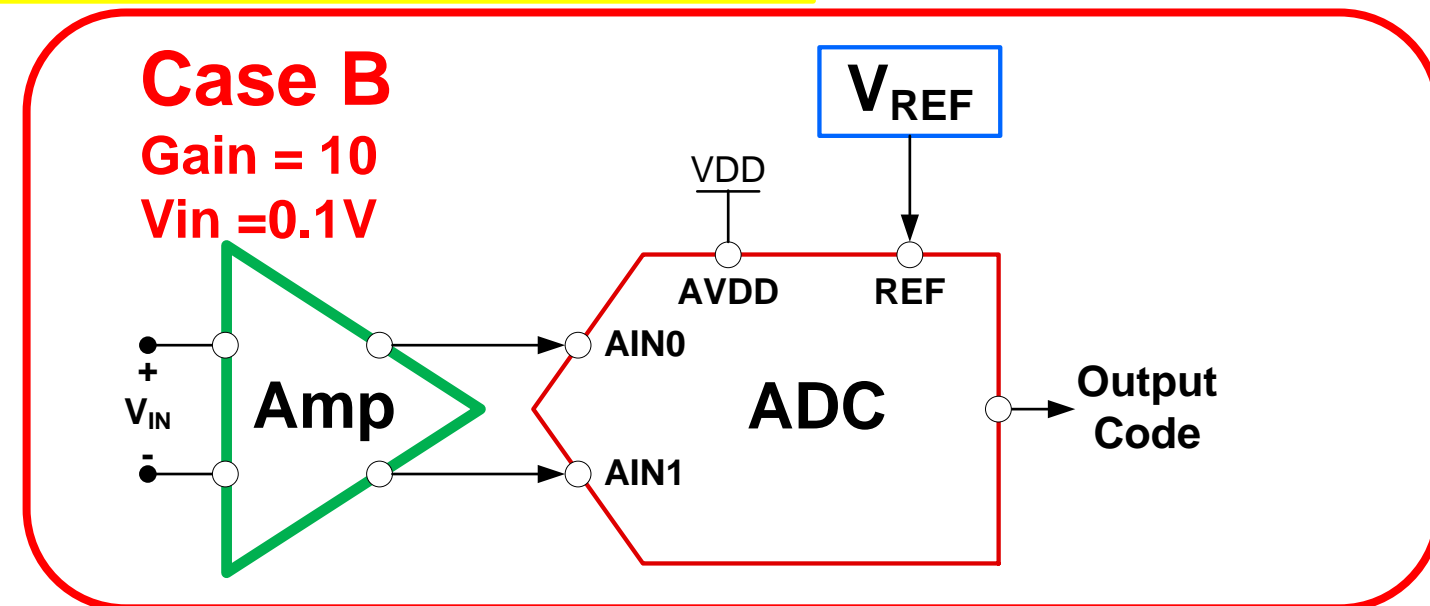
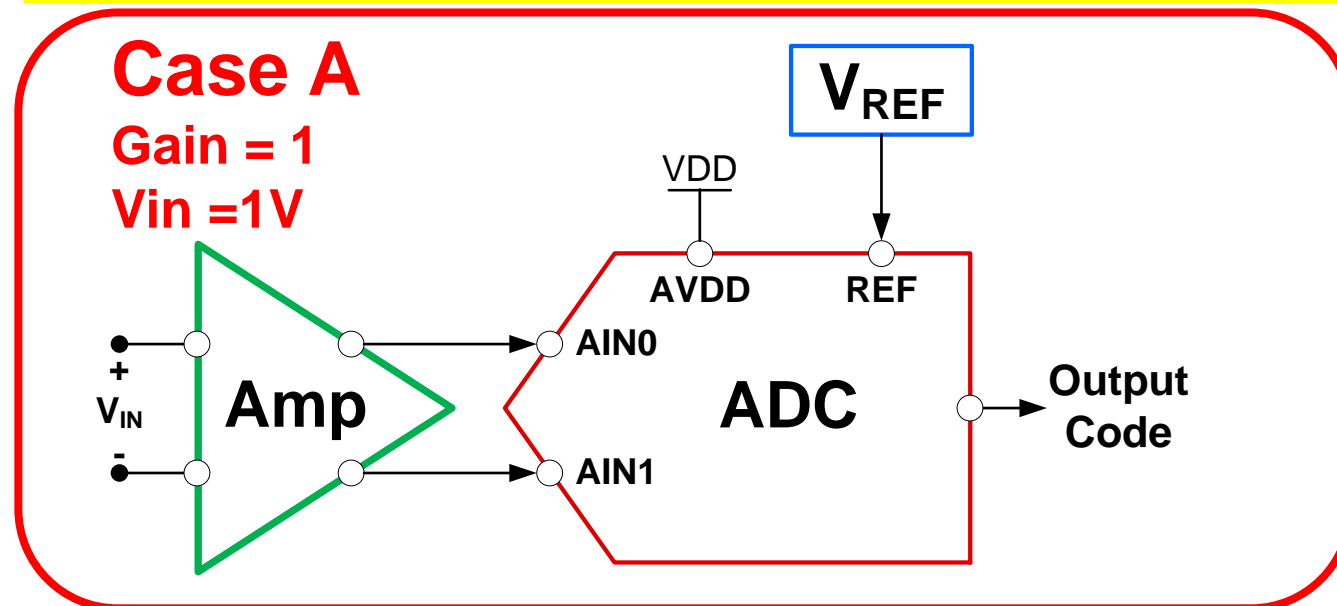
2. Referring to the figure below, assume both circuits are the same except for the gain and input signal. Which of the following are true? Select more than one answer if needed.

