Chapter 9: Op Amp Building Blocks

OPERATIONAL AMPLIFIERS

Operational amplifiers (op amps) are versatile electronic building blocks that can be configured with circuits to perform a wide variety of operations on signals. Examples in this chapter include:

- Compare two voltages
- Buffer a voltage signal that cannot drive a resistive load directly
  (like the RC DAC circuit from Chapter 8, Activity #4)
- Amplify an input voltage
- Invert an input voltage
- Attenuate and invert an input voltage
- Add offset to or remove offset from a signal

Figure 9-1 shows a picture of the Understanding Signals Kit's LM358 op amp along with a pin map similar to one you might find in the device's datasheet. This integrated circuit (IC) has two op amps, shown as triangles labeled A and B. The activities in this chapter will focus on using one op amp to perform operations on one or two signals. Each op amp can be configured separately, and they can both perform operations on signals in parallel. They can also be cascaded to perform a series of operations on one or more signals –an example of this is included in the Projects section at the end of the chapter.

**Figure 9-1:** LM358 IC Photo and Pin Map
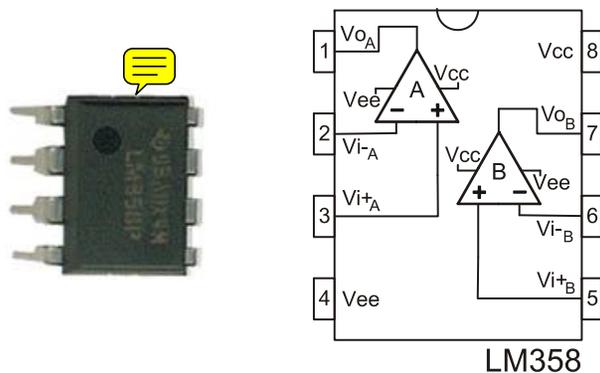
Figure 9-2 shows the op amp symbol with each of its connections labeled. The numbers by each terminal correspond to the pin map numbers for op amp A in Figure 9-1. The op amp has two supply voltage inputs, one positive and one negative. It also has two signal inputs. The one with a + label is called the non-inverting input, and the one with a – label is called the inverting input. The notations for some of the terminals in Figure 9-2 might vary from one datasheet to the next as well as from one manufacturer to the next, but all the LM358 manufacturers and their datasheets follow the same conventions for the terminals' names and their positions around the triangular op amp circuit symbol. The one exception to this is that the top/bottom positions of the non-inverting and inverting input terminals are swapped as needed to simplify schematics.

Positive Supply

Non-Inverting Input   Vi+$_A$ 3   Vcc   8

A

Inverting Input   Vi-$_A$ 2   4   1   Vo$_A$ Output   LM358

Vee

Negative Supply
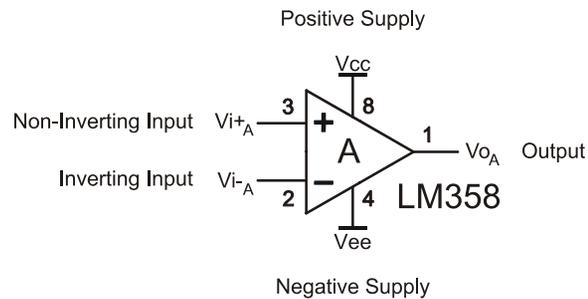
Figure 9-2
Op Amp Terminals

An operational amplifier's output voltage is the difference between the voltages at the non-inverting and inverting inputs multiplied by a very large value. For example, the Fairchild LM358 datasheet specifies a "large signal gain" of 100 V/mV. In other words, the output voltage will be 100,000 times the voltage difference between the two inputs. This gain is also called open loop gain, and will be ~~utilized~~ by a circuit called a comparator in Activity #1.

After the open loop comparator operation, other operations in the list (buffer, amplify, invert, etc.) require circuits that connect the op amp's output to its inverting input. The circuit configuration determines the operation, and the values of the components determine the relationship between input and output voltage levels and signal amplitudes. In these circuits, the output signal is "fed back" into the inverting input, either directly or through a circuit, so they are called "negative feedback" circuits. Activity #2 through Activity #4 ~~utilize~~ negative feedback circuits to buffer, amplify, invert and offset signals.

> **Op amp shopping tip:**
>
> Open loop gain is not just important for op amp comparator operations; it's also an ingredient in negative feedback applications. An op amp's open loop gain decreases with higher frequency signals, and as that gain decreases, so does its performance. Each op amp's datasheet has one or more graphs of its open loop gain's response to frequency. When shopping for op amps, make sure to check those graphs and verify that the open loop gain is still high in your application's frequency range.

ACTIVITY #1: COMPARATOR

A comparator "compares" the voltage difference between its inverting and non inverting inputs. If the non inverting input voltage is greater than the inverting input voltage, the comparator sends a high signal. If the non inverting input voltage is less than the inverting input voltage, it sends a low signal. With a high open loop gain, the comparator will detect even minute differences in voltage and send high or low signals a result. This is useful for converting very small voltage differences into binary values.

An example of a comparator application is a clock signal. The small voltage fluctuations from oscillator circuits can be passed through comparators to create high/low clock signals for computing systems. Comparators can also be used with sensors. A threshold voltage can be set at one of the comparator's inputs, and if the sensor's voltage output rises above the level, the comparator sends a high signal, otherwise, it sends a low signal.

In this activity, an LM358 op amp will be configured to function as a comparator. A voltage divider will be used to set the voltage at its non inverting terminal to 2.5 V. With no feedback, even a small difference above or below 2.5 V will result in the op amp trying to amplify the voltage difference by 100,000. The LM358's output voltage is limited by its supply voltage, so when the output reaches one of those limits, it can't go any further. The result will be that a voltage that's above the voltage applied to the inverting terminal will make the comparator send a high signal, and a voltage that's below it will result in a low signal.

Comparator Test Parts

(1) Potentiometer – 10 kΩ (103)
(2) Resistors – 1 kΩ (brown-black-red)
(1) Op Amp – LM358
(misc) Jumper Wires

Comparator Test Circuit

Figure 9-3 shows a schematic of a 2.5 V threshold comparator and Figure 9-4 shows a wiring diagram example of the circuit. The resistor divider applies approximately 2.5 V to the op amp's inverting input. The potentiometer is connected as a voltage divider, so turning the knob varies the voltage at its wiper terminal. If the potentiometer wiper's voltage is even slightly above the voltage at the comparator's non inverting input, the op amp's output will send high signal that's about 3.6 V. If the potentiometer wiper's voltage is slightly below the 1 kΩ voltage divider output, the op amp's output will send a 0 V low signal.

- ✓ **STOP:** If your CH2 probe's BNC end is still connected to the DAC CARD's function generator output, disconnect it and reconnect it to the PropScope's CH2 BNC input before continuing.
- ✓ Build the circuit shown in Figure 9-3 and Figure 9-4.

Supply Voltage Plus "Headroom"

When the LM358 sends a high signal, it's only 3.6 V instead of the Vdd = 5 V applied to its Vcc power input. Many op amp outputs require this type of headroom between their maximum output levels and their supply rails. Op amps with "rail to rail" outputs are available, but they are typically a little more expensive. The added cost is not typically too steep for projects and prototypes, but for products with high sales volumes, an extra 50 cents per product could add up to high values very quickly.
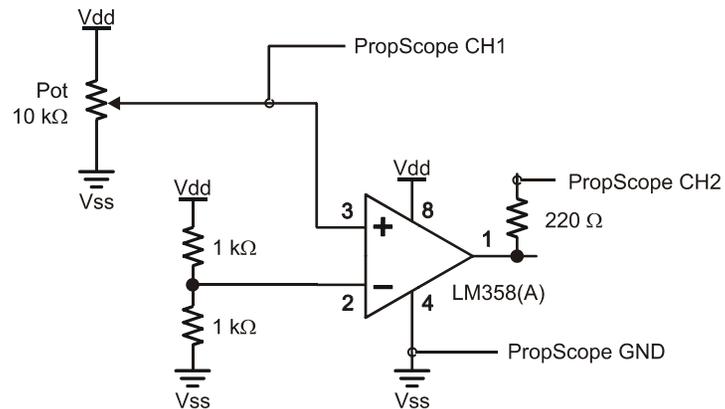

Figure 9-3

Comparator Test Schematic

Figure 9-4: Wiring Diagram Example of Figure 9-3
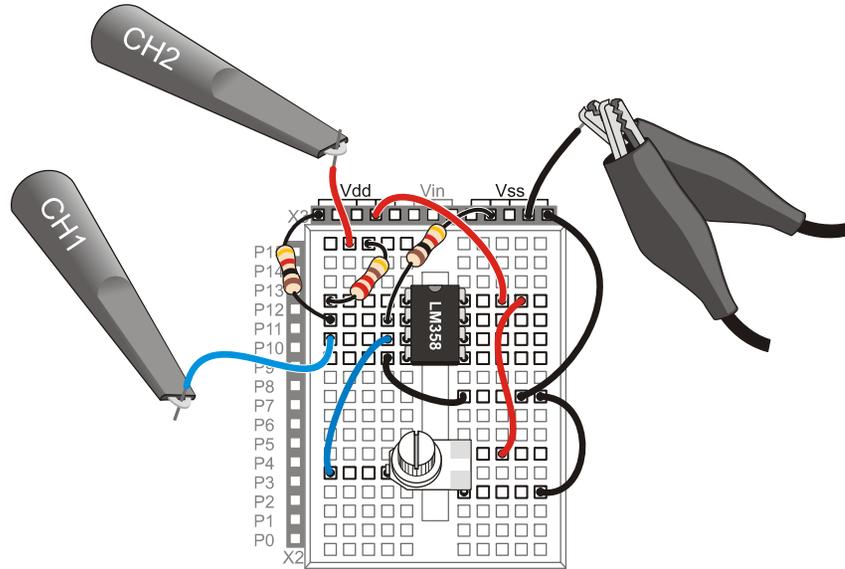
Comparator Test Measurements

Figure 9-5 shows an example of how slight fluctuations at the op amp comparator's non-inverting input result in high and low signals at the output. The lower, red CH2 trace shows the potentiometer wiper terminal's voltage as it is adjusted above and below the 2.5 V threshold, and the upper, blue CH1 trace shows the op amp comparator's output responding by switching high and low.

