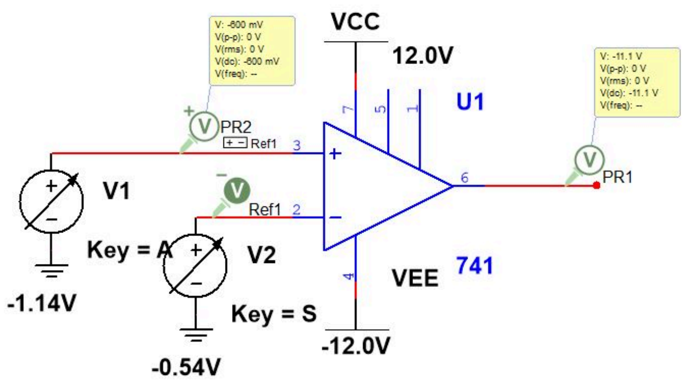
When you were introduced to op amps, you briefly investigated what happens with a high gain amplifier if there is a measurable differential input voltage. From that, you developed a model for op amps ***when they are acting as amplifiers***: the Virtual Short. You've been using that model for so long you may have come to believe that there can never be a difference in voltage between the inputs.

Using Multisim, create the following circuit.

- V1 and V2 are DC_INTERACTIVE_VOLTAGE, available under Sources->SIGNAL_VOLTAGE_SOURCES
- Set both V1 and V2 to Maximum Value = 5 V, Minimum Value = -5V, Increment =0.1%
- Monitor the output using a standard voltage probe, as shown
- Monitor the differential input voltage using a differential voltage probe , with the probe on the non-inverting input and its reference on the inverting input.
- Use +/- 12 VDC to power the 741 op amp.



Set V1 and V2 to the following values, and record the results seen on the voltage probes.

V1 (non-inv), V	V2 (invert), V	Vdiff, V	Vout, V
1.00	-1.00	2	11
-0.05	0.10	-0.15	-11
3.50	2.50	1	11
2.25	2.29	-0.04	-11
-0.01	-0.07	0.06	11

So, when there is a measurable difference in voltage between the two pins of an op amp, there are only two possible outputs: maximum positive voltage or maximum negative voltage. This is affectionately known as "nailed to the rails". Why does this happen? Let's look at the first example above. In this case, the differential voltage between the pins is +2 V. If the amplifier has an open circuit gain of 200,000, what would the theoretical output voltage be? Record the numeric part as a number between 1 and 999

400

and select the correct unit:

- ( ) mV
- ( ) V
- (•) kV

Our amplifier is only powered from +/- 12 VDC, so there is no possible way it can achieve the voltage predicted by the gain formula. In this case, using terminology we learned with transistors, it is saturated, and its output is dictated by components external to the op amp itself, in this case the power supplies. As with transistors, op amps that are not operating in the active linear region are said to be in switch mode. Actually, since this is not a "rail to rail" op amp, it can only come to within about 1 V of the rails.

The good news is that, if there are only two possible outputs, the device is binary. That means it can be used as an interface between the real world and binary digital devices.