a. The amplifier noise referred to the input is the same in both cases

b. The amplifier noise referred to the input is smaller for case B

c. The amplifier noise referred to the output is larger for case A

d. The amplifier noise referred to the output is larger for case B



How reference noise affects signal chain performance

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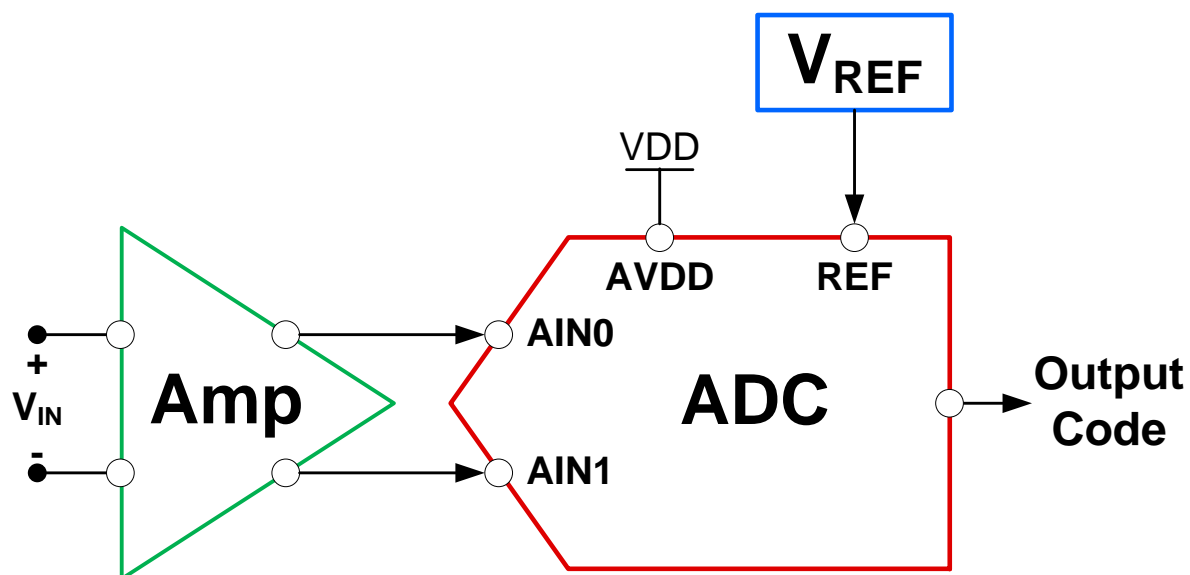
Presented by Alex Smith



how reference noise enters your signal chain, how reference noise is characterized by an ADC, how much reference noise impacts system noise, and how to calculate and simulate reference noise using a component's datasheet. This module applies that information to a signal chain in order to determine total noise and dynamic range for a voltage reference plus amplifier plus ADC system. A follow up presentation discusses ways to minimize reference noise.

To begin, let's recall the ultimate goal that we are trying to accomplish throughout the Precision Labs module series on noise

Total system noise



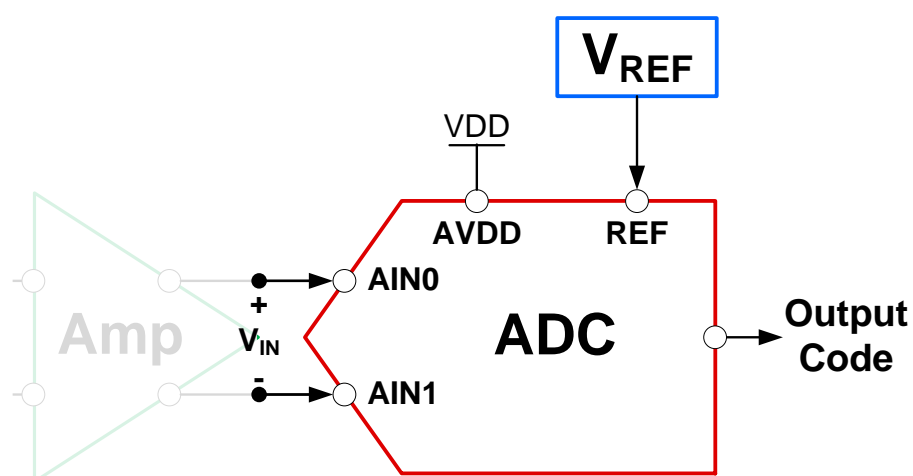
$$\text{Total noise} = \sqrt{V_{N,ADC(RTI)}^2 + V_{N,AMP(RTI)}^2 + V_{N,REF(RTI)}^2}$$

Shown here is the simplified signal chain block diagram that is reused from the previous Precisions Labs module covering reference noise in ADC systems. As was discussed in that presentation, the goal is to understand how noise enters this system, how noise affects each component, and the total system noise represented by the equation at the bottom of the slide.

Now that each noise term has been discussed in detail, this presentation focuses on bringing all of this information together to understand total system performance.

In order to do so, this presentation will be broken up into two parts: first, it will focus on the relationship between ADC noise and voltage reference noise only. This is the equivalent of a system without a gain amplifier, such as one you need to measure a sensor whose output voltage is 0 volts to 2.5 volts using a 2.5 volt reference. Second, we will investigate the total noise performance for systems that include a gain stage, such as a data acquisition board that measures a load cell's low-level output, to see how the noise analysis differs.