- ✓ Adjust the Horizontal, Vertical, and Trigger settings as shown in Figure 9-5.
- ✓ Slide the Plot Area Bar to the far right of the Preview Area so you can see immediate voltage changes as you twist the potentiometer's knob.
- ✓ Use the CH2 trace voltage scale on the right as a guide for adjusting the potentiometer's voltage into the 2 to 3 V range.
- ✓ Adjust the potentiometer back and forth in the 2 to 3 V range and verify that the comparator circuit's output responds with high/low signals.

Figure 9-5: 2.5 V Threshold Crossings Cause High/Low Signals at Comparator Output
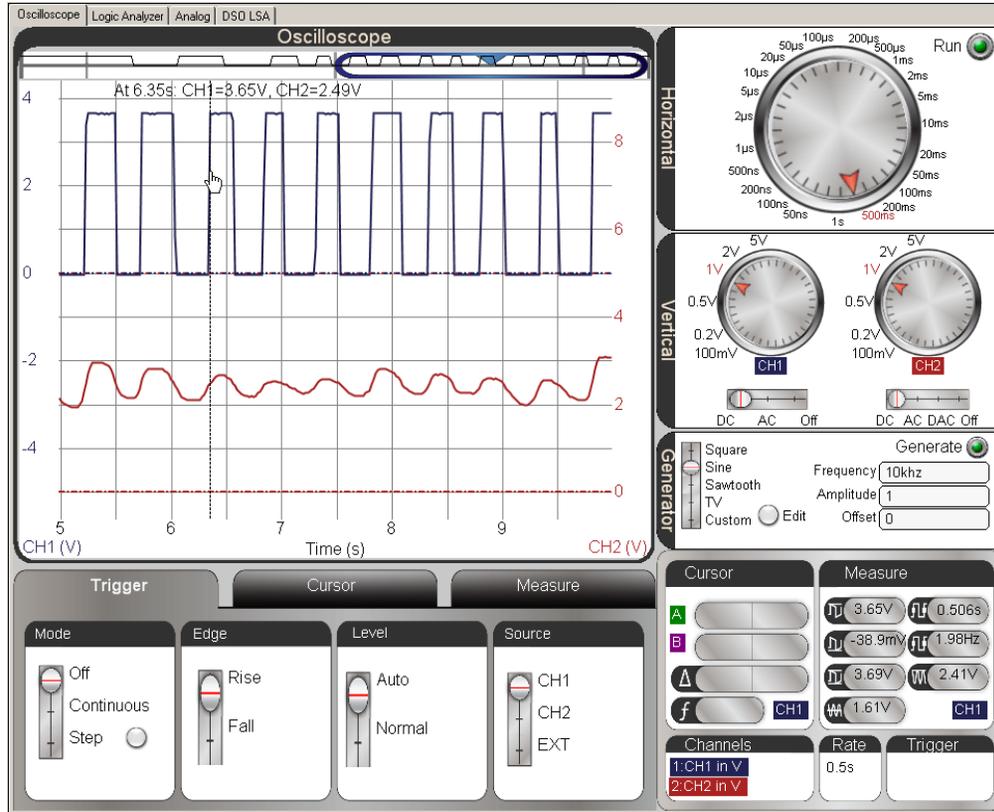
Your Turn: Verify the Threshold Voltage

The gold bars on the 1 kΩ resistors indicate a 5 % tolerance. That means their actual values may be up to 5% above or below their nominal (named) values. In Figure 9-5, the mouse is pointing at one of the transitions and the floating cursor info near the top of the oscilloscope screen is reporting the CH2 voltage as 2.49 V. This voltage will vary, from one transition to the next, but an average of these measurements can be taken to approximate the threshold. This value can be compared to a direct measurement of the threshold voltage.

✓ Use the CH2 probe to test the voltage at the LM358 pin 2. This is the resistor voltage divider output, and it's the actual threshold voltage.

✓ You may need to click the Run button to get the display to hold still.
✓ Try averaging the floating cursor values at the comparator output transitions to approximate the resistor divider's threshold voltage.
✓ Compare the averaged instantaneous threshold voltage measurement to the direct measurement.

ACTIVITY #2: VOLTAGE FOLLOWER AS AN OUTPUT BUFFER

This activity examines a closed loop op amp circuit called a voltage follower and commonly referred to as a buffer. The voltage follower is so named because the output voltage "follows" the input voltage. In other words, the op amp's output voltage should be the same as the voltage applied to its non-inverting input. The name buffer comes from the fact that the op amp buffers or protects the circuit setting the non-inverting input voltage from any load that might be connected to the op amp's output.

Chapter 8, Activity #4 examined the effect of a load resistance on the RC DAC circuit voltage output. In this activity, you will use the same DAC circuit to create a voltage, and an op amp voltage follower to maintain that voltage across an LED circuit load.

Buffer Test Parts

(1) Resistor – 1 kΩ (brown-black-red)
(1) Resistor – 470 Ω (yellow-violet-brown)
(1) Capacitor – 1 μF
(1) Op Amp – LM358
(1) LED – any color
(misc) Jumper Wires

Voltage Follower Test Circuit

Figure 9-6 shows a schematic and wiring diagram example of the voltage follower test circuit with an LED circuit load. One subtle change to this circuit that's easy to miss is that the op amp's Vcc supply input is now connected to Vin. Provided your board's supply is at least 6.5 V, this change should make it possible for the op amp's output to follow the BASIC Stamp RC DAC's voltage through its entire 0 to 4.98 V range.

✓ Build the circuit shown in Figure 9-6.
✓ Make sure the op amp's pin 8 is connected to one of your board's Vin sockets, instead of a Vdd socket.

✓ A 9 V battery supply is recommended for this activity.

Figure 9-6: Voltage Follower Test Circuit
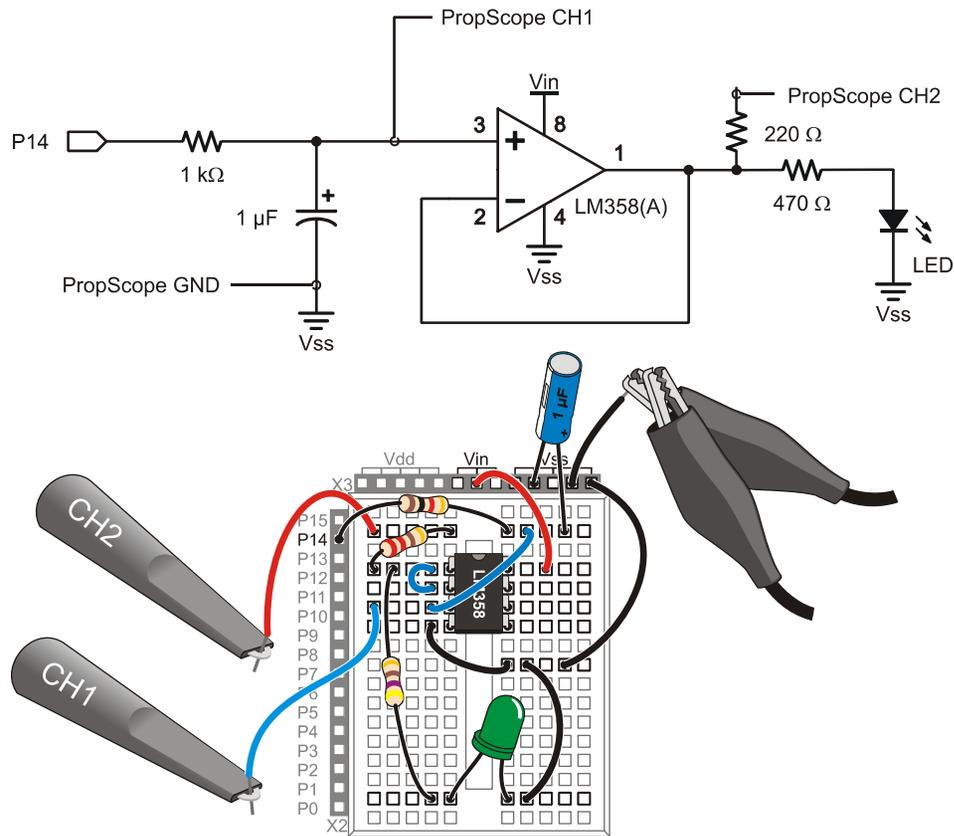
The circuit in Figure 9-6 is called a voltage follower because it forces the op amp's output to "follow" the voltage applied to its non-inverting input. The fact that we have made a circuit that matches the input voltage at its output might not seem like a big deal. Heck, a wire could do that, right? The thing a wire cannot do is prevent a load from affecting the circuit it draws current from, but an op amp voltage follower can. With this circuit, the BASIC Stamp can use its PWM command to set voltages across the RC DAC circuit to control the LED's brightness. The op amp's output supplies the necessary current to make its output voltage match the capacitor voltage applied to the non-inverting input, but there is no decay from the LED circuit load like there would be if the voltage follower circuit was replaced with a wire.

The op amp's inputs have very high input resistances – in the 200 MΩ range. This means that its non-inverting input will place almost no current load on the capacitor in Figure 9-6. So the capacitor will be able to hold its charge almost exactly the same way it did when no load was connected to it. At the voltage follower's output, it doesn't matter whether the load is a 10 kΩ resistor, a 2 kΩ resistor, or even an LED in series with a 470 Ω resistor. The op amp will supply whatever current it takes to keep the voltage at its output terminal the same as the voltage the capacitor applies to its non-inverting terminal. Of course, that's provided the load isn't beyond the amount of current the op amp's output is designed to supply.