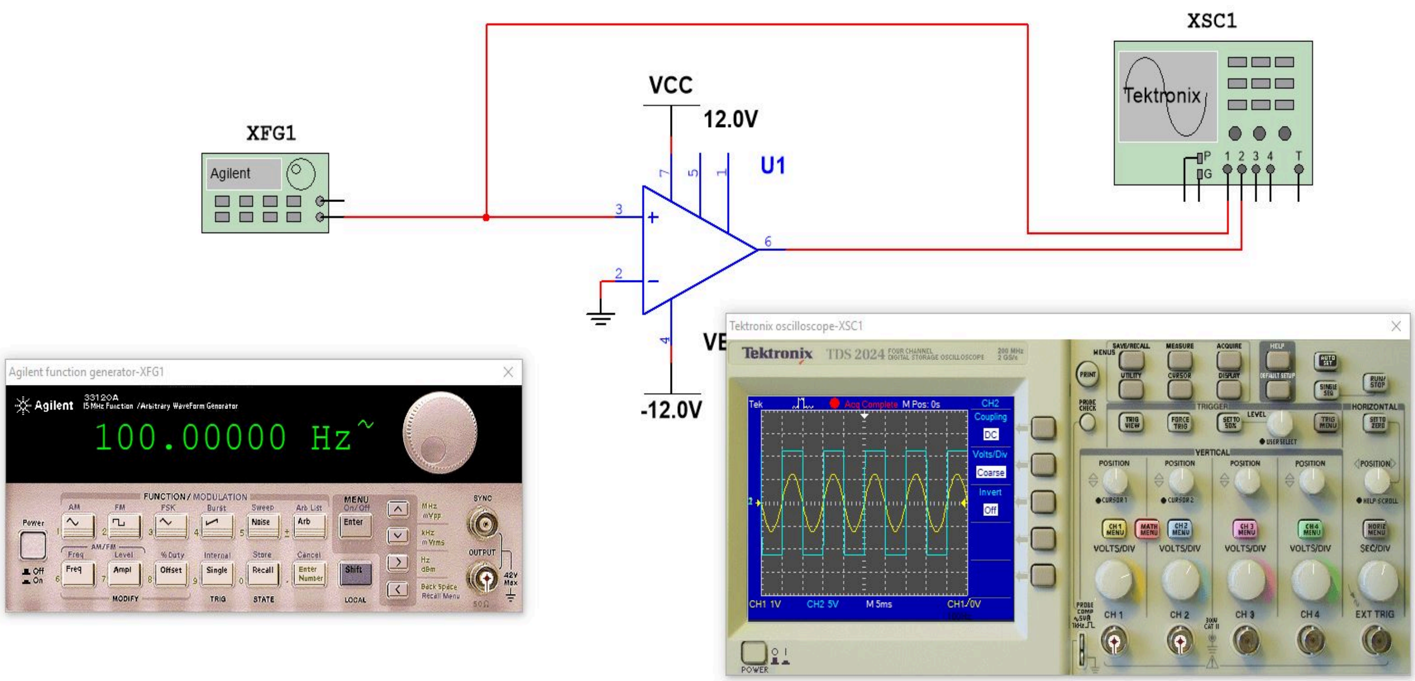
Comparators

The two possible outcomes, in fact, tell us which of the inputs is at a more positive voltage. If the non-inverting input is more positive, the output will be positive; if the inverting input is more positive, the output will be negative. So, in switch mode, the op amp "compares" the two signals and reports which one is more positive; therefore, when in this configuration, we don't call it an ampifier, we call it a ***Comparator***.

Zero Crossing Detectors

If one of the inputs is grounded, the output of the comparator will change states when the other input changes from positive to negative or *vice versa*. Therefore, the comparator detects when the input signal crosses the zero voltage line, and we call it a Zero Crossing Detector.

Modify your circuit in Multisim as shown. Please note that the Agilent Function Generator's true Output is the lower of the two "pins" shown -- the other on is called "Sync", and always generates a large unipolar square pulse, regardless of the waveform settings.



Set up the function generator to produce a 100 Hz sine wave with an amplitude of 2.5 V_{p-p}. Adjust your oscilloscope to display this signal adequately, as shown above.

Notice that, even though the input is a sine wave, the output is square -- there are only two possible output voltages: max+ and max-.