Calculating system (ADC + VREF) noise



$$V_{N,REF(RTI)} = \frac{V_{IN(RMS)}}{V_{REF}} \cdot V_{N,REF(RMS)}$$

$$V_{N,ADC(RTI)} = \text{ADC noise from datasheet}$$

$$\text{Total noise} = \sqrt{V_{N,ADC(RTI)}^2 + V_{N,REF(RTI)}^2}$$



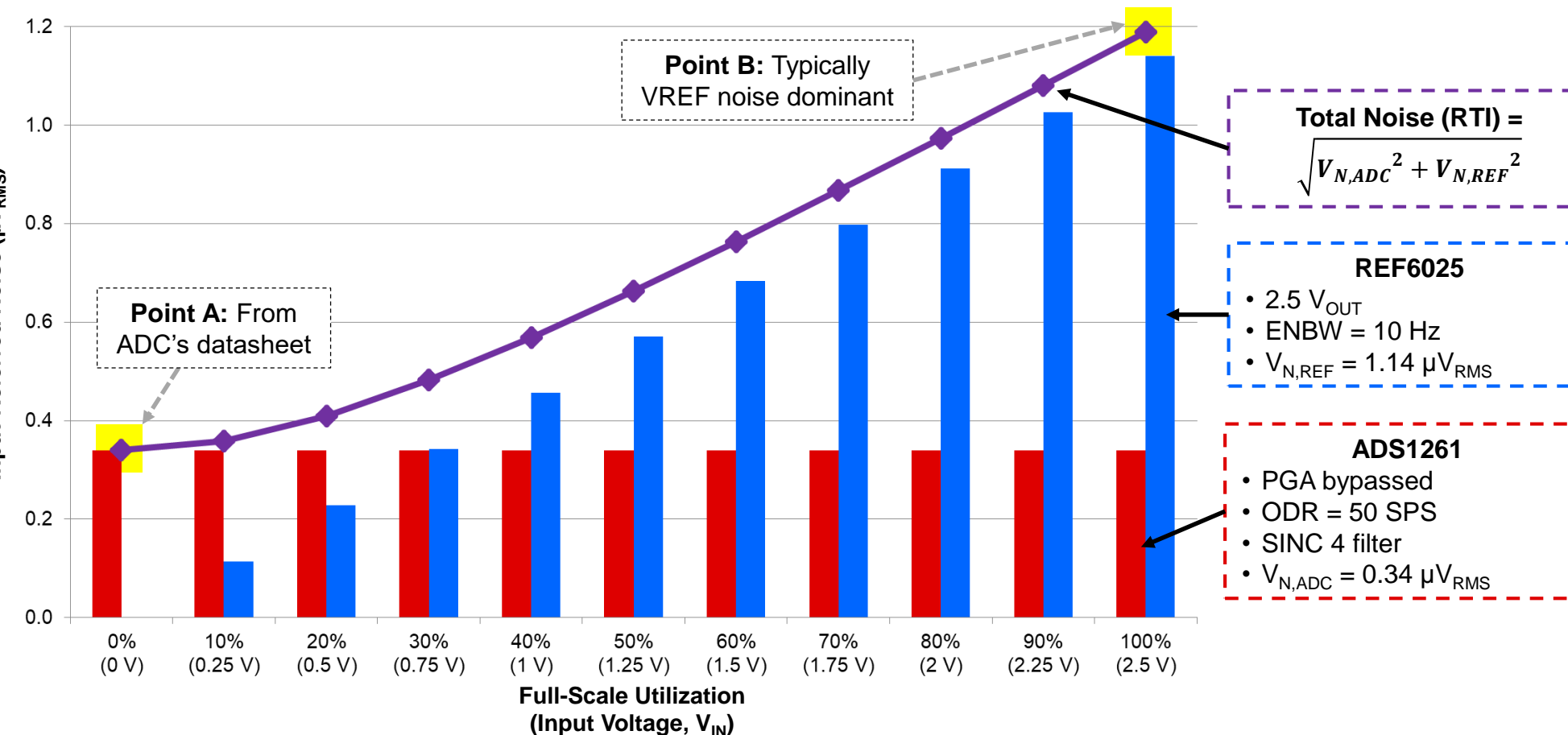
As stated on the previous slide, let's first analyze the ADC-and-voltage-reference system represented by the block diagram on the left. This image represents a system that needs to measure input signals spanning a majority of the ADC's full-scale range. This large input range prohibits the use of a gain amplifier, though the system might require an input buffer or ADC driver amplifier. Either way, this analysis assumes that any amplifier noise is negligible compared to the ADC, since this is best practice for low- or no-gain input amplifiers. Please refer to the Precision Labs modules covering amplifier and ADC noise for more information.

Next, recall that we derived an equation for the input-referred reference noise in the previous Precision Labs module on reference noise. This equation is reiterated in the top right, highlighted in blue, and states that the reference noise is scaled by the ratio of the input signal to the reference voltage. Or, in practical terms, the more of the ADC's full-scale range that you use, the more reference noise you let into your system.

On the bottom right, highlighted in red, the ADC noise can be determined from the datasheet since it is independent of input signal.

Given these relationships, you calculate total noise using the equation at the bottom of this slide. Let's apply values to these parameters and sweep the input signal from zero to full-scale to see how the total system noise changes as a function of input signal.

Plotting system noise across V_{IN} (gain = 1)



The plots shown here represent the ADC, reference, and total system noise, all as a function of full-scale utilization. Only the ADC's positive full-scale range is shown, though negative full-scale would just be an identical plot reflected about the y-axis. The red bar chart represents the ADS1261, a 24-bit delta-sigma ADC. At a data rate of 50 samples per second using the sinc 4 filter, this ADC has an input-referred noise of 0.34 microvolts RMS as shown. However, this analysis applies equally to other data rates, as well as wideband delta-sigma and SAR ADCs. Moreover, the ADS1261 integrates a low-noise PGA, though it is bypassed in this case to mimic the setup on the previous slide. As a result, the ADC noise dominates

The blue bar chart represents the REF6025, a low-noise 2.5 volt voltage reference with integrated buffers. Due to the ADC digital filter's low data rate and output bandwidth, the reference noise is band-limited to approximately 10 hertz as shown. It was determined in the previous Precision Labs module that the REF6025's total output noise at 10 hertz is 1.14 microvolts RMS. As the blue plot illustrates, the input-referred reference noise seen by the system increases linearly up to the total output noise due to the scaling factor shown on the previous slide.

Since these are uncorrelated noise sources you can take their root sum of squares to find the total noise, represented by the purple line chart and the equation on the top right.

