Electronic Circuit II

Comparator

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Comparators with Zero Reference

Introduction

- Often we want to compare one voltage with another to see which is larger.
- In this situation, a comparator may be the perfect solution.
- A comparator is similar to an op amp because it has two input voltages (noninverting and inverting) and one output voltage.
- It differs from a linear op-amp circuit because it has a two-state output, either a low or a high voltage.
- Because of this, comparators are often used to interface with analog and digital circuits.

Basic Idea

- The simplest way to build a comparator is to connect an op amp without feedback resistors, as shown in Fig. 1.

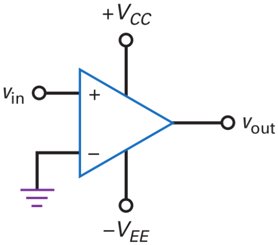


Figure 1: Comparator

Basic Idea

- Because of the high open-loop voltage gain, a positive input voltage produces positive saturation, and a negative input voltage produces negative saturation.
- The comparator of Fig. 1 is called **a zero-crossing detector** because the output voltage ideally switches from low to high or vice versa whenever the input voltage crosses zero.

Basic Idea

- Figure 2 shows the input-output response of a zero-crossing detector.

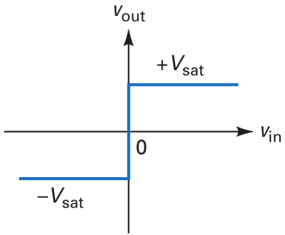


Figure 2: Input/output response

Basic Idea

- The minimum input voltage that produces saturation is:

$$v_{in(min)} = \frac{\pm V_{sat}}{A_{VOL}} \tag{1}$$

- If $V_{sat} = 14$ V, the output swing of the comparator is from approximately -14 to $+14$ V.
- If the open-loop voltage gain is 100,000, the input voltage needed to produce saturation is:

$$v_{in(min)} = \frac{\pm V_{sat}}{A_{VOL}} = \frac{\pm 14 \text{ V}}{100,000} = \pm 0.14 \text{ mV}$$

Basic Idea

- This means that an input voltage more positive than $+0.140$ mV drives the comparator into positive saturation, and an input voltage more negative than -0.140 mV drives it into negative saturation.
- Input voltages used with comparators are usually much greater than ±0.140 mV.
- This is why the output voltage is a two-state output, either $+V_{\text{sat}}$ or $-V_{\text{sat}}$.
- By looking at the output voltage, we can instantly tell whether the input voltage is greater than or less than zero.

Lissajous Pattern

- A **Lissajous pattern** appears on an oscilloscope when harmonically related signals are applied to the horizontal and vertical inputs.
- One convenient way to display the input/output response of any circuit is with a Lissajous pattern in which the two harmonically related signals are the input and output voltages of the circuit.

Lissajous Pattern

- For instance, Fig. 3 shows the input/output response for a 741C with supplies of ± 15 V.

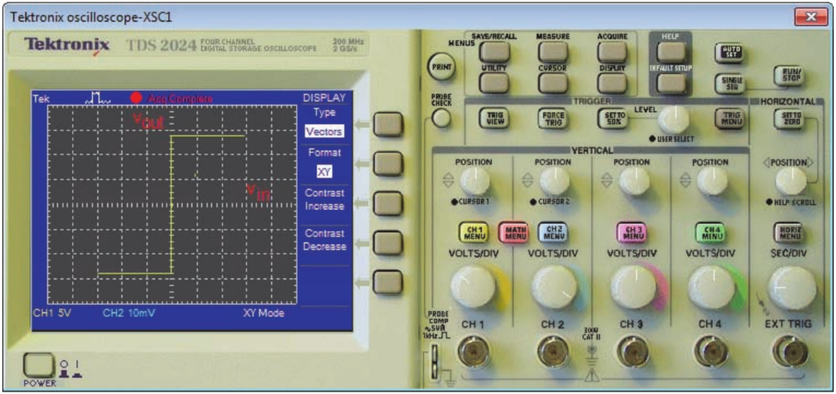


Figure 3: 741C response

Lissajous Pattern

- Channel 1 (the vertical axis) has a sensitivity of 5 V/Div. As we can see, the output voltage is either -14 or +14 V, depending on whether the comparator is in negative or positive saturation.
- Channel 2 (the horizontal axis) has a sensitivity of 10 mV/ Div. In Fig. 3, the transition appears to be vertical.
- This means that the slightest positive input voltage produces positive saturation, and the slightest negative input produces negative saturation.

