# Comparator Applications 2
TIPL 2102
TI Precision Labs – Op Amps

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Hello, and welcome to the TI Precision Labs video discussing comparator applications, part 2. In this video we will introduce how external noise can affect a comparator's basic function. We will then discuss the concept of hysteresis and how it can be used to solve noise problems, including how to select component values to achieve different levels of hysteresis.

Noise Effect on Comparator Output
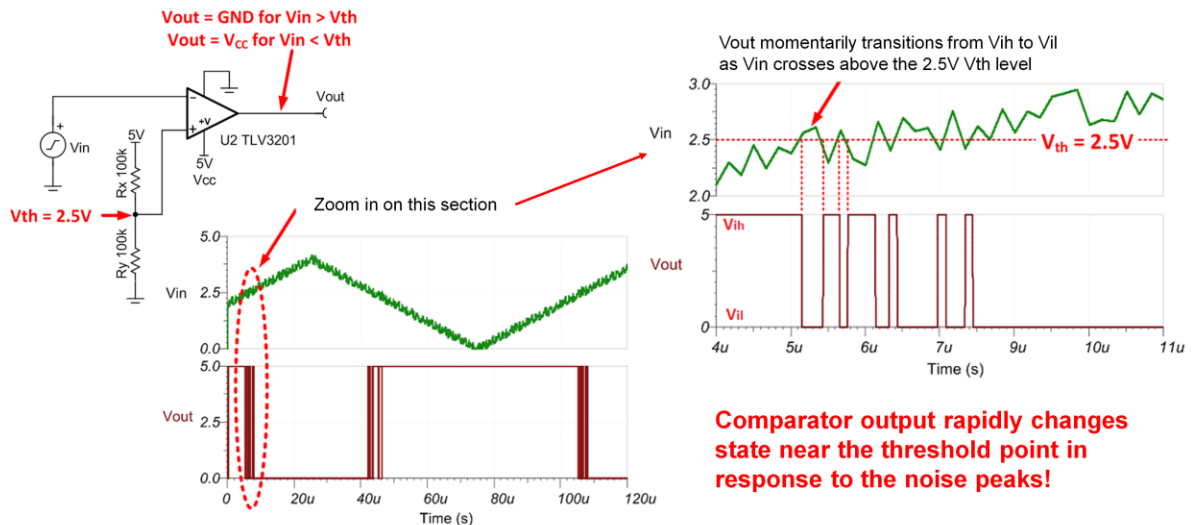
Noise is a common consideration in analog circuits. The comparator is a circuit with an analog input and a digital type of output. Noise will effect the operation of a comparator, whether it's **extrinsic** or **intrinsic** noise. Unfortunately, data sheets don't usually say much about the intrinsic (or internal) noise of the comparator, because intrinsic comparator noise is very difficult to characterize.

Here we show a comparator with a voltage divider that applies 2.5V to the **non-inverting** comparator input, and a generator with a noisy triangle wave applied to the **inverting** comparator input. Looking at

the input and output waveforms, we can observe the noisy triangle waveform and its associated digital output. The diagram at the right shows the results of zooming in on the red circled area.

Inspecting this diagram, you can see that input noise near the 2.5V threshold can cause the output to rapidly change state, sometimes referred to as chatter. This happens because the noise causes the input to move rapidly above and below the threshold. It will continue to change state back and forth until the input voltage stays above the threshold, despite the noise. As you might imagine, this chatter caused by input noise is normally an undesirable condition that we would like to eliminate. For example, suppose that we wanted to count the number of triangle wave edges. The chatter would be interpreted as an error in the count. Next we will consider a method to eliminate this problem.
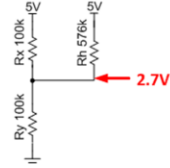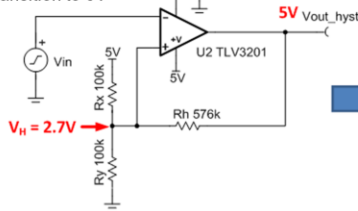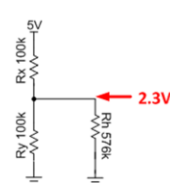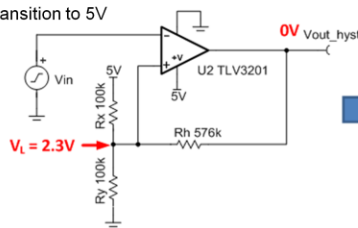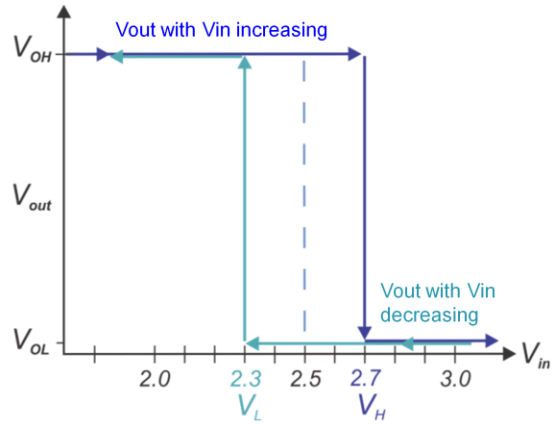
Reducing Noise Sensitivity with Hysteresis

Sensitivity to noise can be reduced through the application of what is called hysteresis. Hysteresis is a form of positive feedback that creates two distinct threshold levels. The first threshold is set for when the input signal is increasing, and the second is set for when the input is decreasing. In this example, the threshold when increasing is set to 2.7V, and the threshold when decreasing is set to 2.3V. This 400mV separation of the thresholds sets the amount of hysteresis in the circuit. The thresholds are set by the values of the resistors in the voltage divider and the feedback.