Looking at the purple plot, Point A represents a zero volt input signal such that the total noise is just the ADC noise, which can typically be read directly from the ADC's datasheet. Compare that to Point B, which is equivalent to the total noise when the input voltage is equal to the reference voltage, or a full-scale measurement. In this example, the reference noise dominates at full-scale such that Point B is just the reference's total output noise at the given bandwidth.

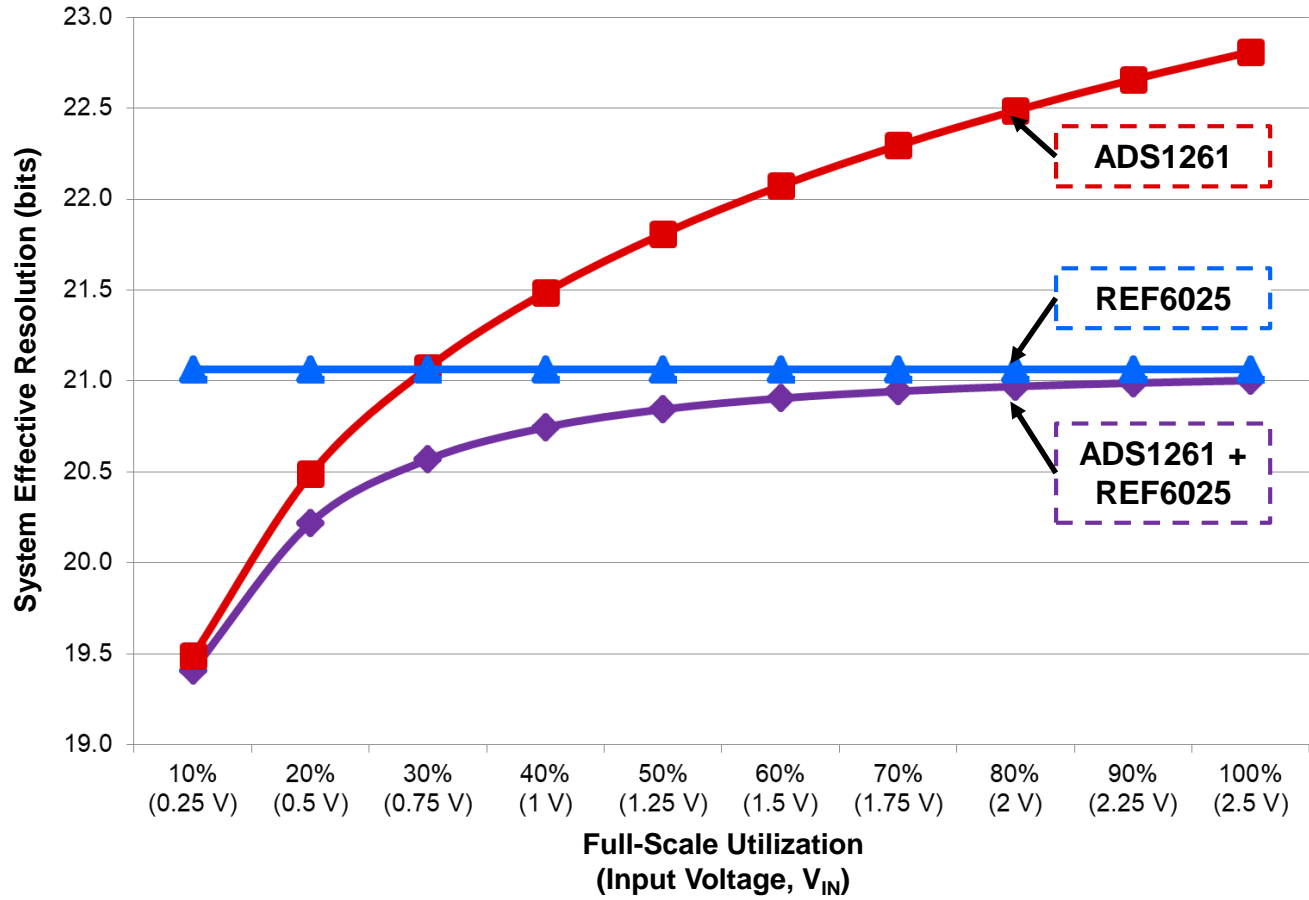
Let's now look at how these results impact the system's effective resolution, or dynamic range

System effective resolution (dynamic range)

$$\text{Effective resolution} = \log_2 \left(\frac{V_{IN}}{V_{N,RTI}} \right)$$

- ADC**
- **Noise** = constant w.r.t. V_{IN}
 - **Effective resolution** = changes w.r.t. V_{IN}

- VREF**
- **Noise** = scales linearly w.r.t. V_{IN}
 - **Effective resolution** = constant w.r.t. V_{IN}



Highlighted in yellow on the left side of the slide is the general equation for calculating the system's effective resolution: log base two of the input signal divided by the noise. Beneath this equation, highlighted in red, it is denoted that the ADC noise is constant across V_{IN} , such that the effective resolution changes as V_{IN} is swept from zero to full-scale. This is represented by the red plot on the right.