Inverting Comparator

- Sometimes, we may prefer to use an inverting comparator like Fig. 4.
- The noninverting input is grounded.
- The input signal drives the inverting input of the comparator.

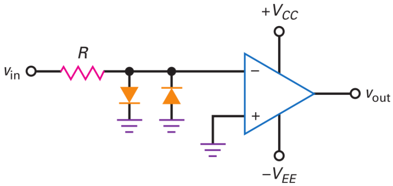


Figure 4: Inverting comparator with clamping diodes

Inverting Comparator

- In this case, a slightly positive input voltage produces a maximum negative output, as shown in Fig. 5.
- On the other hand, a slightly negative input voltage produces a maximum positive output.

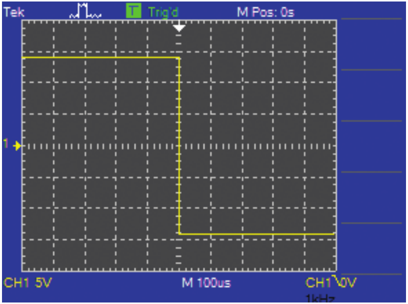


Figure 5: Input/output response

Diode Clamps

- The use of diode clamps to protect sensitive circuits.
- Fig. 4 is a practical example.
- We see two diode clamps protecting the comparator against excessively large input voltages.
- For instance, the LM311 is an IC comparator with an absolute maximum input rating of 615 V.
- If the input voltage exceeds these limits, the LM311 will be destroyed.

Diode Clamps

- With some comparators, the maximum input voltage rating may be as little as ± 5 V, whereas with others it may be more than ± 30 V.
- In any case, we can protect a comparator against destructively large input voltages by using the diode clamps shown in Fig. 4.
- These diodes have no effect on the operation of the circuit as long as the magnitude of the input voltage is less than 0.7 V.
- When the magnitude of the input voltage is greater than 0.7 V, one of the diodes will turn on and clamp the magnitude of the inverting input voltage to approximately 0.7 V.

Diode Clamps

- Some ICs are optimized for use as comparators.
- These IC comparators often have diode clamps built into their input stages. When using one of these comparators, we have to add an external resistor in series with the input terminal.
- This series resistor will limit the internal diode currents to a safe level.

Converting Sine Waves to Square Waves

- The **trip point** (also called the **threshold** or **reference**) of a comparator is the input voltage that causes the output voltage to switch states (from low to high or from high to low).
- In the noninverting and inverting comparators discussed earlier, the trip point is zero because this is the value of input voltage where the output switches states.
- Since a zero-crossing detector has a two-state output, any periodic input signal that crosses zero threshold will produce a rectangular output waveform.

Converting Sine Waves to Square Waves

- For instance, if a sine wave is the input to a noninverting comparator with a threshold of 0 V, the output will be the square wave shown in Fig. 6.
- As we can see, the output of a zero-crossing detector switches states each time the input voltage crosses the zero threshold.

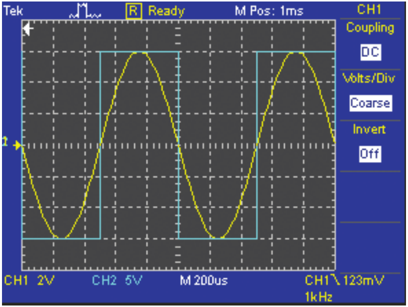


Figure 6: Noninverting comparator converts sine waves to square waves

Converting Sine Waves to Square Waves

- Fig. 7 shows the input sine wave and the output square wave for an inverting comparator with a threshold of 0 V.
- With this zero-crossing detector, the output square wave is 180° out of phase with the input sine wave.