Let's consider the operation of the circuit when the output is high, at 5V. Notice that in this case, the 576k-ohm feedback resistor is in parallel with **Rx**, the upper resistor in the voltage divider. This causes the voltage at the non-inverting input to be equal to 2.7V. This 2.7V is called the upper threshold, **VH**. Since the comparator is in an inverting configuration, if the signal applied to the inverting input goes above this voltage the output will transition from logic high to logic low.

Now let's look at the case where the output is low, at 0V. In this case the 560k-ohm resistor is in parallel with **Ry**, the lower resistor in the divider, setting the lower threshold, **VL**, to 2.3V. If the input signal is driven below VL, the output will transition from logic low to logic high.

This 400mV of separation between VH and VL creates protection against sudden changes in output state, since the level of the expected input noise is much smaller than 400mV.

Reducing Noise Sensitivity with Hysteresis
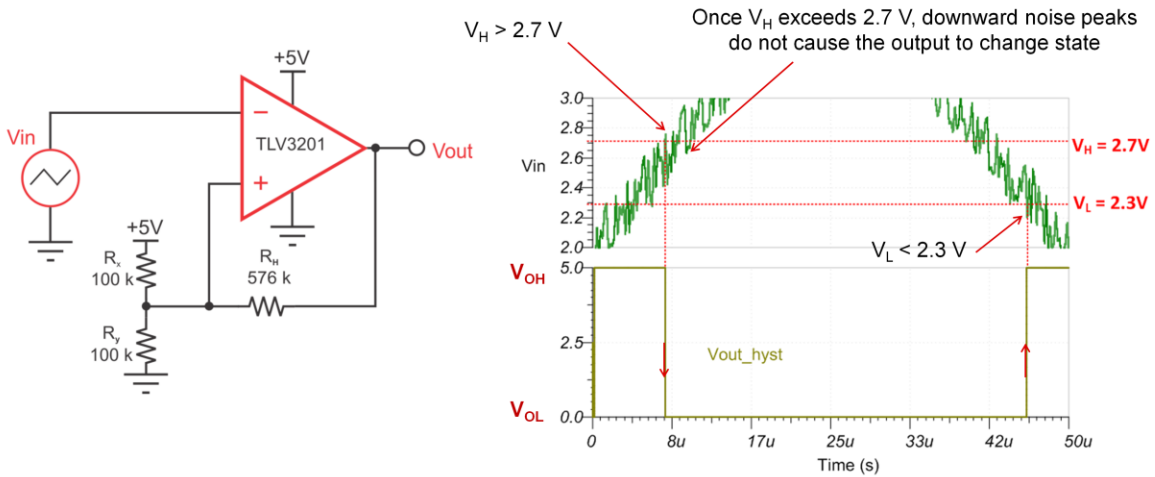
Let's go back to the same circuit that we analyzed previously, now with the 400mV of hysteresis applied. We now have two different thresholds – the **lower** threshold is 2.3V and the **upper** threshold is 2.7V.

Notice that when the input waveform is increasing, the output will not transition until the input goes above the upper threshold of 2.7V. Once the input is above 2.7V, the output will not transition again until the input goes beneath the lower threshold of 2.3V. As as long as the noise is lower that the hysteresis range of 400mV, you will not see the "chatter" that we saw previously. Thus, the amount of hysteresis

used is set according to the noise that you expect to see in your system.

Some Comparators Have Built-in Hysteresis

TI comparators with built-in hysteresis:

- **TLV3202** – 40 ns micropower, push-pull output, V_{HYST} 1.2 mV typ.

- **TLV3501** – 4.5 ns high speed, push-pull output, V_{HYST} 6 mV typ.

- **TL712** – 25 ns high speed, differential open-collector, V_{HYST} 5 mV typ.

- **TL714** – 5 ns high speed, push-pull output, V_{HYST} 10 mV typical

- **LMP7300** – µPower, open-collector, positive and negative hysteresis set independently

NOTE: External hysteresis can still be applied!