In the lower left, highlighted in blue, it is denoted that the reference noise scales linearly with respect to V_{IN} , such that the voltage reference effective resolution is constant across V_{IN} . This is represented by the blue plot on the right

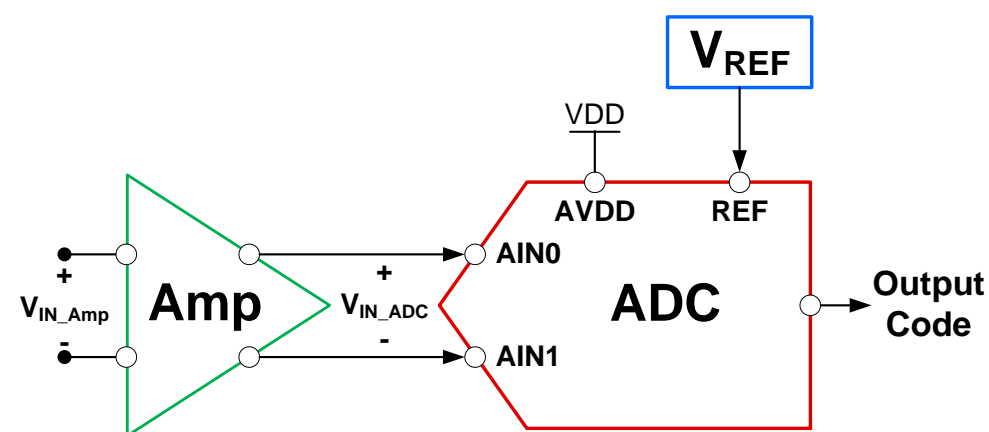
Finally, the purple plot on the right represents the effective resolution across full-scale utilization for the combined ADC plus VREF system. Note that as the full-scale utilization increases, the voltage reference for this system acts as an effective resolution limit. Since the input signals in this example are assumed to be using a majority of the ADC's full-scale range, adding gain is not possible. Therefore, you are left with two options assuming all other system parameters are fixed: use a lower noise voltage reference or a higher noise ADC.

Using a lower noise reference shifts the blue curve up, lowering the total system noise and increasing the available effective resolution. If the voltage reference selection is fixed however, you could potentially save some cost by employing a slightly higher noise ADC instead. Unfortunately this option does not improve the system performance. In both cases, the key takeaway for this

type of system is to ensure that your ADC noise and reference noise are comparable at the system settings. Otherwise, you are not able to fully realize your low-noise ADC or voltage reference's performance.

Now let's move on to analyze a system that has low-level input signals where a gain amplifier can be used

Calculating system (amp + ADC + VREF) noise



$$V_{N,AMP(RTI)} = \text{from datasheet}$$

$$V_{N,ADC(RTI)} = \frac{V_{N,ADC(\text{datasheet})}}{\text{Gain}}$$

Deriving an equation for $V_{N,REF(RTI)}$

	Comment	Equation
Step #1	VREF noise equation	$\frac{V_{IN_ADC(RMS)}}{V_{REF}} * V_{N,REF(RMS)}$
Step #2	Refer to input = divide by gain	$\frac{V_{IN_ADC(RMS)}}{V_{REF} * \text{Gain}} * V_{N,REF(RMS)}$
Step #3	Substitute V_{IN_ADC} for $V_{IN_AMP} * \text{Gain}$	$\frac{V_{IN_AMP(RMS)} * \text{Gain}}{V_{REF} * \text{Gain}} * V_{N,REF(RMS)}$
Step #4	Final equation	$\frac{V_{IN_AMP(RMS)}}{V_{REF}} * V_{N,REF(RMS)}$

$$\text{Total noise} = \sqrt{V_{N,ADC(RTI)}^2 + V_{N,AMP(RTI)}^2 + V_{N,REF(RTI)}^2}$$



Here is the same signal chain analyzed in the previous slides, though now the amplifier has been added back into the system. As stated on the left underneath the block diagram, the amplifier noise needs to be calculated using values or plots from its datasheet. If your ADC includes an amplifier, consult the ADC's datasheet to determine the amplifier's noise contribution. To determine the ADC's input-referred noise, take the ADC output noise from its datasheet and divide by the system gain as shown. Please review the Precision Labs module on how amplifier noise affects ADC performance for more information on this topic.

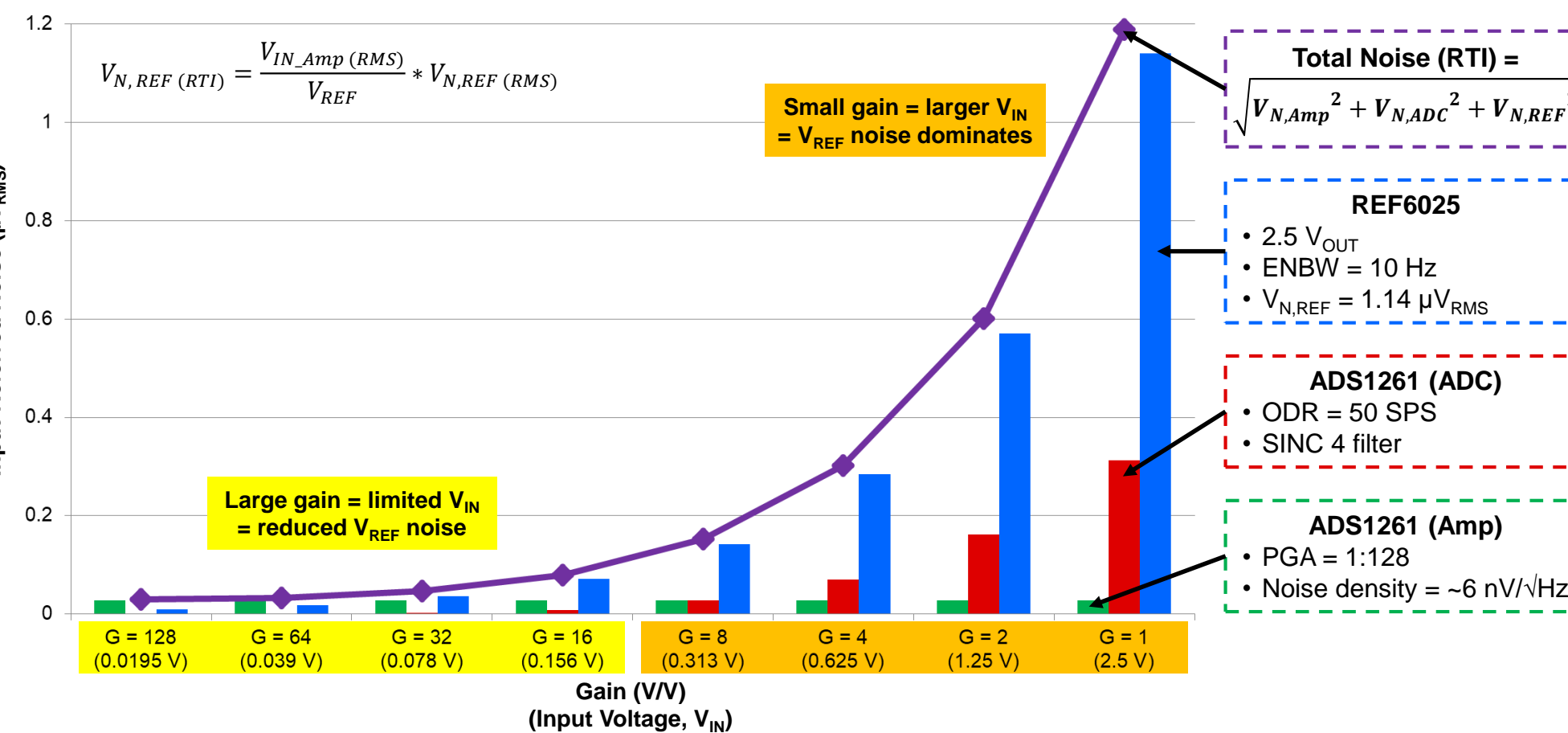
Deriving the equation for the reference noise is a bit more complicated, and is captured step by step in the table on the right. Step one begins with the standard reference noise equation, with the noise specifically referred to the ADC's input as it would be for a gainless system. Similar to the ADC noise, step two refers the reference noise to the input of the amplifier by dividing by the system gain. Step three substitutes the VIN ADC term with the VIN AMP multiplied by gain term, resulting in the two gain terms canceling out. This yields the final equation in step four that is virtually identical to the original input-referred reference noise equation. The key difference however is that now the input scaling factor is referred to the amplifier's input, not the ADC's. Interestingly, this means that if your input signal was 100 millivolts, using a gain of one or a gain of 10 has no effect on how much reference noise passes into your system.