How it Works

The rule for negative feedback op amp circuits is: *If an op amp's inverting input senses its output through a circuit, the op amp adjusts its output to make the voltage at the inverting input match the voltage at the non-inverting input.* In Figure 6-1, the op amp's output is connected to its non-inverting input with a wire, so the output voltage is applied directly to the non-inverting input – they are the same voltage. To enforce the negative feedback rule and make the voltage at the two input terminals match, the op amp has to make its output voltage match the voltage applied to its non-inverting input.

Figure 9-7: Negative Feedback in a Voltage Follower Circuit

To make sure the voltage at the **non-inverting input** is equal to the voltage at the **inverting input**, the op amp has to make its output voltage the same as the voltage applied to the non-inverting input.

Feedback wire applies output voltage to inverting input, so these two voltages are the same.
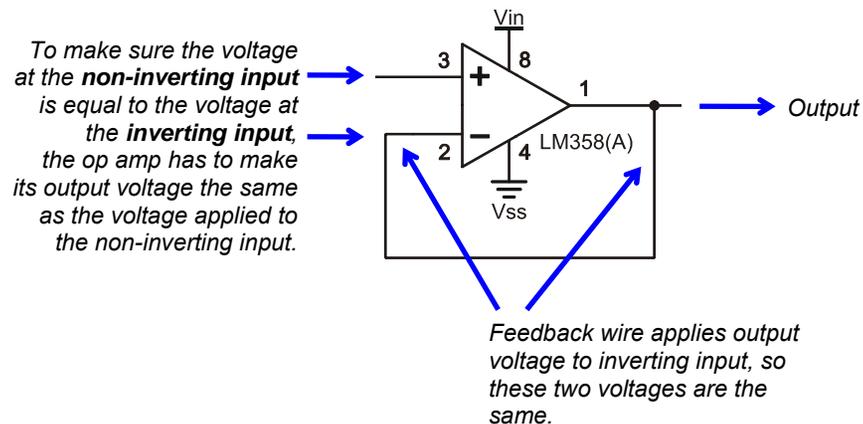
Buffer Test Code

One Hz Sine Wave.bs2 sends a 1 Hz sine wave to the P14 DAC indefinitely. This will make it convenient to compare the DAC's sine wave output to the voltage follower's output.

✓ Enter and run One Hz Sine Wave.bs2

```
' One Hz Sine Wave.bs2
' Transmit a 1 Hz sine wave on P14 indefinitely.

' {$STAMP BS2}                            ' Target module = BASIC Stamp 2
' {$PBASIC 2.5}                           ' Language = PBASIC 2.5

DEBUG "Program running..."                ' Debug Terminal message

DO                                        ' Main Loop

  FREQOUT 14, 60000, 1                     ' Play 1 Hz for 1 minute

LOOP                                      ' Repeat main loop
```

Buffer Test Measurements

Figure 9-8 shows the DAC output on upper, blue CH1 trace and the voltage follower's copy of that signal on the lower, red CH2 trace. Note that the sine waves are the same amplitude and phase. This indicates that the op amp's output is "following" the DAC voltage applied to its non-inverting input, even with the LED current load.

✓ Adjust your Oscilloscope's Horizontal, Vertical and Trigger settings as to match Figure 9-8.
✓ Verify that the DAC's sine wave is identical to the buffer output's copy of it.
✓ Verify that the LED gets brighter and then dimmer at roughly once per second.

Figure 9-8: Buffer Output = DAC Output
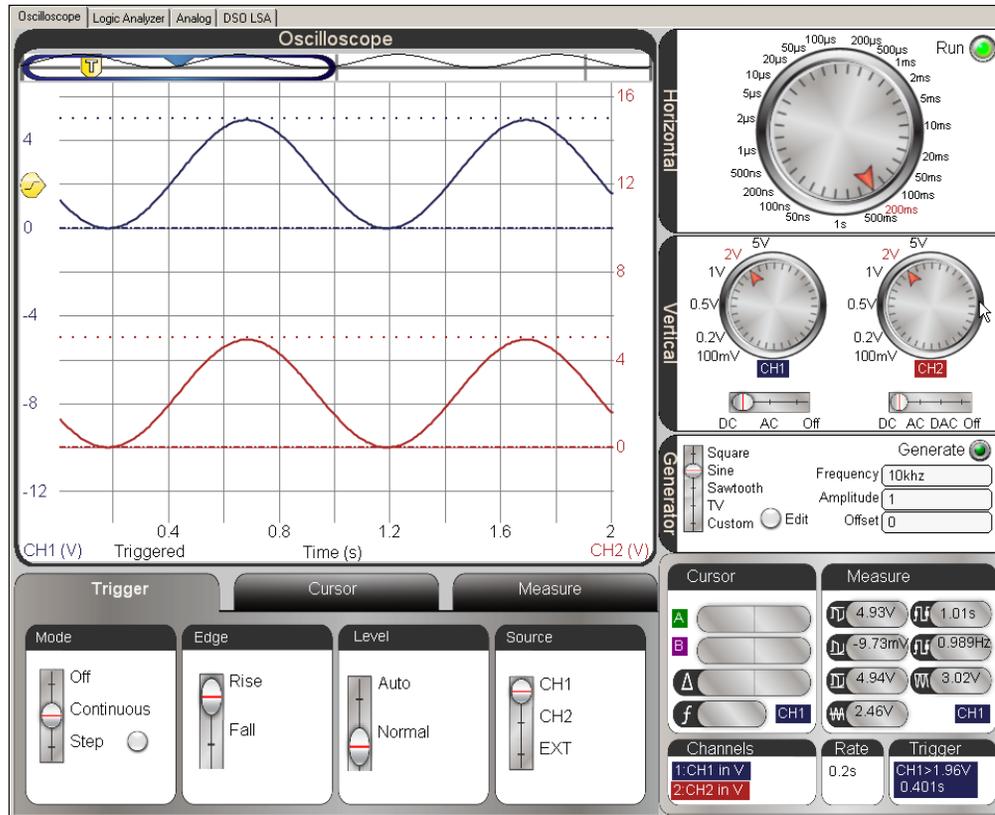
Your Turn: Other RC DAC Waveforms & Chapter 8, Activity #4 Comparison

The LED circuit transmitting the sine wave is interesting because it demonstrates the BASIC Stamp's ability to control brightness with the DAC circuit. This is just one example of many that you can create with the BASIC Stamp. Variations of the PWM command's Duty can be used to create other signals.

- ✓ Try Test Saw Tooth.bs2 from Chapter 8, Activity #4.
- ✓ Repeat the modifications from that activity that make the sawtooth a triangle wave and examine that too.

Chapter 8, Activity #4 mentioned that a voltage follower circuit is a solution to prevent circuit loads from causing the an RC DAC circuit's output voltage to decay. In this activity, the capacitor's output voltage with no load, a 10 kΩ load, and a 2 kΩ load were compared. Without the voltage follower, the capacitor did an okay job of maintaining its output voltage with no load, but its voltage decayed rapidly with the 10 kΩ resistor and even more rapidly with the 2 kΩ resistor load.

> **Comment [AL81]:** Did chapter 8 refer to a buffer or a voltage follower? It should probably be voltage follower. Reconcile.

✓ Repeat the Chapter 8, Activity #4 program and load tests, but apply the loads to the voltage follower's output instead of directly to the capacitor.

✓ For each load resistance, test the outputs of both the RC circuit and the voltage follower.

For all three load tests, both traces should match the no load behavior of the Chapter 8, Activity #4 circuit.

ACTIVITY #3: NONINVERTING AMPLIFIER

The previous activity mentioned a rule for op amp circuits with negative feedback that is very important.

> *Op Amp Negative Feedback Rule: If an op amp's inverting input senses its output through a circuit, the op amp adjusts its output to make the voltage at the inverting input match the voltage at the non-inverting input.*

The voltage follower circuit in the previous activity was the first example of this rule. The op amp's output was shorted to its inverting input, which forced its output to always match the voltage applied to its non-inverting input.

The non-inverting amplifier is another application of the op amp negative feedback rule. Take a look at the voltage divider at the op amp's output in Figure 9-9. It sends some fraction of the op amp's output voltage back to the inverting input. So, to get the voltage at the inverting input to match the voltage at the non-inverting input, the op amp's output has to send a larger voltage. The net effect is that it amplifies the output signal. For example, if Rf and Ri are the same value, the voltage between Rf and Ri would be ½ of Vo. So, to make the voltage at the inverting – terminal match the voltage at the non-inverting + terminal, the op amp has to make Vo twice the value of Vi, the voltage applied to the non-inverting terminal.
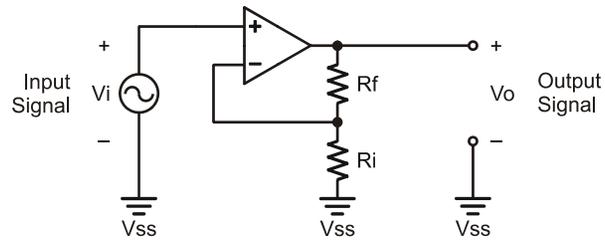
Figure 9-9
Non-Inverting Amplifier

Feedback and Input Resistors: Rf is called the feedback resistor and Ri is called the input resistor.

Common Textbook Version of the Same Circuit. Compare the circuit below to the one in Figure 9-9. They are the same circuit, just drawn differently.
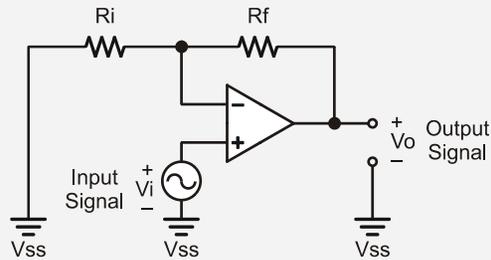
Understanding and Applying Gain

The amount an amplifier "amplifies" voltage is measured as gain, and it's the ratio of output voltage (Vo) to input voltage (Vi). You can also think about it as the ratio of output signal amplitude to input signal amplitude.

$$Gain = \frac{Vo}{Vi}$$

Gain is a convenient value for predicting output voltage based on input voltage. Simply multiply both sides of the Gain ratio by Vi, and you get an equation that predicts Vin. This equation is called a transfer function.

$$Vo = Gain \times Vin$$

A non-inverting amplifier's gain is:

$$Gain = 1 + \frac{Rf}{Ri}$$

We already know because of how voltage dividers work that the non inverting amplifier's output will be twice it's input if Rf and Ri are equal. In other words, we expect the amplifier circuit's gain to be 2. Let's try two 10 kΩ resistors and calculate the gain.

$$
\begin{aligned}
Gain &= 1 + \frac{Rf}{Ri} \\
&= 1 + \frac{10\,k\Omega}{10\,k\Omega} \\
&= 2
\end{aligned}
$$

If the gain is 2, we can predict the output for a given input with the transfer function:

$$
\begin{aligned}
Vo &= Gain \times Vi \\
&= 2 \times Vi
\end{aligned}
$$

This activity will start with Rf = 10 kΩ and Ri = 10 kΩ, and also test with Rf = 20 kΩ and Ri = 10 kΩ.