TLV3501 simulation model with built-in hysteresis
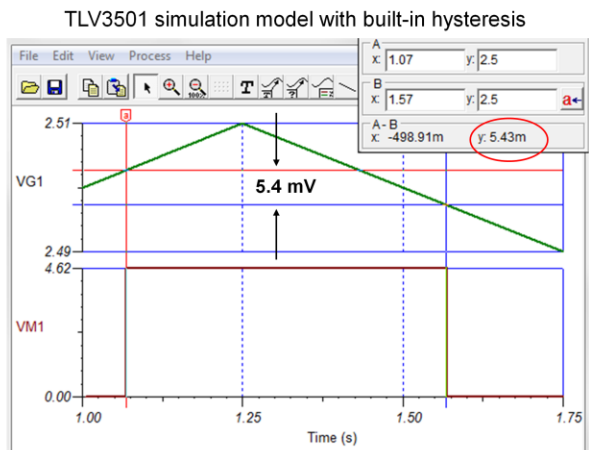
Some of our comparators at Texas Instruments have built in hysteresis, but in general, the **amount** of built-in hysteresis is normally just a few millivolts. This list gives examples of several comparators with built-in hysteresis. For example, the TLV3202 micropower comparator with a push-pull output has a hysteresis of just 1.2 mV. The TLV3501 high speed comparator has 6mV of hysteresis. Note that devices with built in hysteresis can still use the external hysteresis circuit that we described in the previous slide if you need more hysteresis than what is internally provided. The example simulation shown here is using the TLV3501 SPICE model. The input waveform VG1, a low level

triangle wave, shows the points at which the upper and lower thresholds VH and VL occur. Note that the simulated hysteresis is about 5.4mV, very close to the 6mV specified in the data sheet.

Hysteresis Design Procedure – Non-inverting

Design goals
- V_{HYST} = 100 mV
- V_{ref} = 2.5 V
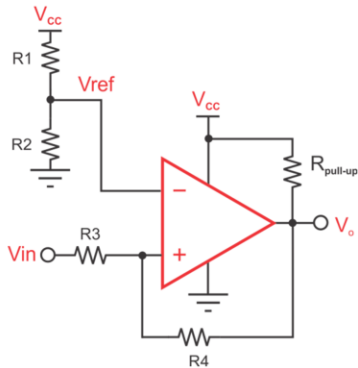
Select starting values

$Vcc = 5\ V,\quad V_{O(max)} = 5\ V,\quad V_{O(min)} = 50\ mV$

$R1 = 100\ k,\quad R_{pull\text{-}up} = 10\ k$

Calculate remaining values

$$R2 = \frac{R1}{\left(\frac{Vcc}{Vref}-1\right)} = \frac{100\ k}{\left(\frac{5.0}{2.5}-1\right)} = 100\ k$$

$$R3 = \frac{(R1 \cdot R2)}{(R1+R2)} = \frac{(10^5 \cdot 10^5)}{(10^5+10^5)} = 50\ k$$

$$R4 = R3\left[\frac{(V_{O(max)} - V_{O(min)})}{V_{HYST}} - 1\right] = 5 \cdot 10^4\left[\frac{(5.0 - 0.05)}{0.10} - 1\right]$$
$$R4 = 2.43\ MEG$$

The equations here provide a general procedure for determining the resistor values to set the hysteresis requirement. This particular design process is specific to a **non-inverting** comparator circuit with an open-drain, or open-collector output. In this example, the design goals are to set the hysteresis to 100mV with a reference voltage of 2.5V. The supply voltage for the comparator Vcc is 5V. This makes the output swing equal to 5V maximum and 50mV minimum.

We must first select values for R1, the upper resistor in the Vref voltage divider, as well as Rpull-up. Once these are selected, we can easily calculate the

remaining resistances in the circuit. In order to prevent excessive current draw, we'll set R1 to 100k and Rpull-up to 10k.

Next, using the voltage divider equation, we can calculate the value for R2 in order to create the desired Vref voltage of 2.5V. This works out to be 100k.

We then calculate R3, setting it equal to the parallel combination of R1 and R2, which in this example is equal to 50k.

Finally, we'll calculate R4, the feedback resistor, using the equation shown here which depends on the value of R3, the comparator output swing, and the desired hysteresis voltage. The result is that R4 must be equal to 2.43 M.