However, gain can indirectly help reduce reference noise by limiting the

allowable input signal range. Moreover, you may also directly reduce your ADC noise by gaining up the input

Like we did in the previous analysis, let's apply values to these parameters to see how the total system noise behaves as both gain and input signal change

Plotting system noise across gain ($V_{IN} = 100\% \text{ FS}$)



Similar to the previous plot comparing ADC and reference noise only, this plot shows the ADC noise in red, the reference noise in blue, and the total noise in purple. Additionally, the amplifier noise is shown in green. Note that the ADS1261 includes both the ADC and amplifier, and the datasheet reports noise as a combined input-referred value. However, since the amplifier noise dominates at high gain, the input-referred amplifier noise can be inferred from the noise tables as approximately 28 nanovolts RMS at the given settings.

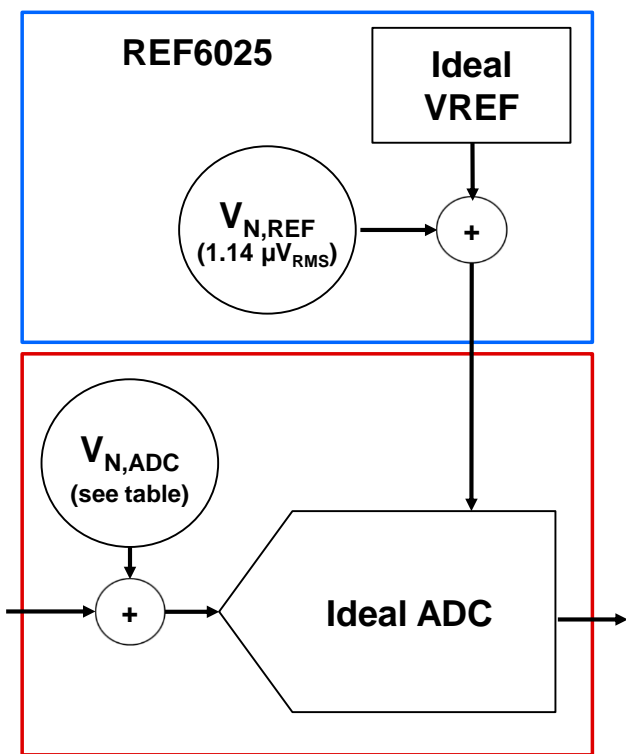
One major difference between this plot and the previous example is that the input voltage for each gain value is the maximum allowable, or 100% of full-scale. For example, the noise values shown for the gain of 128 volts per volt assumes that the input to the amplifier is 19.5 millivolts, which is the maximum allowable. Given this condition, the reference noise passed to the system is comparable to the amplifier noise for gains of 16, 32, 64, and 128 volts per volt, as highlighted in yellow. This is true even though the full-scale range is maximized in all cases and the reference noise only depends on the ratio of V_{IN} to V_{REF} . Instead, it is the amplifier gain that is limiting the maximum input signal and therefore reducing the reference noise seen by the system. Comparatively, the smaller gains highlighted in orange enable a larger maximum input signal such that the reference noise dominates the total system noise.

Ultimately, this plot tells us that applying gain is essential when designing a low-noise, small-signal data acquisition system. Not only does gain help reduce the effects of noise contributed by the ADC, but it indirectly reduces reference noise

by limiting the input signal range. This is important because this plot clearly indicates that reference noise is often the dominant noise source when paired with a low-noise amplifier and a higher-resolution ADC.

However, what if the reference noise didn't dominate at full-scale? For example, what if you were using a 12-bit ADC instead of a 24-bit ADC. How would the analysis change if you are using a lower-resolution versus a higher resolution ADC?