✓ Repeat this calculations for Rf = 20 kΩ and Ri = 10 kΩ. What will the gain be with this different resistor combination?

Keep in mind that these voltage equations only apply if the output is within the limits set by the op amp's Vcc and Vee power supply rails. For the LM358, that's Vee ≤ Vo ≤ Vcc − 1.4 V. If Vo is outside that range, it will simply stop at the limit imposed by the supply rail.

> **i**   **The minimum gain** for a non-inverting amplifier is 1. So it cannot attenuate a signal, only amplify. For a gain of 1, Rf has to be 0 Ω, which is a wire. So, a voltage follower is really a special case of non-inverting amplifier.

Non-Inverting Amplifier Test Parts

(2) Resistors – 10 kΩ (brown-black-orange)
(1) Resistor – 20 kΩ (red-black-orange)
(1) Op Amp – LM358
(Misc) Jumper Wires

Non-Inverting Amplifier Test Circuit

Figure 9-10 shows a test circuit for our non-inverting amplifier, and Figure 9-11 shows an example of the wired circuit. The PropScope's function generator will send a test signal to the op amp's non-inverting input, and CH1 will monitor the resulting signal at the op amp circuit's output.

   ✓ **STOP:** Disconnect the CH2 probe from the breadboard first.
   ✓ Disconnect the probe from the PropScope's CH2 BNC connector in, and connect it to the DAC CARD's function generator output. See Figure 2-14 on page 44.
   ✓ Build the circuit in Figure 9-10, using Figure 9-11 as a guide.
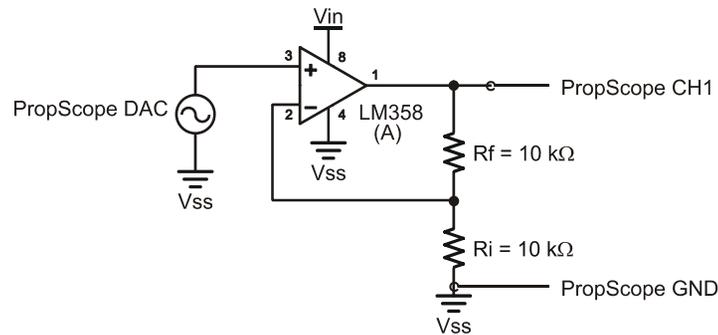
Figure 9-10

Non Inverting
Amplifier Test Circuit
with a Gain of 2

Figure 9-11: Wiring Diagram Example of Figure 9-10
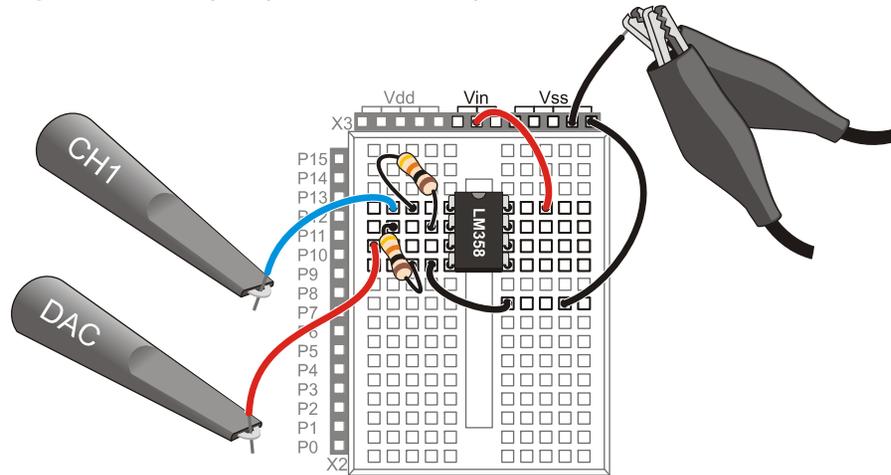
Figure 9-12 shows a quick amplitude check for a 100 Hz, 1 Vpp, 0.5 V offset sine wave generated by the DAC Card and displayed in the lower, red CH2 trace. The amplitude of the output in the upper, blue CH1 trace is approximately 2 Vpp, so it verifies the gain of 2 with Rf = Ri = 10 kΩ.

- ✓ Configure the PropScope's Horizontal, Vertical, Generator and Trigger settings according to Figure 9-12.
- ✓ Make sure to Click the Generator button to start the DAC CARD's signal.

Figure 9-12: Non-inverting Amplifier Gain Test with Rf = Ri = 10 kΩ
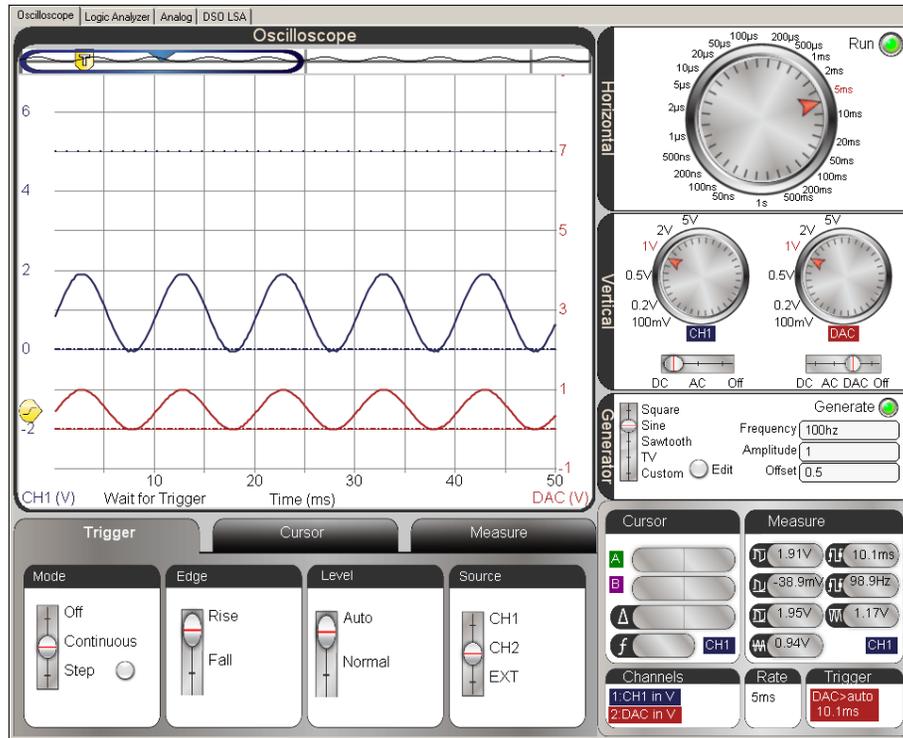
Figure 9-13 shows what happens to the output signal when you replace the 10 kΩ feedback resistor (Rf) with a 20 kΩ one. The gain increased to 3.

- ✓ Replace [≡] 10 kΩ Rf feedback resistor in Figure 9-10 on page 421 with one that's 20 kΩ. I[≡] he top resistor in the Figure 9-11 wiring diagram.
- ✓ Verify the gain increase.
- ✓ Try increasing the input signal's offset to 0.75 and its amplitude to 1.5 in the Generator panel. How did the output respond?

Figure 9-13: Gain with Two Different Feedback Resistor Values
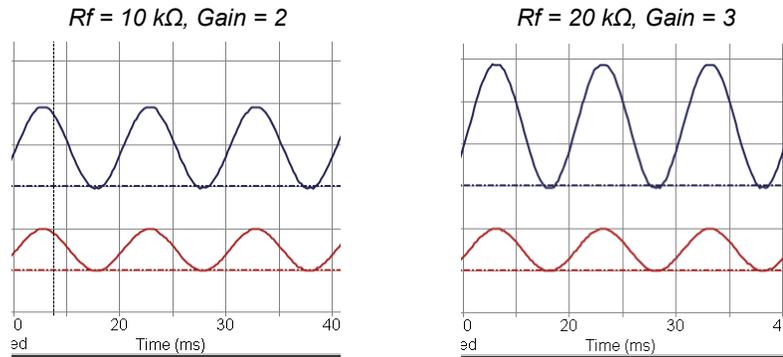
Op Amp Supply Voltages and Clipping Signal Distortion

Remember that the upper limit for the op amp's output signal is 1.5 V less than Vcc, and the lower limit is Vee. Since Vcc is connected to the your board's Vin supply, that maximum voltage would be around 9 V – 1.5 V = 7.5 V. (Assuming you are using a 9 V battery) An output signal that swings from 0 to 4.5 V is well within that range, but what happens if you change the op amp's Vcc connection from Vin ≈ 9 V to Vdd = 5 V? Figure 9-14 shows an example. Notice that the output signal in the upper CH1 trace reaches the op amp's voltage limit and just levels off. It can't go any higher. This symptom is a form of signal distortion called clipping because the tops of the sine wave appeared to be "clipped" off.

✓ Make sure your generator panel is set to Offset = 0.75 V and Amplitude = 1.5 V.
✓ Disconnect the end of the jumper wire plugged into Vin and plug it into Vdd instead.
✓ Verify that your trace resembles Figure 9-14.
✓ For clipping at the op amp output's lower power supply limit, try Amplitude = 1 V and Offset 0.25 V.
✓ Reconnect the op amp's Vee positive supply input to Vin before continuing.