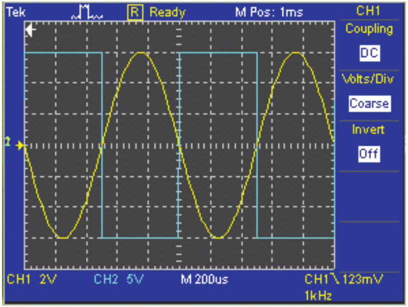


Figure 7: Inverting comparator converts sine waves to square waves

Linear Region

- Fig. 8 shows a zero-crossing detector.
- If this comparator had an infinite open-loop gain, the transition between negative and positive saturation would be vertical.
- In Fig. 3, the transition appears to be vertical because the sensitivity of the 2 channel is 10 mV/Div.

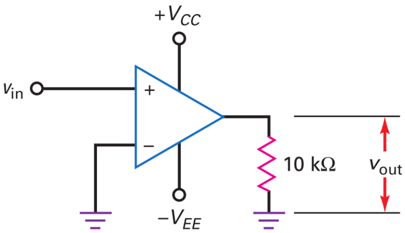


Figure 8: Narrow linear region of typical comparator

Linear Region

- When the sensitivity of the 2 channel is changed to 200 μV/Div, we can see that the transition is not vertical, as shown in Fig. 9.

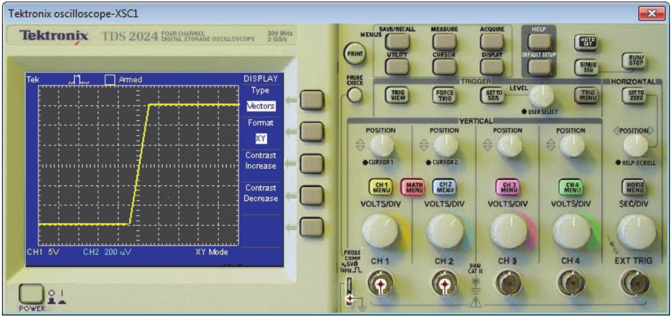


Figure 9: Narrow linear region of typical comparator

Linear Region

- It takes approximately $\pm 100\ \mu$V to get positive or negative saturation.
- This is typical for a comparator.
- The narrow input region between approximately -100 and $+100$ μV is called the **linear region of the comparator**.
- During a zero crossing, a changing input signal usually passes through the linear region so quickly that we see only a sudden jump between negative and positive saturation, or vice versa.

Interfacing Analog and Digital Circuits

- Comparators usually interface at their outputs with digital circuits such as CMOS, EMOS, or TTL (stands for transistor-transistor logic, a family of digital circuits).

- Fig. 10 shows how a zero-crossing detector can interface with an EMOS circuit.
- Whenever the input voltage is greater than zero, the output of the comparator is high. This turns on the power FET and produces a large load current.

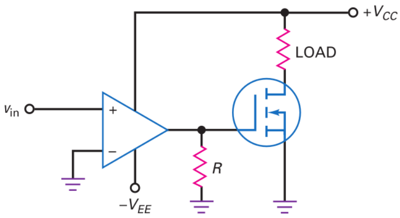


Figure 10: Comparator interfaces with power FET

Interfacing Analog and Digital Circuits

- Fig. 11 shows a zero-crossing detector interfacing with a CMOS inverter.
- The idea is basically the same.
- A comparator input greater than zero produces a high input to the CMOS inverter.

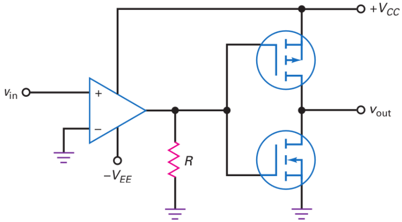


Figure 11: Comparator interfaces with CMOS

Interfacing Analog and Digital Circuits

- Most EMOS devices can handle input voltages greater than ± 15 V, and most CMOS devices can handle input voltages up to ± 15 V.
- Therefore, we can interface the output of a typical comparator without any level shifting or clamping.
- TTL logic, on the other hand, operates with lower input voltages.
- Because of this, interfacing a comparator with TTL requires a different approach (to be discussed in the next section).