Lower- vs higher-resolution ADCs: references



Parameter	Conditions	Units	ADC Resolution (bits)								
			8	10	12	14	16	20	24	32	
ADC noise	G=1, 50 SPS, V _{REF} = 2.5 V	μV _{RMS}	19,531	4,883	1,221	305	76	11.2	0.53	0.18	
LSB size	FSR = 2*V _{REF}	μV	19,531	4,883	1,221	305	76	4.76	0.29	0.001	
VREF noise	BW = 10 Hz	μV _{RMS}	1.14								
Total noise	V _{IN} = 100% FS	μV _{RMS}	19,531	4,883	1,221	305	76	11.3	1.3	1.2	
Increase in noise	n/a	%	0%	0%	0%	0%	0.01%	0.9%	148%	589%	

For **lower-resolution ADCs**, reference noise has **virtually no impact** on total noise

For **higher-resolution ADCs**, reference noise has a **large impact** on total noise



To answer this question, let's use the generic, gainless system shown on the left that has the REF6025 connected to an ADC. The first row in the table on the right summarizes the input-referred noise from ADCs with resolutions ranging from 8 to 32 bits at the given settings, while the second row shows the corresponding LSB size. The third row shows the REF6025 noise is 1.14 microvolts RMS at 10 hertz

Assuming each ADC could support an external 2.5 volt reference and that you are measuring a full-scale input, the fourth row calculates the combined noise of the ADC plus reference by taking the root-sum-square of each noise component. The last row in the table includes the percent increase in noise from just the ADC to the ADC plus reference combination.

If you look at just the lower-resolution ADCs, which is any device less than or equal to 16 bits, the reference has virtually no impact on the total noise. This is due to the fact that the ADC's quantization noise is so much larger than the reference noise. As a result, many lower-resolution ADCs don't have external reference inputs, often just using the supply voltage as a reference. Compare that to the 24-bit, higher-resolution ADC that experiences an incredible 148% increase in noise relative to the ADC by itself!

To be clear: this is not to say that you should never worry about reference noise with 16-bit or lower ADCs. In reality, you should always perform some quick calculations to determine the general effect any external components might

have on your system. However, you will most likely find minimal change for lower-resolution ADCs, which is why we have focused our efforts throughout this module analyzing the impact component noise has on higher-resolution ADC systems.

To that end, lets recall the key takeaways for this presentation.

Key takeaways

Input closer to full-scale = system is in low gain with high utilization, ensure that ADC + VREF noise are comparable

Small input signals = large gain reduces ADC noise and allowable full scale input, which indirectly limits VREF noise

Lower- vs higher-resolution ADCs = amp and VREF noise effects have a greater impact on higher-resolution ADCs, while quantization noise dominates in lower-resolution ADCs

In general, if your input signals use a majority of the ADC's full-scale range, you can expect the reference noise to dominate. In these cases, you should always make sure the ADC noise and reference noise are comparable, as you don't want to pay for a low-noise ADC when your reference noise will dominate anyway.

Or, if your input signals are small and cannot be changed, gaining up your input signal reduces your ADC noise and therefore the total system noise, though this has a practical limit. Moreover, gain reduces the allowable input range to your system, making reference noise negligible in many cases. This may allow you to use a noisier reference as a result, since very little reference noise will actually be passed into the system.

Finally, your system will be more sensitive to amplifier and voltage reference noise when using a higher-resolution ADC, due to the relatively low levels of ADC noise that make other noise sources more obvious. This is not the case for lower-resolution ADCs where quantization noise dominates.

If reference noise is a consideration for your system, there are some methods you can use to reduce the amount of reference noise passed to your signal chain. Please review the Precision Labs module on reference noise mitigation techniques to learn more

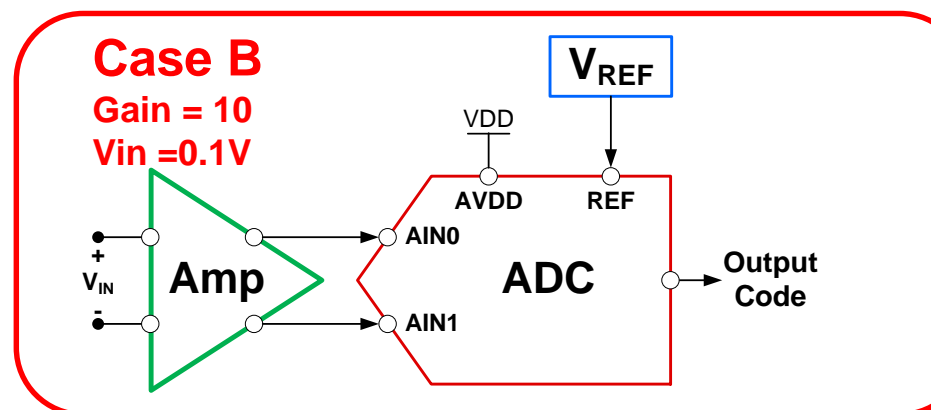
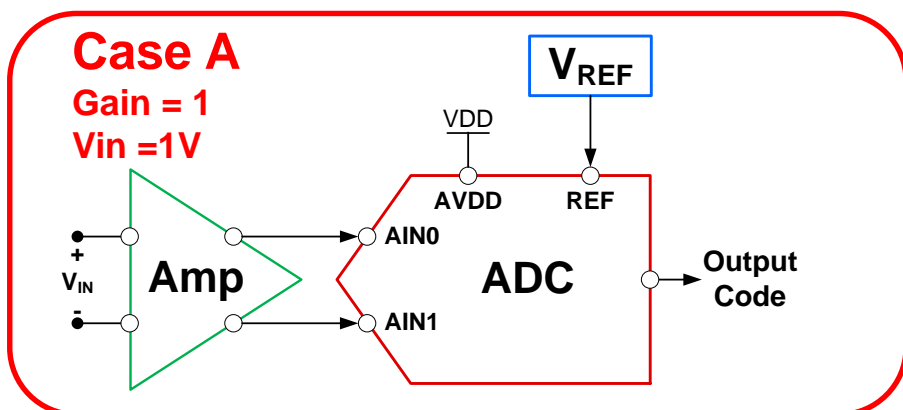
Thanks for your time! Please try the quiz.