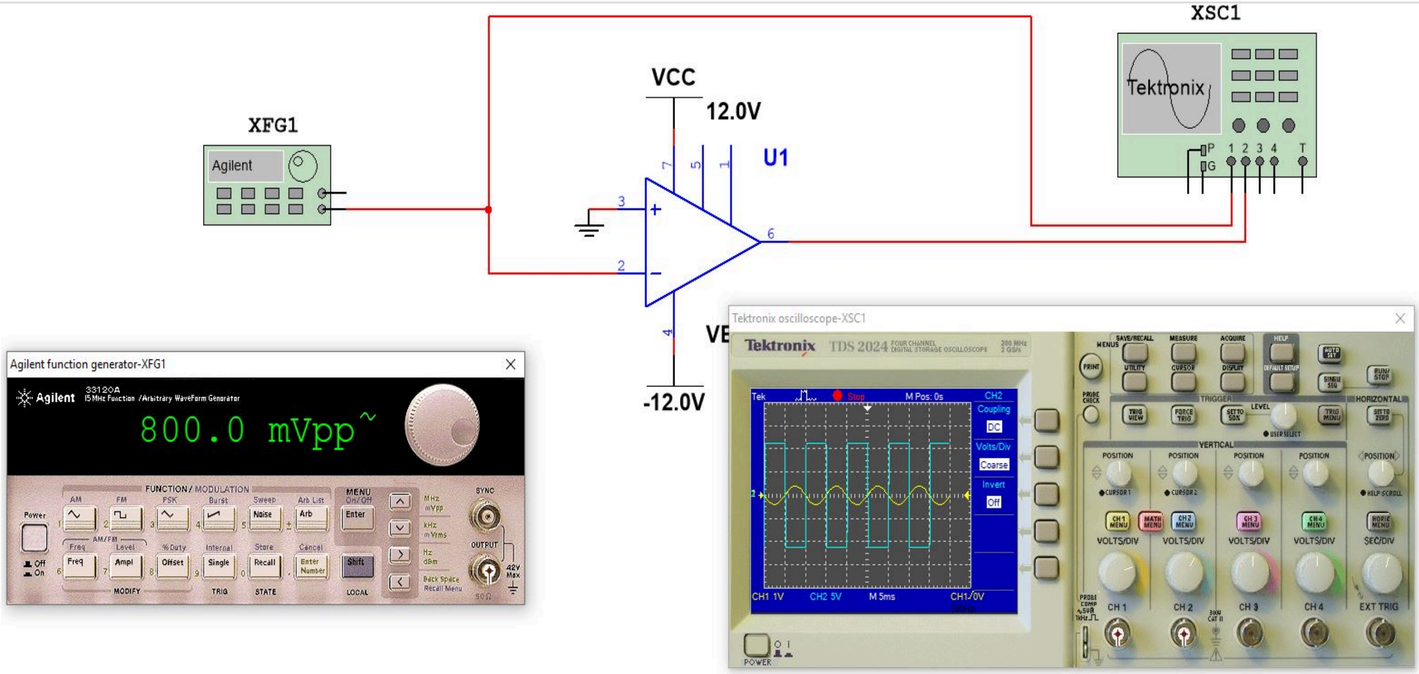
Also notice that, with the input signal connected to the non-inverting terminal, the output is positive when the input is positive, and negative when the input is negative. This makes it a ***Non-Inverting Zero Crossing Detector***.

Now, decrease the amplitude of the input signal slowly, all the way down to 50 mV_{p-p}. The amplitude of the input signal

- Directly affects the amplitude of the output signal.
- Does not affect the amplitude of the output signal.
- Directly controls the shape of the output signal.

To prove that the last statement is not true, try switching to a square wave input, then a triangle wave input.

Now, ground the non-inverting input and connect the function generator to the inverting input, as shown. You can increase the amplitude back to where the input signal is clearly visible again.



Notice now that, although the output looks the same (rail to rail), it is positive when the input is negative and negative when the input is positive. This makes it an ***Inverting Zero-Crossing Detector***.

Dedicated comparators

While we have the previous circuit operational, increase the frequency slowly from the 100 Hz you started with up to 10 kHz. You should notice that the output is no longer a square wave. This is caused by

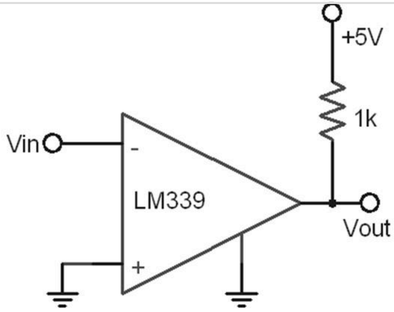
- Slew Rate
- Small-Signal Bandwidth
- Low-Pass Filtering
- High-Pass Filtering

To overcome this problem, IC manufacturers have developed "dedicated comparators" -- op-amp-based ICs that can only be used as comparators. Most of these have transistor switches in their outputs to make sure the output level shifts are as rapid as possible. ***Dedicated Comparators*** come in two basic flavours:

- Open Collector (or Open Drain) Outputs
- Driven Outputs

The ones with driven outputs do not need any external components to make them work. However, the Open Collector or Open Drain output devices require an external pullup resistor in order to work. The Collector (or Drain, if it's a FET) of the internal transistor is simply presented to the user to connect as desired. If the desired logic levels are to be 0 and 5 V, the user would connect a pullup resistor to a $+5V_{DC}$ supply. Any other supply could be used, regardless of what is being used to power the comparator. Typically, comparators reference their outputs to ground, so they automatically generate "Unipolar" signals -- signals with only one non-zero voltage and zero volts as the other option.

The LM339 is one such open collector comparator, pictured below. This is actually just one of four comparators in an LM339 quad IC.



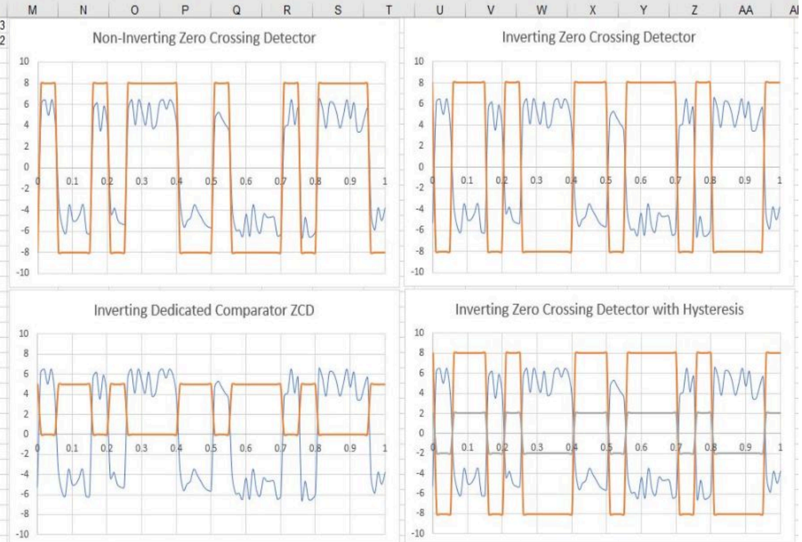
In this configuration, it is set up as an inverting zero crossing detector with TTL Logic outputs.

Since the dedicated comparators are designed to be very fast, and since their outputs are single transistors, the issue of Slew Rate is dealt with.

Data Regeneration

One application for Zero Crossing Detectors is in regenerating digital signals that have deteriorated during transmission due to amplitude attenuation and the introduction of noise. In Moodle, you'll find an Excel file called "Data Regeneration". Open it up, and you should see something like the following:

time	data	noise	square	sum	Output+	Output-	Output-Uni	OutputHys	ThrHyst	noise fact	0.3
0	0	-0.3	-5	-5.3	-8	8	5	8	2	Hyst	2
0.01	1	1.2	5	6.2	8	-8	0	-8	-2		
0.02	1	1.5	5	6.5	8	-8	0	-8	-2		
0.03	1	0	5	5	8	-8	0	-8	-2		
0.04	1	1.5	5	6.5	8	-8	0	-8	-2		
0.05	1	-0.9	5	4.1	8	-8	0	-8	-2		
0.06	0	1.5	-5	-3.5	-8	8	5	8	2		
0.07	0	-0.6	-5	-5.6	-8	8	5	8	2		
0.08	0	-1.2	-5	-6.2	-8	8	5	8	2		
0.09	0	1.5	-5	-3.5	-8	8	5	8	2		
0.1	0	0	-5	-5	-8	8	5	8	2		
0.11	0	0	-5	-5	-8	8	5	8	2		
0.12	0	0.6	-5	-4.4	-8	8	5	8	2		
0.13	0	1.5	-5	-3.5	-8	8	5	8	2		
0.14	0	-1.2	-5	-6.2	-8	8	5	8	2		
0.15	0	-1.2	-5	-6.2	-8	8	5	8	2		
0.16	1	0.6	5	5.6	8	-8	0	-8	-2		
0.17	1	1.2	5	6.2	8	-8	0	-8	-2		
0.18	1	-1.5	5	3.5	8	-8	0	-8	-2		
0.19	1	0.9	5	5.9	8	-8	0	-8	-2		
0.2	1	-1.2	5	3.8	8	-8	0	-8	-2		
0.21	0	0.6	-5	-4.4	-8	8	5	8	2		
0.22	0	1.2	-5	-3.8	-8	8	5	8	2		
0.23	0	0	-5	-5	-8	8	5	8	2		
0.24	0	-0.3	-5	-5.3	-8	8	5	8	2		
0.25	0	-0.3	-5	-5.3	-8	8	5	8	2		
0.26	1	0.6	5	5.6	8	-8	0	-8	-2		
0.27	1	1.5	5	6.5	8	-8	0	-8	-2		
0.28	1	-0.9	5	4.1	8	-8	0	-8	-2		
0.29	1	1.5	5	6.5	8	-8	0	-8	-2		
0.3	1	0.3	5	5.3	8	-8	0	-8	-2		
0.31	1	-0.9	5	4.1	8	-8	0	-8	-2		
0.32	1	1.2	5	6.2	8	-8	0	-8	-2		
0.33	1	-1.2	5	3.8	8	-8	0	-8	-2		



This file is dynamic. If you press F9 (or do almost anything in the spreadsheet), the data and output graphs will change. The "noise" on the signal is controlled by a random generator that can be refreshed at any time.

The thin blue line in each of the graphs represents a degraded digital signal, and the heavier sepia (I think that's its colour) line represents the output of the particular comparator circuit described in each chart title.

Notice how, with the initial settings, the fairly noisy input signal is always "regenerated" to the same correct data, in all of the charts. Since the new signal could now be transmitted again without the noise, Zero-Crossing Detectors as applied to data are called ***Data Regenerators***.

The top two charts are very similar, except for the polarity. Satisfy yourself that one of them in non-inverting and the other is inverting.

The bottom left chart shows the output for a Dedicated Comparator, like the LM339, configured as an inverting zero-crossing detector, with a pullup resistor to $+5V_{DC}$. This is the circuit shown previously. Notice that this circuit generates logic levels like the ones you've become accustomed to in you Digital Logic course.

The "noise fact" number in the spreadsheet represents the ratio of the noise to the signal size. Slowly increase this from 0.3 to 1.4. When is the noise big enough to start to introduce transitions that aren't in the original data, for the three charts previously discussed?

- ○ 0.5
- ○ 0.8
- ◉ 1.0
- ○ 1.2

The reason these two Zero Crossing Detectors start to fail is that the noise is now big enough to cross the zero line even when the data is not supposed to.

But take a look at the bottom right chart. It doesn't show the false transitions the other ones are showing. With the "Hyst" setting at 2, further increase the noise factor until this one starts failing. This happens at

- ○ 0.8
- ○ 1.0
- ○ 1.2
- ◉ 1.4

Notice how badly the other ones are failing, but that the bottom right one is just catching the occasional noise spike. Set the "Hyst" to 1.35 to return to a clean output on this one. The bottom right chart represents the output from a comparator with positive feedback, also known as "Hysteresis", which is a topic in the next Online Lesson.

So, from this lesson, you've learned:

- Op amps with measurable voltages between the input pins will be in saturation, with only two output options: max+ and max-.
- Comparators indicate which input is more positive by the polarity of the output voltage.
- Zero Crossing Detectors compare an input signal to ground, and therefore report whether the input is positive or negative.
- Depending on which input is grounded, a zero crossing detector can be inverting or non-inverting.
- The slew rate of a standard op amp limits its usefulness; Dedicated comparators overcome this issue, and may provide additional external control if they are open collector or open drain. Typically, these devices produce Unipolar output signals.
- Zero Crossing Detectors can be used as Data Regenerators to clean up data that has been degraded due to attenuation and noise during transmission over a distance.
- If the noise is too great, even a Zero Crossing Detector will allow errors to be re-transmitted.