Clamping Diodes and Compensating Resistors

- When a current-limiting resistor is used with clamping diodes, a compensating resistor of equal size may be used on the other input of the comparator, as shown in Fig. 12.

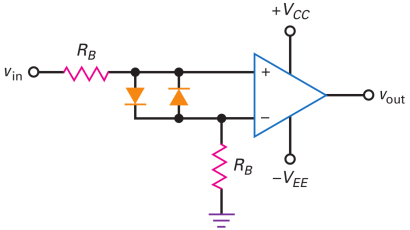


Figure 12: Using a compensating resistor to minimize the effect of $I_{in(bias)}$

Clamping Diodes and Compensating Resistors

- This is still a zero-crossing detector, except that it now has a compensating resistor to eliminate the effect of input bias current.
- As before, the diodes are normally off and have no effect on the operation of the circuit. It is only when the input tries to exceed ± 0.7 V that one of the clamping diodes turns on and protects the comparator against excessive input voltage.

Bounded Output

- The output swing of a zero-crossing detector may be too large in some applications.
- If so, we can bound the output by using back-to-back zener diodes, as shown in Fig. 13.

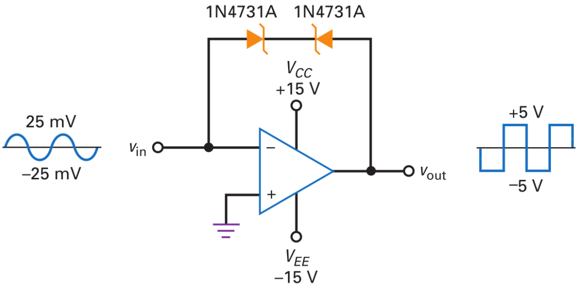


Figure 13: Bounded outputs using Zener diodes

Bounded Output

- In this circuit, as shown in Fig. 13, the inverting comparator has a bounded output because one of the diodes will be conducting in the forward direction and the other will be operating in the breakdown region.
- For instance, a 1N4731A has a zener voltage of 4.3 V.
- Therefore, the voltage across the two diodes will be approximately ± 5 V.
- If the input voltage is a sine wave with a peak value of 25 mV, then the output voltage will be an inverted square wave with a peak voltage of 5 V.

Bounded Output

- Fig. 14 shows another example of a bounded output.
- This time, the output diode will clip off the negative half-cycles of the output voltage.
- Given an input sine wave with a peak of 25 mV, the output is bounded between -0.7 and +15 V as shown.

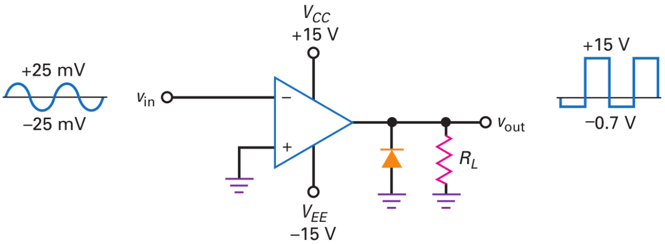


Figure 14: Bounded outputs using rectifier diode

TIME TO QUIZIZZ

Comparators with Nonzero Reference

Introduction

- In some applications, a threshold voltage different from zero may be preferred.
- By biasing either input, we can change the threshold voltage as needed.

Moving the Trip Point

- In Fig. 15, a voltage divider produces the following reference voltage for the inverting input:

$$v_{ref} = \frac{R_2}{R_1 + R_2} V_{CC} \quad (2)$$

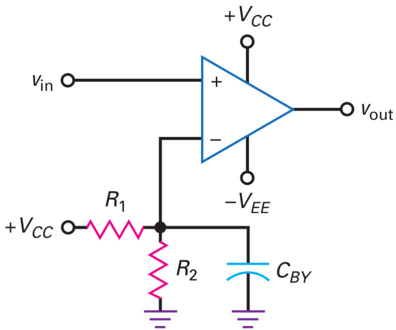


Figure 15: Positive threshold

Moving the Trip Point

- When v_{in} is greater than v_{ref}, the differential input voltage is positive and the output voltage is high. When v_{in} is less than v_{ref}, the differential input voltage is negative and the output voltage is low.
- A bypass capacitor is typically used on the inverting input, as shown in Fig. 15.
- This reduces the amount of power-supply ripple and other noise appearing at the inverting input.