This completes the necessary design calculations. Keep in mind that the hysteresis voltage will be most accurate when $R_{pull-up}$ is less than $1/10^{th}$ the value of R4. At the end of the design calculations, you should always double check the pull-up value to make sure this relationship is maintained. In this case, Rpull-up is 10k and R4 is 2.43M ohm, so there is no issue.
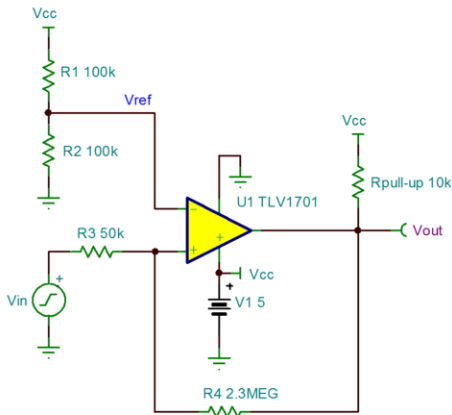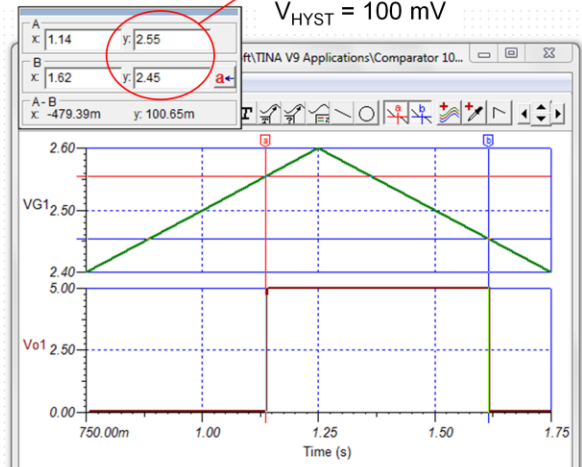
Let's now verify our design with hysteresis using SPICE simulation. Here we show the circuit as designed on the previous page using the TLV1701 comparator. Applying a slow-moving triangle wave to the non-inverting input, we can use cursors to mark the points where the output voltage transitions. In this example we see that the output transitions when the input passes a VH, or upper threshold, of 2.55V, and when the input passes a VL, or lower threshold, of 2.45V. This results in 100mV of hysteresis, matching the design goals very well.

Hysteresis Design Procedure – Inverting

Design goals
- V_{HYST} = 50 mV
- V_{ref} = 2.5 V
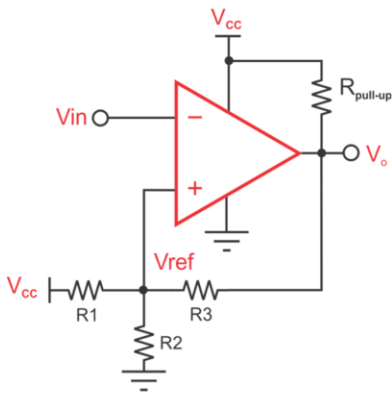
Select starting values

$Vcc = 5$ V, $V_{O(max)} = 5.0$ V, $V_{O(min)} = 0.05$ V

$R1 = 10$ k, $R_{pull-up} = 10$ k

Calculate remaining values

$$R2 = \frac{R1}{\left(\frac{Vcc}{Vref}-1\right)} = \frac{10\ k}{\left(\frac{5.0}{2.5}-1\right)} = 10\ k$$

$$R3 = \frac{(R1 \cdot R2)}{(R1+R2)}\left[\frac{\left(V_{O(max)}-V_{O(min)}\right)}{V_{HYST}}-1\right]$$

$$R3 = \frac{(10^4 \cdot 10^4)}{(10^4+10^4)}\left[\frac{(5.0-0.05)}{0.05}-1\right] = 490\ k$$
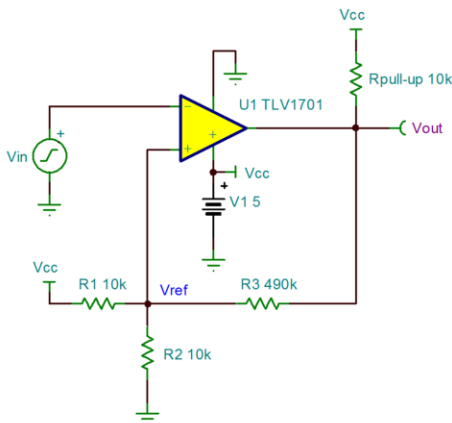
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Let's do the same type of design procedure, this type for an **inverting** comparator configuration. Notice that the input signal for this circuit is connected to the **inverting** input of the comparator, where in the non-inverting circuit it was applied to the **non-inverting** input.

In this example, the design goals are to set the hysteresis to 50mV with a reference voltage of 2.5V. The supply voltage and output swing are the same as before. This time we will set R1 to 10k and Rpull-up to 10k, where in the previous example R1 was equal to 100k. The remaining resistors, R2, and R3, can now
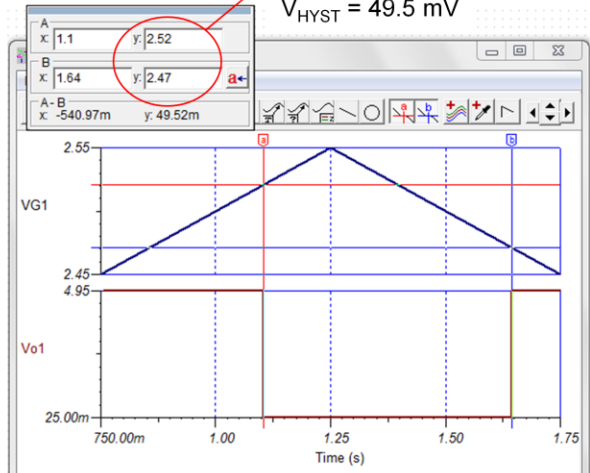
be calculated. Please notice that the design equations are different for this circuit configuration!

Using the first equation to calculate R2 yields a value of 10k. The second equation yields 490k ohm for R3 the hysteresis resistor. Again, double check that Rpull-up is less than 10% of R3, the hysteresis feedback resistor.