**Figure 9-14:** Output Signal Clipping
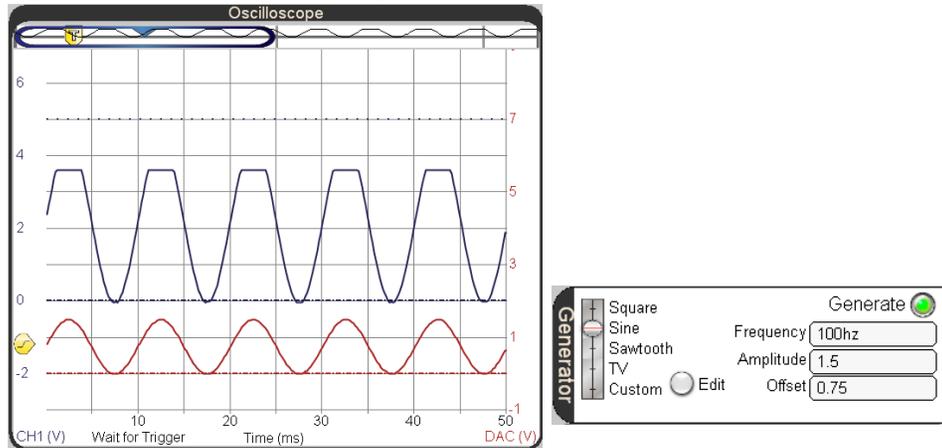
Your Turn: How the Op Amp Translates Offset Voltage

Figure 9-15 shows an example of how a non-inverting op amp circuit amplifies both the offset and the amplitude. The offset of the input sine wave is 1.1 V. Since the gain of the circuit is 3, the amplitude of the sine wave is about 3 V peak to peak, and the offset is almost 1.1 × 3 = 3.3 V.

- ✓ Change the Generator settings back to Amplitude = 1 V and Offset = 0.5 V.
- ✓ Increase the offset from 0.5 to 1.2 V in increments of 0.1 V. The signal's amplitude should stay at 3 Vpp, but the offset should increase by 0.3 V for every 0.1 V increase in your input signal's offset.

Figure 9-15: 1.1 V Offset Amplified to almost 3.3 V
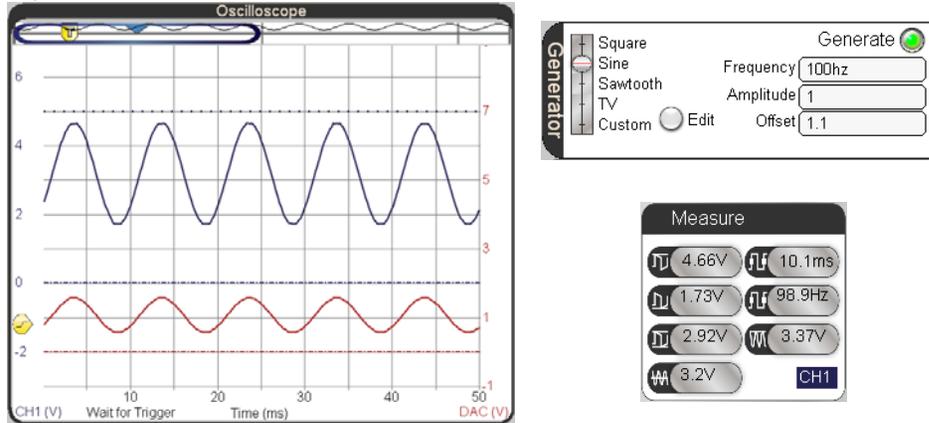
It's also useful to look at just a DC signal amplified.

- ✓ Set the Trigger Mode to Off.
- ✓ Change the Generator Amplitude to 0 V.
- ✓ Apply different DC voltages to the amplifier's input by entering values into the Offset field. Try 0.5 to 1.2 V in increments of 0.1 V again.

ACTIVITY #4: INVERTING AMPLIFIER

The input signals up to this point have been fed to the op amp's non inverting input. In contrast, the inverting amplifier circuit feeds the input signal to the amplifier's inverting input. Figure 9-16 shows the inverting amplifier circuit. This is still a negative feedback amplifier because the inverting input is still connected to the output through Rf.
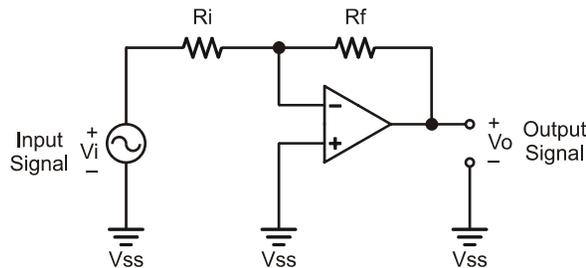
Figure 9-16
Inverting Amplifier

Remember the rule of negative feedback with op amps, the output will adjust to keep the voltage at the inverting input equal to the voltage at the non-inverting input. Let's say the resistors are equal, and Vi = +2 V. In that case, the output would have to transmit –2 V to keep the voltage at the inverting input equal to 0 V, which is the value at the non-inverting input. Another example with Rf = Ri, if Vi is –1 V, Vo has to be +1 V to keep the voltage at the inverting input at 0 V so that it is equal to the non-inverting input. These are two examples where the op amp's output inverts the signal. More generally, the gain for an inverting amplifier is:

$$Gain = -\frac{Rf}{Ri}$$

The negative sign in the gain comes into play when expressing the relationship of output to input signal:

$$Vo = -\frac{Rf}{Ri} \times Vi$$

If we use Rf = Ri = 1, then the output signal Vo is –1 multiplied by the input signal. Substituting Vi = +2 or Vi = –1 verifies the earlier predictions of Vo = –2 V and Vo = +1 V.

In contrast to the non-inverting amplifier, which had a minimum gain of 1, this amplifier can be configured for fractional gains that attenuate the signal by using a value of Ri that's larger than Rf. For example, if Ri = 10 kΩ and Rf = 1 kΩ, the output signal will be attenuated to –Rf/Ri = –1/10 the amplitude of the input signal.

Another difference with possible consequences is the fact that the input signal feeds into a relatively small resistor. The signals in the previous two example circuits were fed into the op-amp's non-inverting input, which has resistance in the hundreds of mega ohms. The inverting amplifier in Figure 9-16 has input resistance of Ri, which might be a comparatively low value, like 10 kΩ. While that's fine for the PropScope's function generator, we have already seen how that can cause decay across a DAC circuit's capacitor. For a design that needs an inverted signal out of an RC DAC, two op amp circuits can be cascaded. The DAC's output can be fed into a buffer, and then the buffer's output could be fed into an inverting amplifier. More on this in the Projects section at the end of the chapter.

Inverting Op Amp Test Circuit Parts

(2) Resistors – 1 kΩ (brown-black-red)
(2) Resistors – 10 kΩ (brown-black-orange)
(1) Resistor – 20 kΩ (red-black-orange)
(1) Op Amp – LM358
(misc) Jumper Wires

Inverting Op Amp Test circuit

The op amp circuit in Figure 9-16 on page 426 is typically implemented with a negative supply voltage connected to the op amp's Vee terminal. That makes it possible for the output voltage to swing above and below ground in an inverted version of the input signal (which also swings above/below ground). The board of education does not have a negative supply, so our inverting amplifier test circuit in Figure 9-17 and Figure 9-18 will use 2.5 V as a reference voltage instead of 0V ground. A resistor divider with two 1 kΩ resistors supplies the non-inverting input with 2.5 V. So long as the function generator output is configured with a 2.5 V offset, the op amp's output will be an inverted version of the input signal. The only difference will be that the input and output signals will swing above and below 2.5 V instead of ground.

✓ Build the circuit in Figure 9-17, optionally using the example wiring in Figure 9-18 as a guide.
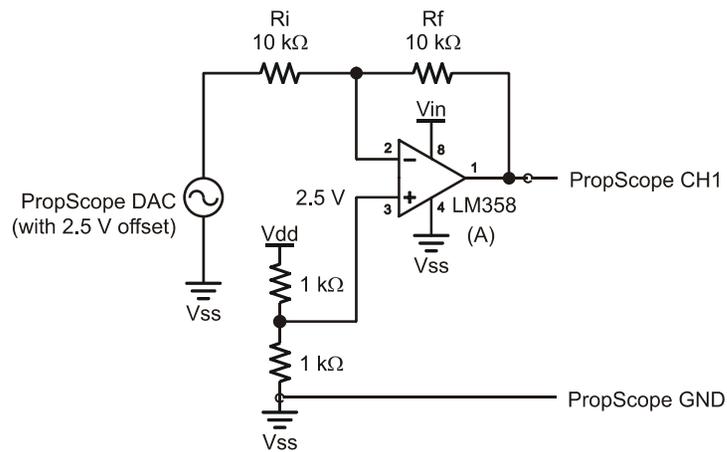
Figure 9-17

Inverting Amplifier Test Circuit

Figure 9-18: Wiring Diagram Example of Figure 9-17
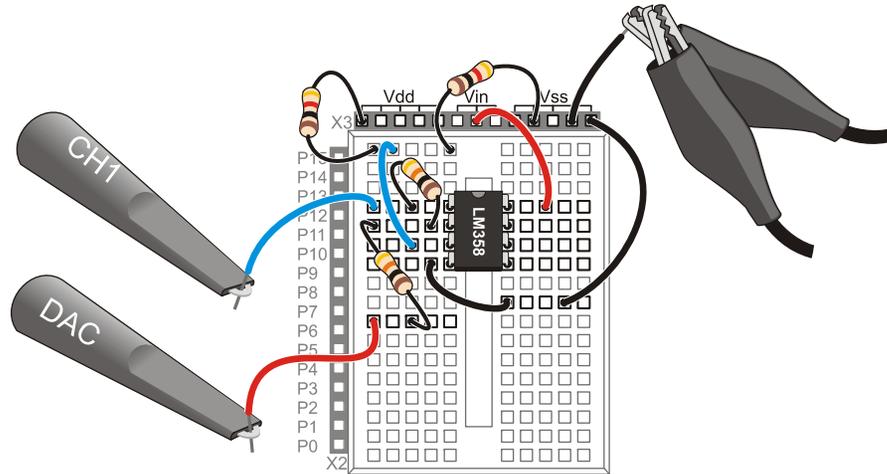
Figure 9-19 shows the lower DAC trace with an amplitude of 1 Vpp and offset of 2.5 V, which is applied to the amplifier's input. The upper CH1 trace, is the amplifier's output. Remember that the gain for this amplifier is –Rf/Ri = –10 kΩ ÷ 10 kΩ = –1. That's why the amplifier output signal in the upper CH1 trace is the voltage opposite of the lower DAC trace. ~~Look carefully,~~ the output signal is an inverted version of the input signal with the top of every high peak in the upper trace lined up with the bottom of a valley in the lower trace.