Moving the Trip Point

- To be effective, the cutoff frequency of this bypass circuit should be much lower than the ripple frequency of the power supply.
- The cutoff frequency is given by:

$$f_c = \frac{1}{2\pi(R_1||R_2)C_{BY}} \tag{3}$$

Moving the Trip Point

- Figure 16 shows the transfer characteristic (input/output response).
- The trip point is now equal to v_{ref}.
- When v_{in} is greater than v_{ref}, the output of the comparator goes into positive saturation.
- When v_{in} is less than v_{ref}, the output goes into negative saturation.

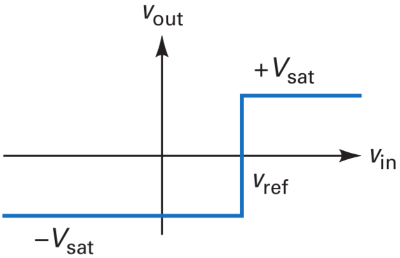


Figure 16: Positive input/output response

Moving the Trip Point

- A comparator like this is sometimes called a limit detector because a positive output indicates that the input voltage exceeds a specific limit.
- With different values of R_1 and R_2, we can set the limit anywhere between 0 and V_{CC}.

Moving the Trip Point

- If a negative limit is preferred, connect $-V_{EE}$ to the voltage divider, as shown in Fig. 17.
- Now a negative reference voltage is applied to the inverting input.

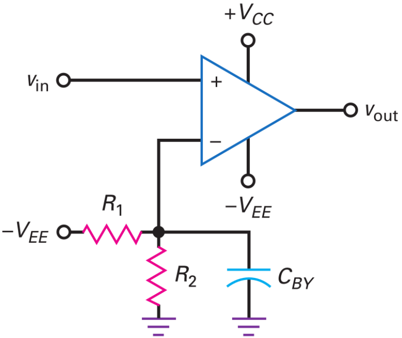


Figure 17: Negative threshold

Moving the Trip Point

- When v_{in} is more positive than v_{ref}, the differential input voltage is positive and the output is high, as shown in Fig. 18.
- When v_{in} is more negative than v_{ref}, the output is low.

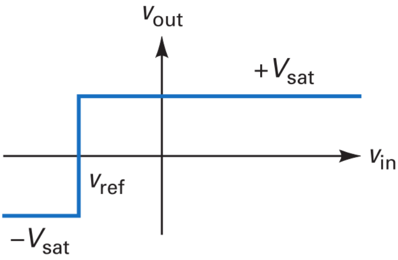


Figure 18: Negative input/output

Single-Supply Comparator

- A typical op amp like the 741C can run on a single positive supply by grounding the $-V_{EE}$ pin, as shown in Fig. 19.
- The output voltage has only one polarity, either a low or a high positive voltage.
- For instance, with V_{CC} equal to $+15$ V, the output swing is from approximately $+1.5$ V (low state) to around $+13.5$ V (high state).

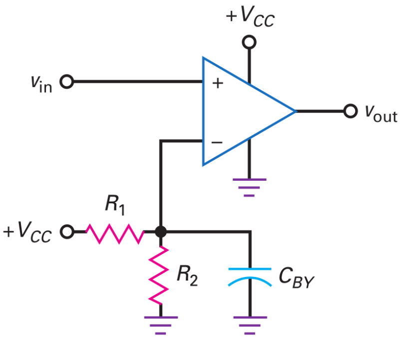


Figure 19: Single-supply comparator

Single-Supply Comparator

- When v_{in} is greater than v_{ref}, the output is high, as shown in Fig. 20.
- When v_{in} is less than v_{ref}, the output is low. In either case, the output has a positive polarity.
- For many digital applications, this kind of positive output is preferred