Checking this design in TINA-TI, the simulation result shows that VH = 2.52V and VL = 2.47V, corresponding to 49.5mV of hysteresis. Our design goal was 50mV, so this is a good result. Again, remember that the design procedure depends on setting the pull-up resistor to be less than a tenth of hysteresis resistor R3.

Please note that these design procedures, both non-inverting and inverting, work with push pull output comparators as well, just remove the pull-up resistor!

Hysteresis Design Procedure – Summary

- The resistor values affect either the reference voltage and/or the V_H and V_L levels. Their tolerances are an important factor in hysteresis accuracy.

- The feedback resistor is usually very high in value compared to the others. Its loading on the non-inverting input divider is usually minimal.

- Keeping $R_{pull\text{-}up}$ less than 10 % of the feedback resistor value assures more accurate V_H and V_L voltage levels.

- The inverting and non-inverting equations can be used for push-pull output comparators

  - Remove $R_{pull\text{-}up}$ from the circuit

  - Use the datasheet *Output Voltage vs Output Current* curves to establish $V_{O(max)}$ and $V_{O(min)}$ from the V_{OH} and V_{OL} levels
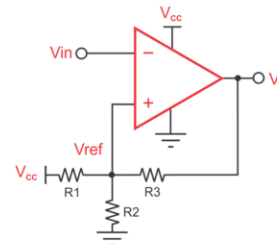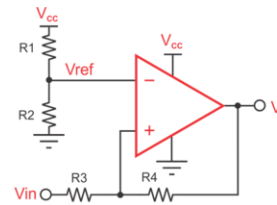
Push-pull comparators with hysteresis applied

Let's summarize the key points from this video:

Adding hysteresis to a comparator circuit greatly helps reduce its sensitivity to input noise. Hysteresis is applied by adding resistors to the input and feedback networks of the comparator circuit.

- These resistor values affect both the reference voltage Vref, and the upper and lower thresholds VH and VL. Keep in mind that the tolerance of

these resistors will affect your hysteresis accuracy!

- The feedback resistor is usually higher in value than the other resistors, therefore its loading on the voltage divider in the non-inverting is minimal.

- Make sure that the value of Rpull-up is less than 10% of the feedback resistor in order to ensure accurate hysteresis voltage.

- This design procedure can also be used for push-pull output comparators! Simply remove Rpull-up from the circuit, and use the datasheet curves for *Output Voltage vs Output Current* to establish $V_{O(max)}$ and $V_{O(min)}$ from the V_{OH} and V_{OL} levels.

As one final note, these design guidelines will work for the majority of your hysteresis needs. However, there are exceptions for more complex circuits where other design constraints are involved. Please don't hesitate to reach out to your applications engineers at Texas Instruments for guidance with these types of designs!

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.
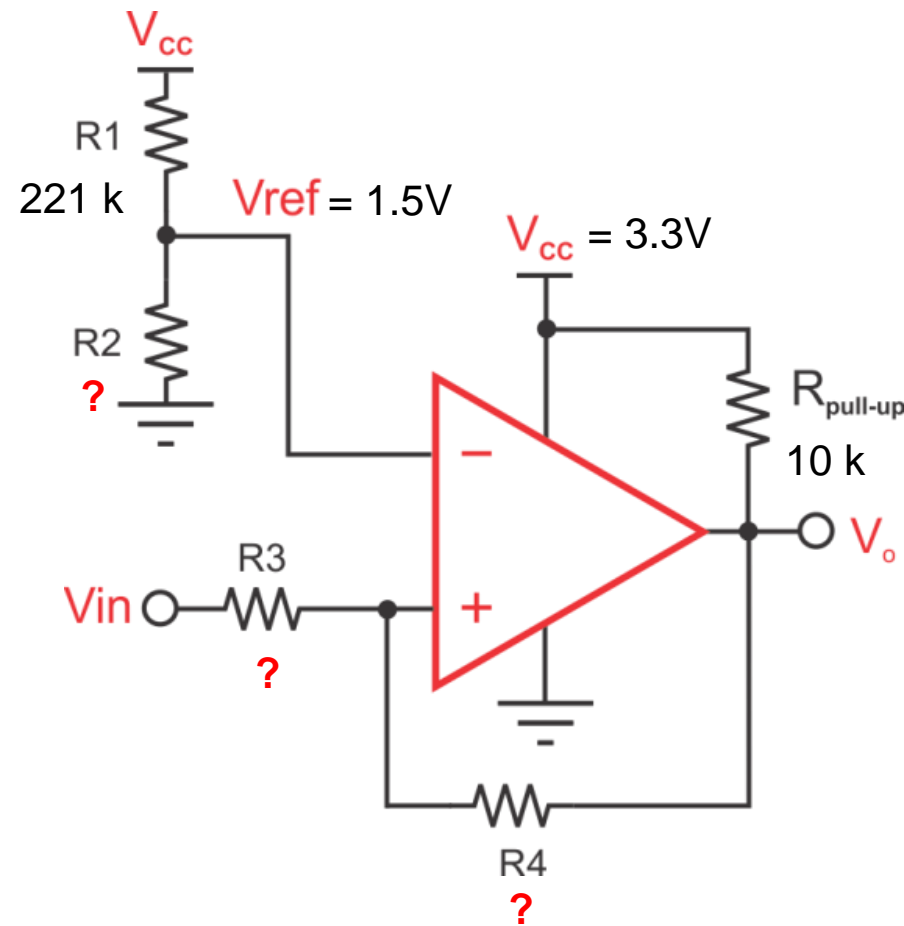
Comparator Applications 2 Quiz