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

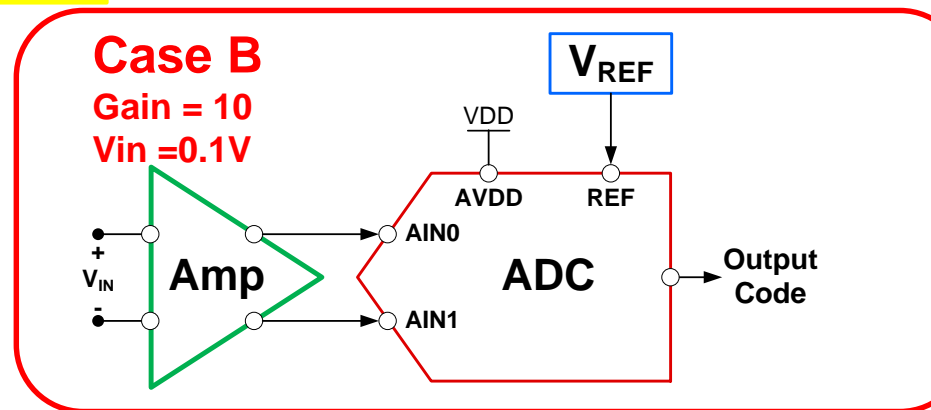
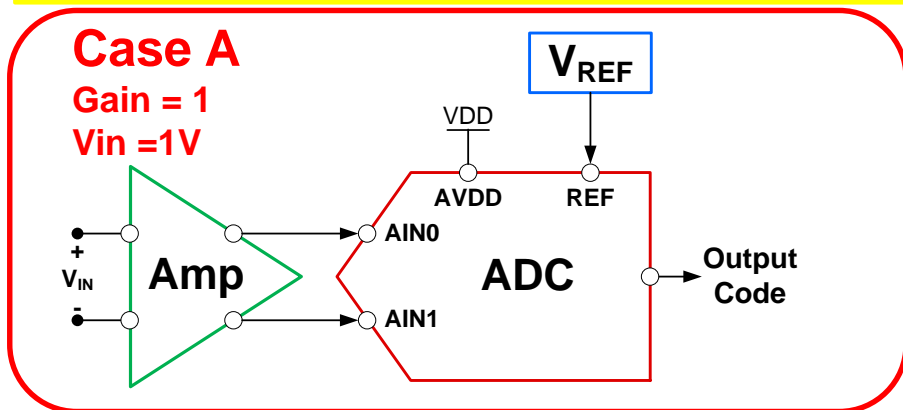
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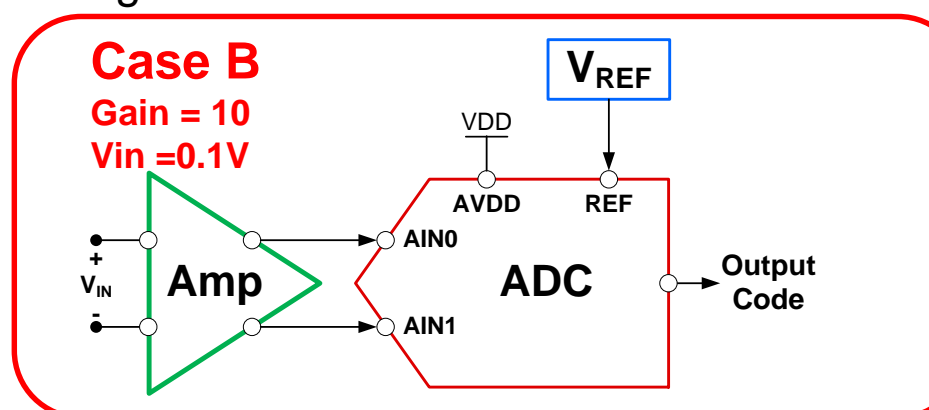
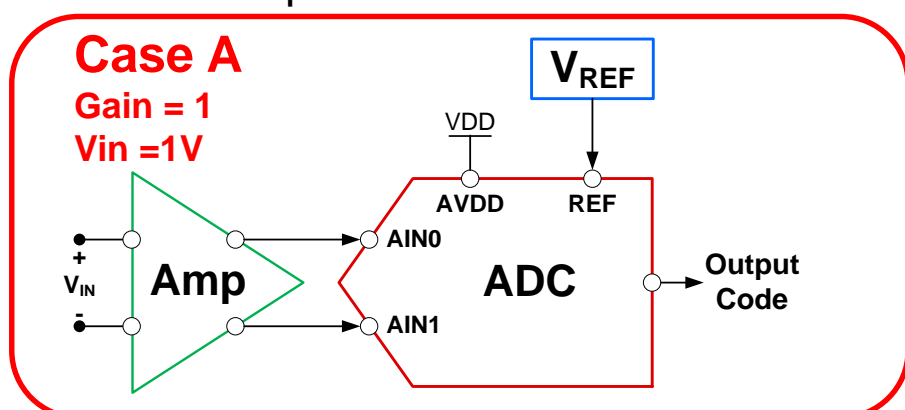
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 - The reference noise is minimized in case B



Quiz: How reference noise affects signal chain

2. Referring to the figure below, assume both circuits are the same except for the gain and input signal. Which of the following are true? Select more than one answer if needed.
- a. The amplifier noise referred to the input is the same in both cases
 - b. The amplifier noise referred to the input is smaller for case B
 - c. The amplifier noise referred to the output is larger for case A
 - d. The amplifier noise referred to the output is larger for case B



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