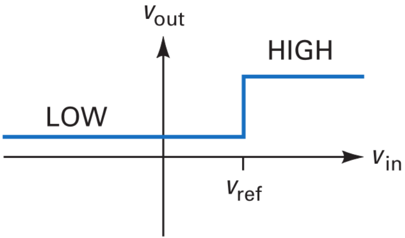


Figure 20: Input/output responser

IC Comparators

- An op amp like a 741C can be used as a comparator, but it has speed limitations because of its slew rate.
- With a 741C, the output can change no faster than 0.5 V/μs.
- Because of this, a 741C takes more than 50 μs to switch output states with supplies of $\pm$15 V.
- One solution to the slew-rate problem is to use a faster op amp like an LM318. Since it has a slew rate of 70 V/μs, it can switch from $-V_{sat}$ to $+V_{sat}$ in approximately 0.3 μs.

IC Comparators

- Another solution is to eliminate the compensating capacitor found in a typical op amp.
- Since a comparator is always used as a nonlinear circuit, a compensating capacitor is unnecessary.
- A manufacturer can delete the compensating capacitor and significantly increase the slew rate.
- When an IC has been optimized for use as a comparator, the device is listed in a separate section of the manufacturer's data book.
- This is why you will find a section on op amps and another section on comparators in the typical data book.

Open-Collector Devices

- Fig. 21 is a simplified schematic diagram for an **open-collector comparator**.
- Notice that it runs off a single positive supply.
- The input stage is a diff amp (Q_1 and Q_2).
- A current source Q_6 supplies the tail current.

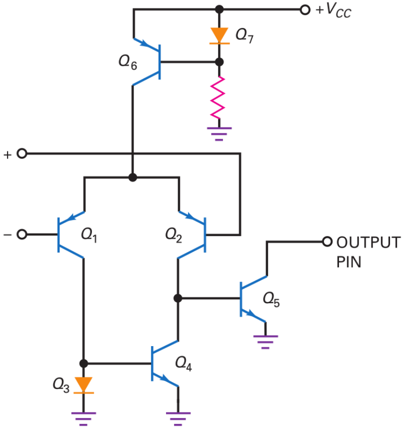


Figure 21: Simplified schematic diagram of IC comparator

Open-Collector Devices

- The diff amp drives an active-load Q_4.
- The output stage is a single transistor Q_5 with an open collector.
- This open collector allows the user to control the output swing of the comparator.

Open-Collector Devices

- A typical op amp has an output stage that can be described as an active-pullup stage because it contains two devices in a Class-B push-pull connection.
- With the active pullup, the upper device turns on and pulls the output up to the high output state.
- On the other hand, an open-collector output stage of Fig. 21 needs external components to be connected to it.

Open-Collector Devices

- For the output stage to work properly, the user has to connect the open collector to an external resistor and supply voltage, as shown in Fig. 22.

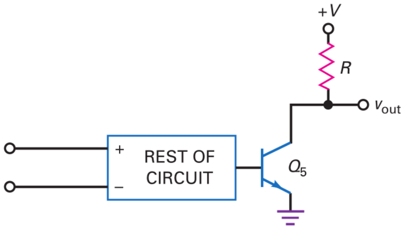


Figure 22: using pullup resistor with open-collector output stage

Open-Collector Devices

- The resistor is called a pullup resistor (Fig. 22) because it pulls the output voltage up to the supply voltage when Q_5 is cut off.
- When Q_5 is saturated, the output voltage is low.
- Since the output stage is a transistor switch, the comparator produces a two-state output.

Open-Collector Devices

- With no compensating capacitor in the circuit, the output in Fig. 21 can slew very rapidly because only small stray capacitances remain in the circuit.
- The main limitation on the switching speed is the amount of capacitance across Q_5.
- This output capacitance is the sum of the internal collector capacitance and the external stray wiring capacitance.

Open-Collector Devices

- The output time constant is the product of the pullup resistance and the output capacitance.
- For this reason, the smaller the pullup resistance in Fig. 22, the faster the output voltage can change. Typically, R is from a couple of hundred to a couple of thousand ohms.