TIPL 2102
TI Precision Labs – Op Amps

TEXAS INSTRUMENTS

Question 1

a) Design the non-inverting comparator with hysteresis circuit to meet the design goals.
b) Verify with simulation in TINA-TI using the related file **2102_Q1.tsc**

Design goals

$V_{HYST} = 200$ mV, $V_{ref} = 1.5$ V

Starting values

$V_{cc} = 3.3$ V, $V_{O(max)} = 3.3$ V, $V_{O(min)} = 50$ mV

$R1 = 221$ k, $R_{pull-up} = 10$ k

Calculate remaining values

$R2 = ?$, $R3 = ?$, $R4 = ?$

Multiple Choice

- Noise can affect the operation of a comparator by _____.
  a. Causing the output to rapidly change state
  b. Changing the effective threshold voltage
  c. Reducing the rise time and fall time
  d. Both a. and b.

- Noise on which inputs of a comparator can affect its operation?
  a. Input signal V_{IN} only
  b. Reference signal V_{REF} only
  c. Both V_{IN} and V_{REF}
  d. Neither V_{IN} nor V_{REF}

Multiple Choice

- Hysteresis is a form of _____ that _____.
    a. Positive feedback; creates two distinct threshold levels
    b. Positive feedback; creates a single noise-immune threshold level
    c. Negative feedback; creates two distinct threshold levels
    d. Negative feedback; creates a single noise-immune threshold level

- When designing a comparator circuit with external hysteresis, the amount of hysteresis should be _____.
    a. Less than 10% of the hysteresis feedback resistor value
    b. Greater than the maximum peak-to-peak noise you expect in your system
    c. Less than the minimum peak-to-peak noise you expect in your system
    d. Less than or equal to the built-in hysteresis of the comparator

Solutions

Question 1a – Solution

Design goals
- $V_{HYST} = 200$ mV
- $V_{ref} = 1.5$ V

Starting values

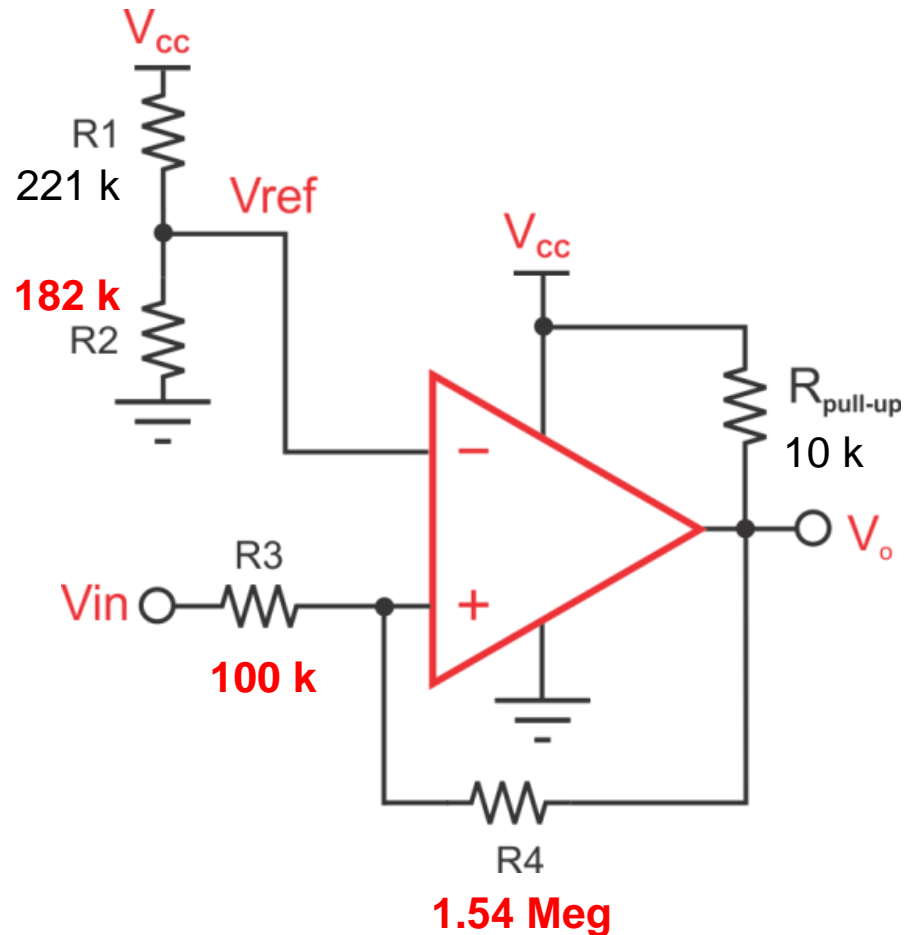$V_{cc} = 3.3$ V, $V_{O(max)} = 3.3$ V, $V_{O(min)} = 50$ mV