- ✓ Adjust the Horizontal, Vertical, Generator and Trigger settings according to Figure 9-20.
- ✓ Verify that CH1 shows an inverted version of the DAC output with the same amplitude.

Figure 9-19: Inverting Amplifier Output with a Gain of –1
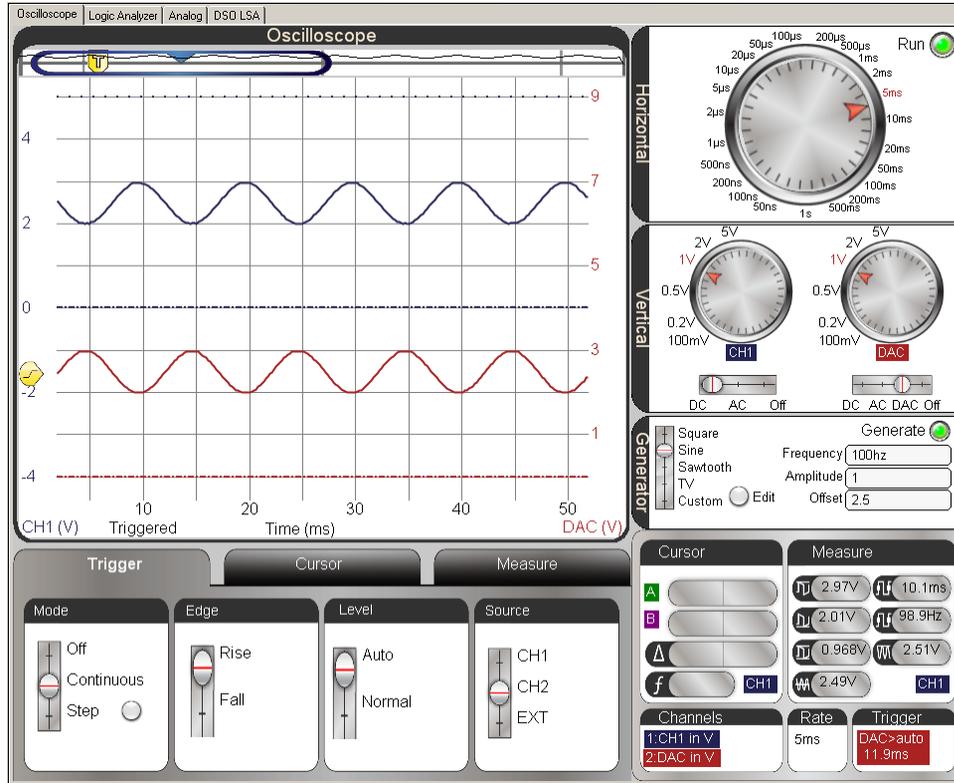
Figure 9-20 compares the –1 gain amplifier circuit against one with Rf = 20 kΩ and Ri = 10 kΩ. The gain with the 20 kΩ feedback resistor is –Rf /Ri = –20 kΩ ÷ 10 kΩ = –2. and this is verified with the upper trace on the right, which is an inverted 2 Vpp inverted version of the lower 1 Vpp DAC trace that goes to the amplifier's input.

✓ Replace the 10 kΩ Rf feedback resistor a 20 kΩ verify the –2 gain.

Figure 9-20: Gain = –1 (left) and -2 (right)
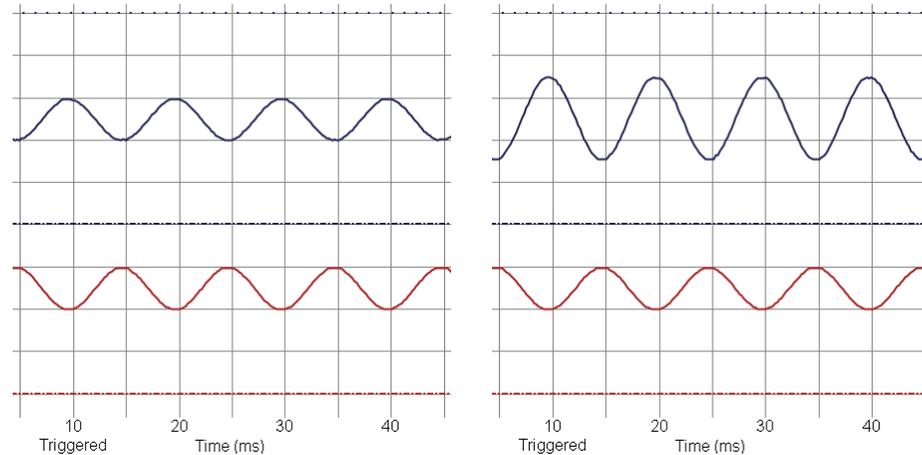
Your Turn: Voltage Offset Response and other Gain Values

With a gain of 2, and if the input signal's offset is 3 V, (0.5 V above 2.5 V), the output signal should have an offset of 1.5 V. (That's 1 V below 2.5 V.)

✓ Test the offset response by adjusting the Offset in the PropScope's Generator panel. Is the prediction correct?.

As mentioned earlier, the inverting op amp can also attenuate the signal with fractional gains.

✓ Adjust the Generator back to 1 Vpp, 2.5 V offset.
✓ Swap the Rf and Ri resistors. Calculate the gain and verify with the PropScope.

Of course, larger magnitude gains are also an option, try this:

✓ Rf = 10 kΩ and Ri = 2 kΩ.
✓ Calculate the gain.
✓ You may need to reduce the DAC signal's amplitude at the op amp circuit's input to prevent clipping at the output.
✓ Verify the gain with the Parallax PropScope.

SUMMARY

This chapter introduced the operational amplifier or op amp. Op amps can be used to perform a variety of operations on signals including: compare, buffer, amplify, attenuate, invert, and many more. The op amp has a large open loop gain. This chapter demonstrated how the open loop gain can be utilized in a comparator circuit to convert small signal differences into digital outputs.

Many signal operations rely on negative feedback circuits where the op amp's inverting input senses its output through a circuit. When an op amp's inverting input senses the output through a circuit, the op amp adjusts its output to make the voltage at the inverting input match the voltage at the non-inverting input. This behavior was used to demonstrate buffer, non-inverting amplifier, and inverting amplifier circuits.

Clipping is a form of signal distortion ~~where~~ the op amp's output tries to send a voltage that is outside the limitations of its supply voltages.

Gain is a measurement of the ratio of output to input signal amplitude. This value can be multiplied by the input signal to predict the output signal in an equation called a transfer function. For non-inverting and inverting amplifier circuits, the gain can be set by choosing a ratio of feedback and input resistors according to the gain equation for the circuit.

Questions

1. What kind of output does a comparator circuit have?
2. What can a voltage follower's output offer that the circuit connected to its input might not be able to do?
3. If the absolute value of an inverting amplifier's gain is the same as that of a non-inverting amplifier's gain, what difference would you expect to see in the output signals? Assume the offsets are identical for both amplifiers.
4. Which gain would you expect to be larger, open or closed loop?
5. In a negative feedback circuit, what does the op amp's output do?
6. What ratio determines a non-inverting op amp's gain?
7. Can a non-inverting amplifier attenuate a signal?
8. How does gain affect offset voltage?
9. If the voltage applied to an inverting amplifier's input is greater than the voltage at the non inverting input, what does the output have to do?
10. How can the BASIC Stamp be a signal source for an amplifier?

Exercises

1. An output signal's amplitude is 5 V and the input signal is 1 V. Calculate the gain.
2. The LM358 needs to transmit 0 and 5 V comparator signals. Calculate the supply voltages.
3. You have a 5 and 0 V supply, 2 2 kΩ resistors, 1 1 kΩ resistor, and an LM358. Set up a comparator that indicates whether a signal is above or below 1 V.
4. A non-inverting amplifier has Rf = 1 kΩ and Ri = 10 kΩ. Calculate the gain.
5. A non-inverting amplifier receives a signal that's 0.3 Vpp and it has a gain of 15. What should the output amplitude be?
6. For an inverting amplifier, Rf = 10 kΩ, Ri = 2 kΩ. Calculate the gain.

Projects

1. Slew rate is used to measure how quickly an op-amp can change its output and is measured in volts per second (V/s). You can observe this when a comparator is switching from low to high or high to low. Try sending a 10 kHz square wave into a comparator and examine the output. Instead of vertical lines transitioning from low/high and from high/low, you will see the voltage ramp up and ramp down. By dividing the change in voltage by the change in time, you can determine the slew rate for this op amp. Express your result in millivolts per microsecond.
2. Make an inverting op amp with adjustable gain that ranges from 0 to 5. Hint: replace the feedback resistor with a potentiometer. You will only need 2 terminals to make it a variable resistor, the middle wiper, and one of the two outside terminals. Leave the third terminal floating. Since there is no negative supply, remember to also set up a 2.5 V voltage divider that feeds to the non-inverting input. Test with a 100 Hz, 1 Vpp, 2.5 V offset signal.
3. If you try to make an RC DAC the signal source for an inverting amplifier, the input resistor will place a load on the circuit and cause the voltage across the capacitor to decay. One way to prevent the voltage decay would be to set up a two stage amplifier using the second op amp in the LM358. The first op amp can buffer the signal, and its output can feed to the inverting op amp's input resistor. Use a 200 Hz, 1 minute FREQOUT command to test the system. The inverting amplifier stage can have a gain of −1 and an offset of 2.5 V with a resistor divider for offset, or a potentiometer for adjustable offset.