Open-Collector Devices

- Examples of IC comparators are the LM311, LM339, and NE529.
- They all have an open-collector output stage, which means that you have to connect the output pin to a pullup resistor and a positive supply voltage.
- Because of their high slew rates, these IC comparators can switch output states in a microsecond or less.

Open-Collector Devices

- The LM339 is a *quad comparator*—four comparators in a single IC package.
- It can run off a single supply or off dual supplies.
- Because it is inexpensive and easy to use, the LM339 is a popular comparator for general-purpose applications.

Open-Collector Devices

- Not all IC comparators have an open-collector output stage.
- Some, like the LM360, LM361, and LM760, have an active-collector output stage.
- The active pullup produces faster switching.
- These high-speed IC comparators require dual supplies.

Driving TTL

- The LM339 is an open-collector device.
- Fig. 23 shows how an LM339 can be connected to interface with TTL devices.
- A positive supply of $+15$ V is used for the comparator, but the open collector of the LM339 is connected to a supply of $+5$ V through a pullup resistor of 1 kΩ.

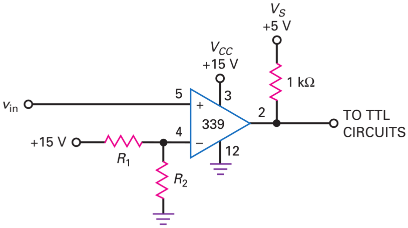


Figure 23: LM339 comparator

Driving TTL

- Because of this, the output swings between 0 and $+5$ V, as shown in Fig. 24.
- This output signal is ideal for TTL devices because they are designed to work with supplies of $+5$ V.

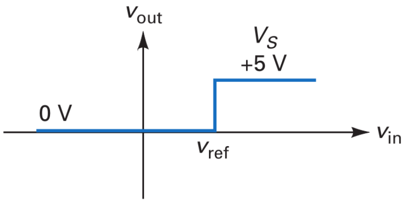


Figure 24: input/output response

Comparators with Hysteresis

- If the input to a comparator contains a large amount of noise, the output will be erratic when vin is near the trip point.
- One way to reduce the effect of noise is by using a comparator with positive feedback. The positive feedback produces two separate trip points that prevent a noisy input from producing false transitions.

Noise

- *Noise* is any kind of unwanted signal that is not derived from or harmonically related to the input signal.
- Electric motors, neon signs, power lines, car ignitions, lightning, and so on produce electromagnetic fields that can induce noise voltages into electronic circuits.
- Power-supply ripple is also classified as noise since it is not related to the input signal.
- By using regulated power supplies and shielding, we usually can reduce the ripple and induced noise to an acceptable level.

- Thermal noise, on the other hand, is caused by the random motion of free electrons inside a resistor (see Fig. 25).
- The energy for this electron motion comes from the thermal energy of the surrounding air.
- The higher the ambient temperature, the more active the electrons.

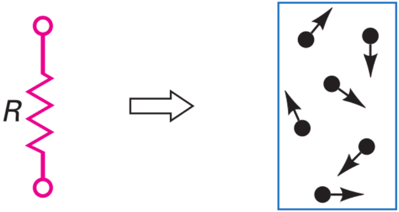


Figure 25: Thermal noise: Random electron motion in resistor

Noise

- The motion of billions of free electrons inside a resistor is pure chaos.
- At some instants, more electrons move up than down, producing a small negative voltage across the resistor.
- At other instants, more electrons move down than up, producing a positive voltage.
- If this type of noise were amplified and viewed on an oscilloscope, it would resemble Fig. 26.
- Like any voltage, noise has an rms or effective value.
- As an approximation, the highest noise peaks are about four times the rms value.

Figure 26: Thermal noise: noise on oscilloscope.

Noise

- The randomness of the electron motion inside a resistor produces a distribution of noise at virtually all frequencies.
- The rms value of this noise increases with temperature, bandwidth, and resistance.
- For our purposes, we need to be aware of how noise may affect the output of a comparator.

Noise Triggering

- As discussed in Sec. 20-1, the high open-loop gain of a comparator means that an input of only 100 μV may be enough to switch the output from one state to another.
- If the input contains noise with a peak of 100 μV or more, the comparator will detect the zero crossings produced by the noise.