R1 = 221 k, $R_{pull-up} = 10$ k

Calculate remaining values

$$R2 = \frac{R1}{\left(\frac{V_{cc}}{V_{ref}}-1\right)} = \frac{221 \text{ k}}{\left(\frac{3.3}{1.5}-1\right)} = 184.2 \text{ k} = \textbf{182 k} \text{ (nearest 1\% value)}$$
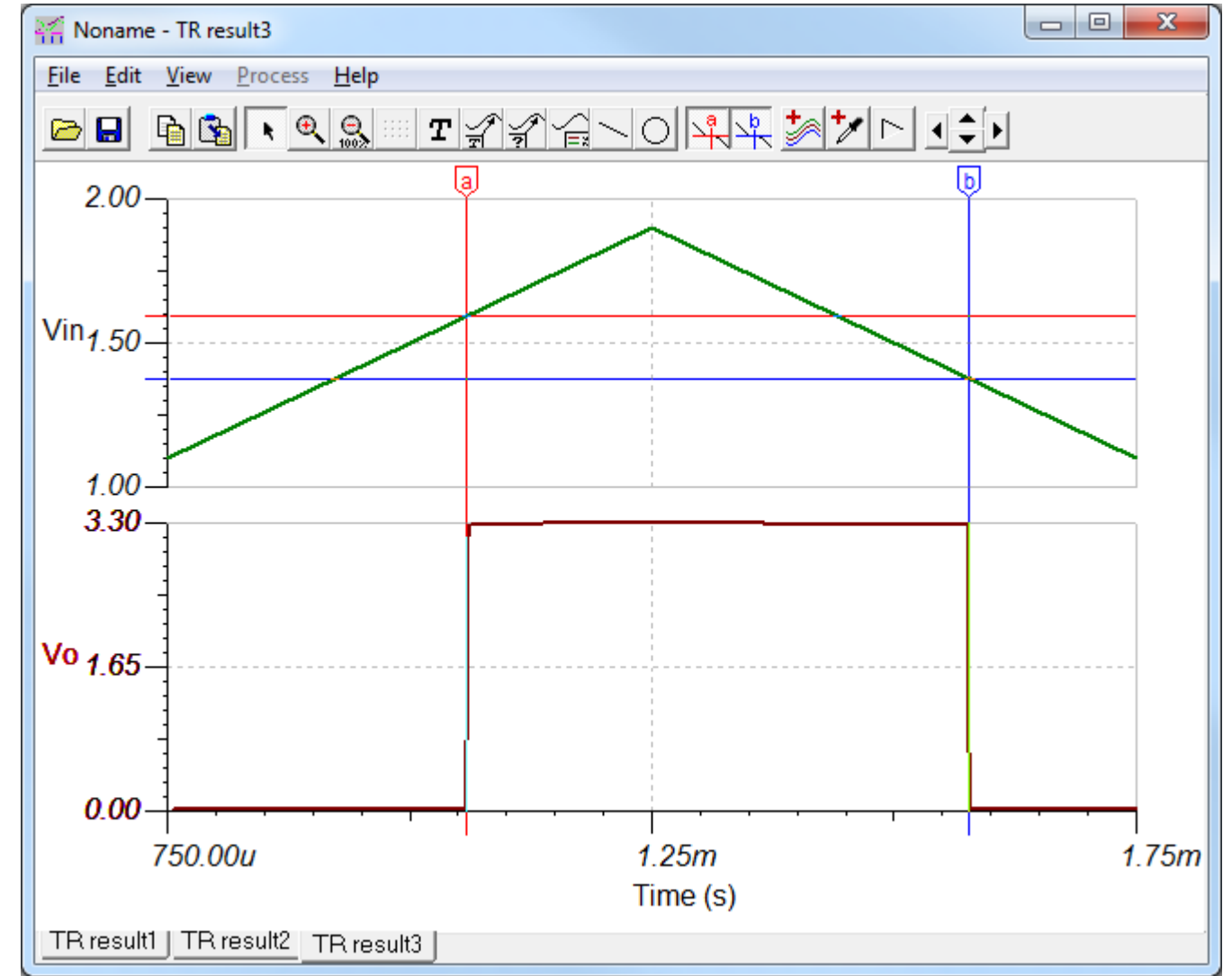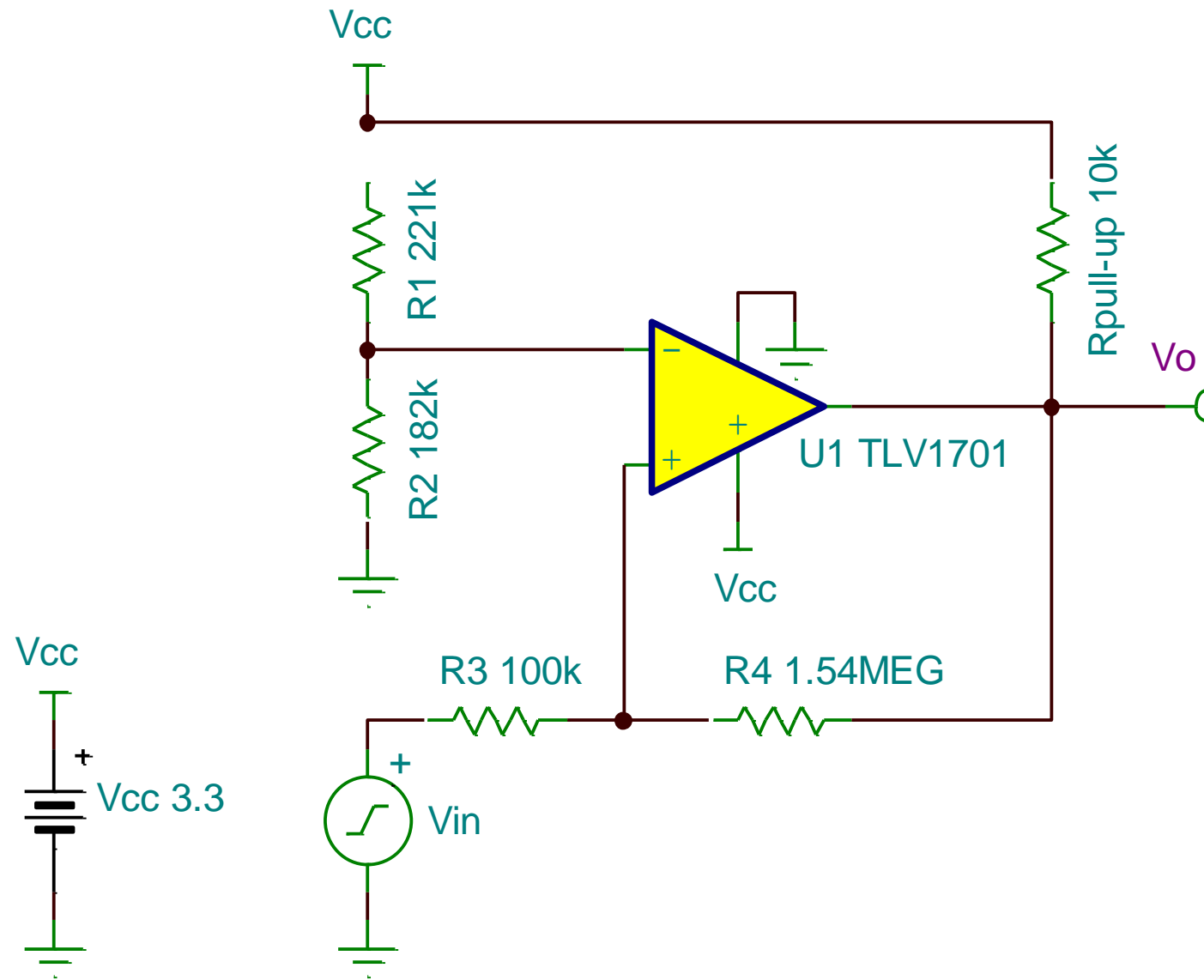
$$R3 = \frac{(R1 \cdot R2)}{(R1+R2)} = \frac{(221e3 * 182e3)}{(221e3 + 182e3)} = 99.8k = \textbf{100 k} \text{ (nearest 1\% value)}$$