Solutions

Q1. High/low.

Q2. Supply current to a circuit load.

Q3. The inverting amplifier's output will be the inverted version of the non-inverting amplifier's output.

Q4. Open loop gain is very large; whereas, closed loop gain is a value that is regulated by a negative feedback circuit.

Q5. It adjusts itself to make the voltage at the non inverting input match the voltage at the inverting input.

Q6. Rf/Ri + 1.

Q7. No, its smallest gain is 1. Attenuation would be a fractional gain.

Q8. The same way it affects signal amplitude. Vf = Gain × Vi.

Q9. Transmit a voltage that's lower than the non inverting input's voltage to make the voltage at the inverting input match.

Q10. With a DAC circuit and the FREQOUT command. The PWM command would work too.

E1. Gain = Vout/Vin = 5/1 = 5.

E2. Vcc = 5 + approx (1.4) = 6.4 V. Vee = 0 V.

E3. Use circuit in Figure 9-3, and replace the upper 1 kΩ resistor with two 2 kΩ resistors in series. This results in a voltage divider of 1 kΩ ÷ 5 kΩ = 1/5. Since Vdd is 5 V, this would set the non-inverting input to 1 V.

E4. 1 + Rf/Ri = 1 + 1/10 = 1.1.

E5. Vo = Gain × Vi = 15 × .3 = 4.5 Vpp.

E6. Gain = –Rf/Ri = –5.

P1. This project ~~utilizes~~ the comparator circuit from Activity #1, but with the function generator connection shown here:
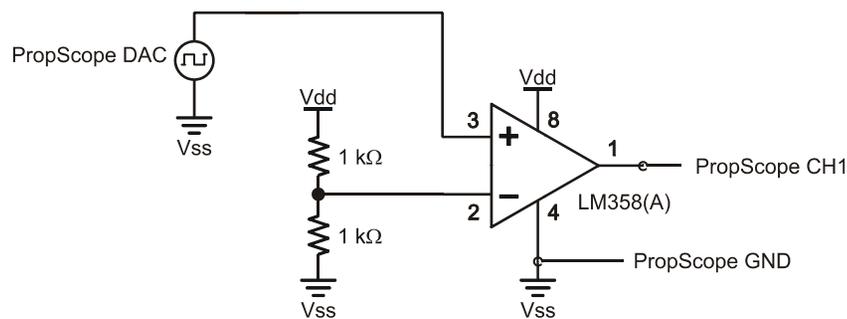
The lower Trace is the DAC square wave supplied to the comparator's input. Vertical and horizontal cursors were placed at the start and end points of the first voltage increase in the upper CH1 trace. The voltage increased by 5.06 V in 21.7 µs. Since slew rate is $\Delta V/\Delta t$, that's slew rate = 5.06 V ÷ 21.7 µs ≈ 233 mV/µs. So, this op amp's output can increase its output voltage by about ¼ of a volt every microsecond.
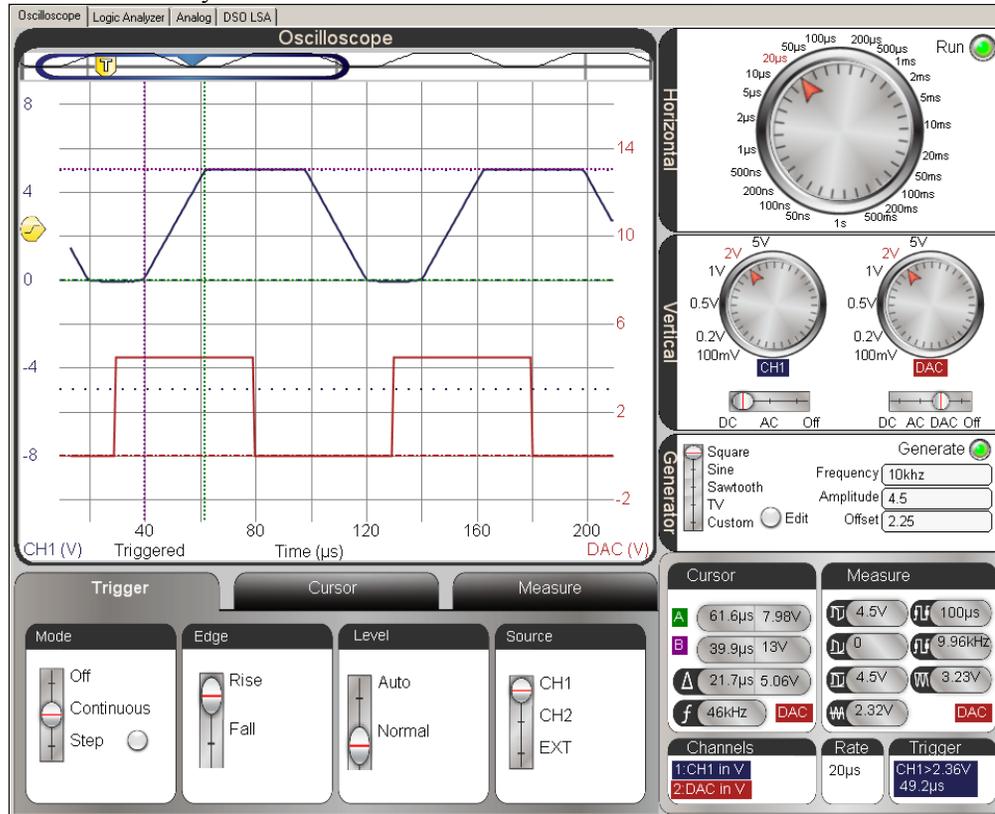
P2. Test Circuit.
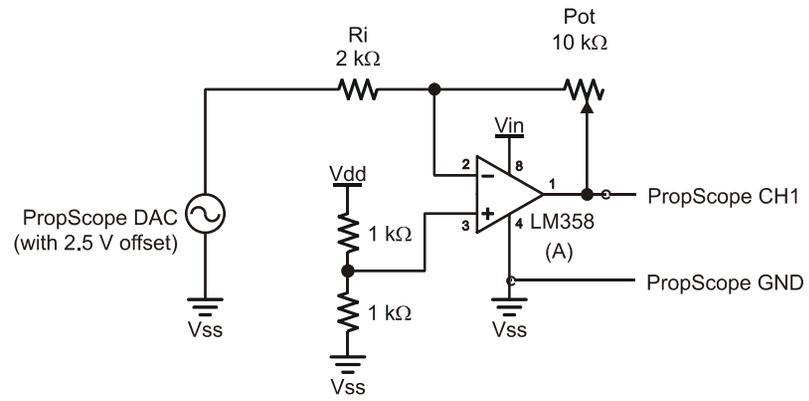
Example with potentiometer set for a gain of about –1/2. The potentiometer resistance is about 1 kΩ.
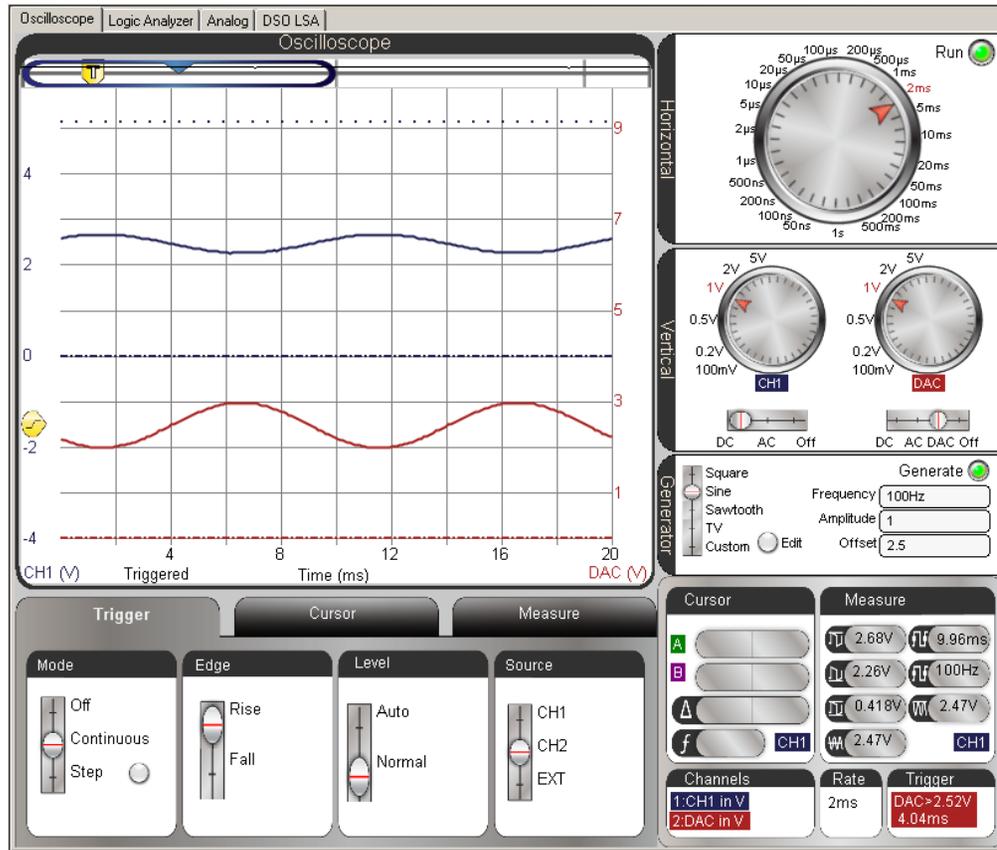
This is a test with a gain of about 1.5.
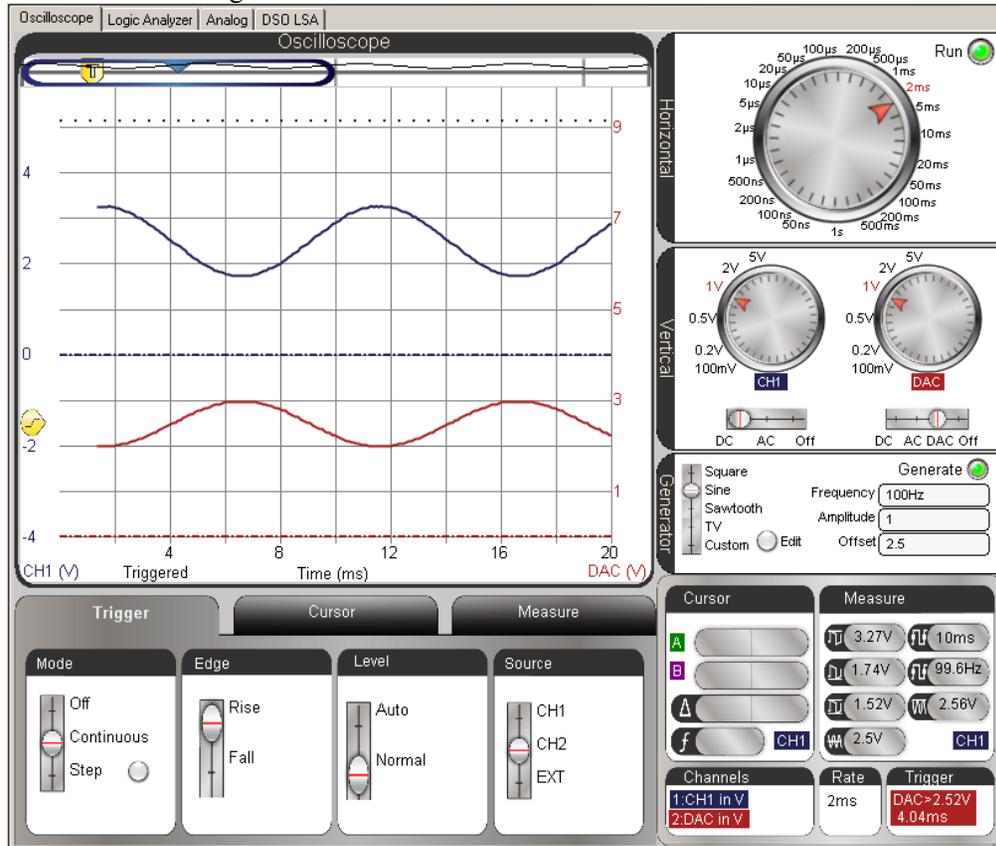
This is a test with the potentiometer set to about 7.2 kΩ for a gain of about 3.6.
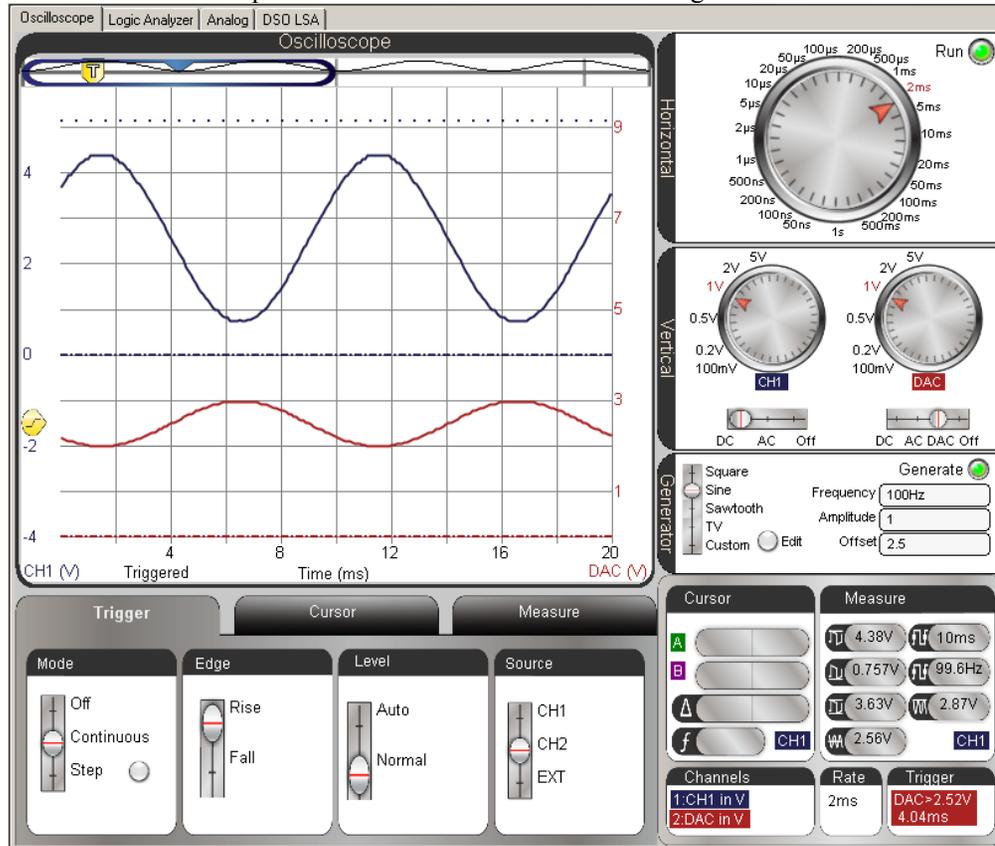
P3. Two stage op amp test circuit. ~~First stage is a buffer, second stage~~ is an inverting
amplifier with a gain of −1 and an adjustable offset.
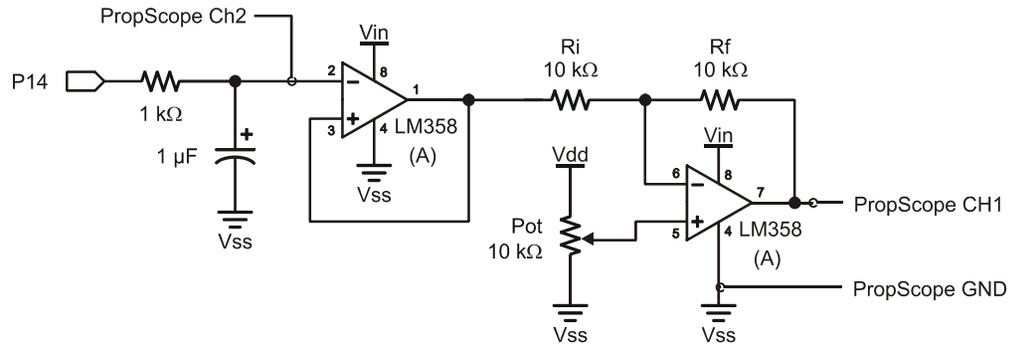
Test Code

```
' Sine Wave 200 Hz.bs2
' Transmit a 10 Hz sine wave on P14 indefinitely.

' {$STAMP BS2}                 ' Target module = BASIC Stamp 2
' {$PBASIC 2.5}                ' Language = PBASIC 2.5

DEBUG "Program running..."     ' Debug Terminal message

DO                             ' Main Loop

  FREQOUT 14, 60000, 200       ' Play 200 Hz for 1 minute

LOOP                           ' Repeat main loop
```