Noise Triggering

- Fig. 27 shows the output of a comparator with no input signal, except for noise.
- When the noise peaks are large enough, they produce unwanted changes in the comparator output.
- For instance, the noise peaks at A, B, and C are producing unwanted transitions from low to high.
- When an input signal is present, the noise is superimposed on the input signal and produces erratic triggering.

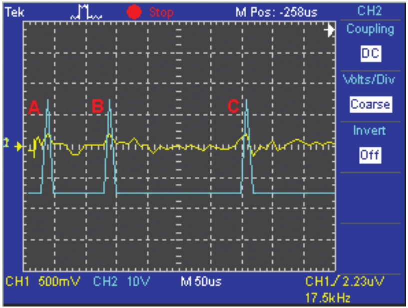
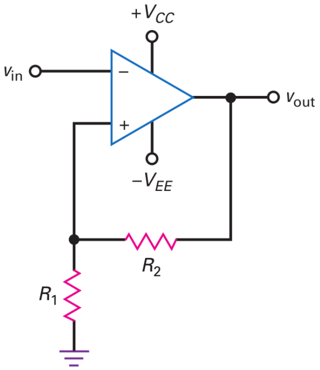


Figure 27: Noise produces false triggering of comparator.

Schmitt Trigger

- The standard solution for a noisy input is to use a comparator like the one shown in Fig. 28(a).
- The input voltage is applied to the inverting input.
- Because the feedback voltage at the noninverting input is aiding the input voltage, the feed-back is positive.
- A comparator using positive feedback like this is usually called a Schmitt trigger.

Schmitt Trigger



$$B = \frac{R_1}{R_1 + R_2}$$

$$\mathrm{UTP} = BV_{sat}$$

$$\mathrm{LTP} = -BV_{sat}$$

$$H = 2BV_{sat}$$

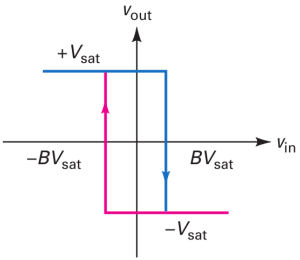


Figure 28: (a) Inverting Schmitt trigger; (b) input/output response has hysteresis.

Schmitt Trigger

- When the comparator is positively saturated, a positive voltage is fed back to the noninverting input.
- This positive feedback voltage holds the output in the high state.
- Similarly, when the output voltage is negatively saturated, a negative voltage is fed back to the noninverting input, holding the output in the low state.
- In either case, the positive feedback reinforces the existing output state.

Schmitt Trigger

- The feedback fraction is:

$$B = \frac{R_1}{R_1 + R_2} \tag{4}$$

- When the output is positively saturated, the reference voltage applied to the non- inverting input is:

$$v_{ref} = +BV_{sat} \tag{5}$$

- When the output is negatively saturated, the reference voltage is:

$$v_{ref} = -BV_{sat} \tag{6}$$

Schmitt Trigger

- The output voltage will remain in a given state until the input voltage exceeds the reference voltage for that state.
- For instance, if the output is positively saturated, the reference voltage is $+BV_{sat}$.
- The input voltage must be increased to slightly more than $+BV_{sat}$ to switch the output voltage from positive to negative, as shown in Fig. 28(b).
- Once the output is in the negative state, it will remain there indefinitely until the input voltage becomes more negative than $-BV_{sat}$.
- Then, the output switches from negative to positive (Fig. 28(b)).

Hysteresis

- The unusual response of Fig. 28(b) has a useful property called hysteresis.
- To understand this concept, put your finger on the upper end of the graph where it says $+V_{sat}$.
- Assume that this is the current value of output voltage.
- Move your finger to the right along the horizontal line.
- Along this horizontal line, the input voltage is changing but the output voltage is still equal to $+V_{sat}$.
- When you reach the upper-right corner, v_{in} equals $+BV_{sat}$.
- When v_{in} increases to slightly more than $+BV_{sat}$, the output voltage goes into the transition region between the high and the low states.