$$R4 = R3\left[\frac{(V_{O(max)} - V_{O(min)})}{V_{HYST}} - 1\right] = 100e3\left[\frac{(3.3 - 0.05)}{200e-3} - 1\right]$$

$R4 = 1.53$ Meg $= \textbf{1.54 Meg}$ (nearest 1% value)

Question 1b – Solution

216 mV of hysteresis (some error caused by 1% resistor values)

Multiple Choice – Solutions

- Noise can affect the operation of a comparator by _____.
    a. Causing the output to rapidly change state
    b. Changing the effective threshold voltage
    c. Reducing the rise time and fall time
    d. **Both a. and b.**

- Noise on which inputs of a comparator can affect its operation?
    a. Input signal V_{IN} only
    b. Reference signal V_{REF} only
    c. **Both V_{IN} and V_{REF}**
    d. Neither V_{IN} nor V_{REF}

Multiple Choice – Solutions

- Hysteresis is a form of _____ that _____.
  a. Positive feedback; creates two distinct threshold levels
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- When designing a comparator circuit with external hysteresis, the amount of hysteresis should be _____.
  a. Less than 10% of the hysteresis feedback resistor value
  b. Greater than the maximum peak-to-peak noise you expect in your system
  c. Less than the minimum peak-to-peak noise you expect in your system
  d. Less than or equal to the built-in hysteresis of the comparator