Verify gain = –1
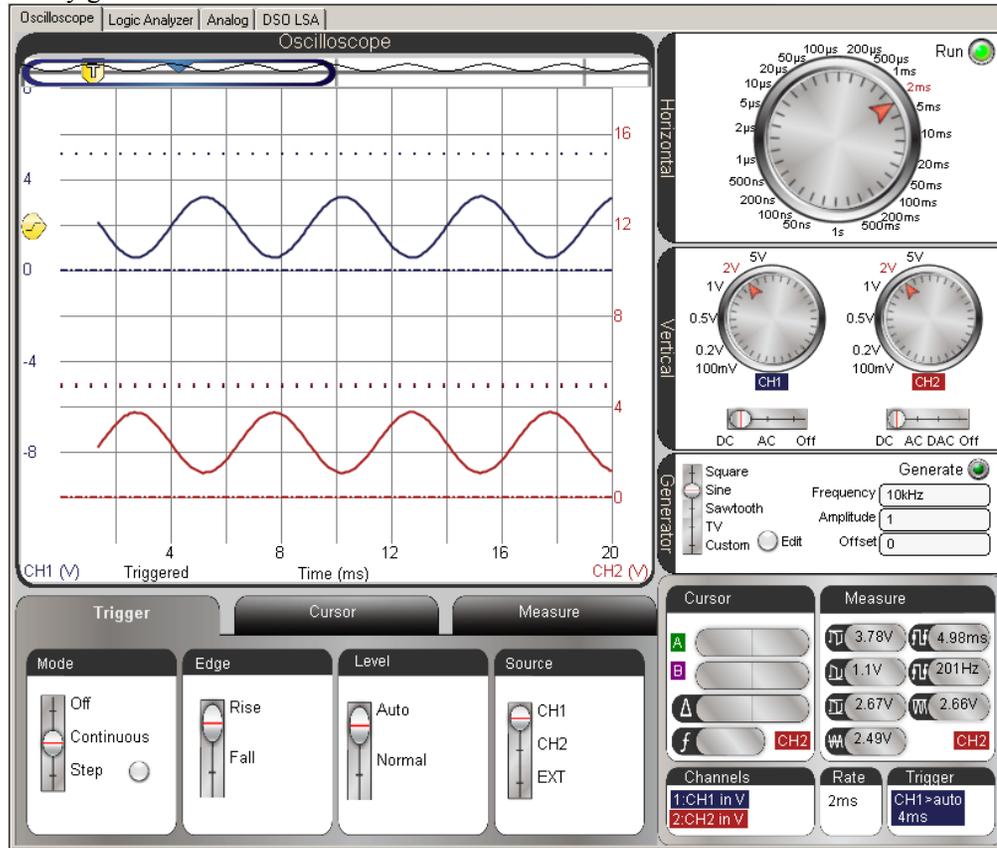
Test an offset adjustment limit.