

## Chapter 8: RC Circuit Measurements

### RESISTORS, CAPACITORS, AND RC CIRCUITS

A resistor “resists” the flow of current, and a capacitor stores charge, kind of like a tiny, rechargeable battery. These two components form the building blocks for a variety of resistor-capacitor (RC) circuits. In addition to taking a closer look at the signals in the circuits that were used for D/A conversion and low-pass filtering, this chapter also examines how the circuit and another signaling approach can be useful for BASIC Stamp sensor measurements.

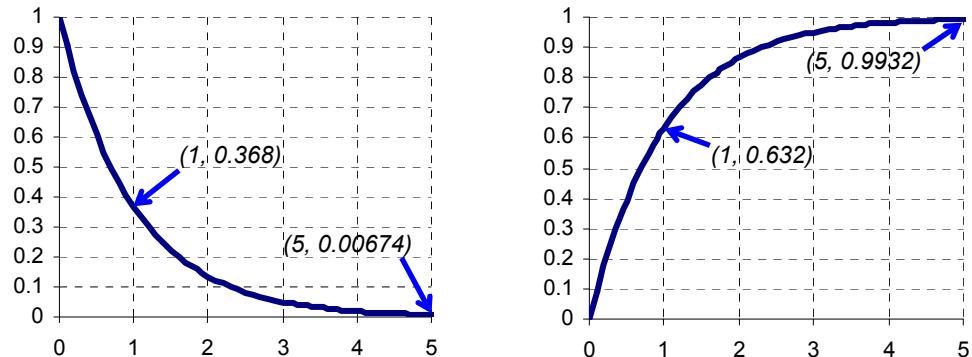
#### ACTIVITY #1: RC GROWTH AND DECAY

Charging and discharging a capacitor through a resistor takes a certain amount of time, and it's related to the natural logarithmic constant  $e$ . The value of  $e$  is approximately 2.718. Variations on the exponential growth equation  $y = e^x$  are best known for their use in modeling population growth. Variations on the exponential decay equation  $y = e^{-x}$  also have many uses, and one of them is to describe how voltage changes as a capacitor loses or gains charge through a resistor. When applied to capacitor as it charges and/or discharges through a resistor, exponential decay is called RC decay.

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The left side of Figure 8-1 shows a graph of  $y = e^{-x}$ . This graph shows how the voltage across a capacitor behaves as it loses its charge through a resistor. When  $x = 1$ ,  $y = e^{-1} \approx 0.368$ . Another way to say that is when  $x$  gets to 1,  $y$  has decayed to 36.8% of its starting value. 36.8% is an important number for RC decay measurements. Also, by the time  $x$  reaches 5, the  $y$  value is only 0.00674, which is less than 1% of its starting value. The graph on the right is  $y = 1 - e^{-x}$ , and it describes a capacitor gaining charge through a resistor. The corresponding 63.2% level when  $x = 1$  is also important, along with the  $y$  value when  $x = 5$ , which is within 1% of its final value of 1.

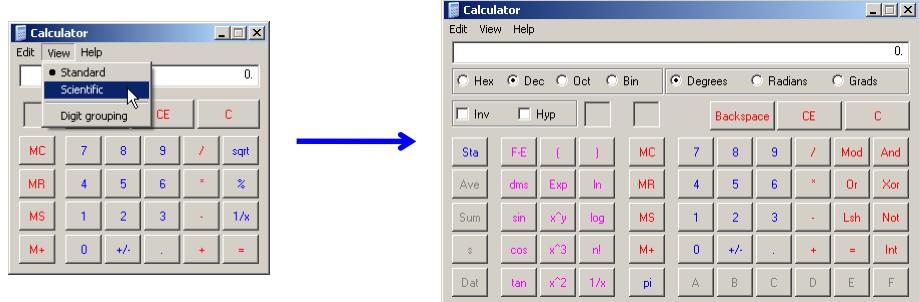
**Figure 8-1:** Graphs of  $y = e^{-x}$  and  $y = 1 - e^{-x}$



Let's use the Windows Calculator to verify a few values from the graphs in Figure 8-1.

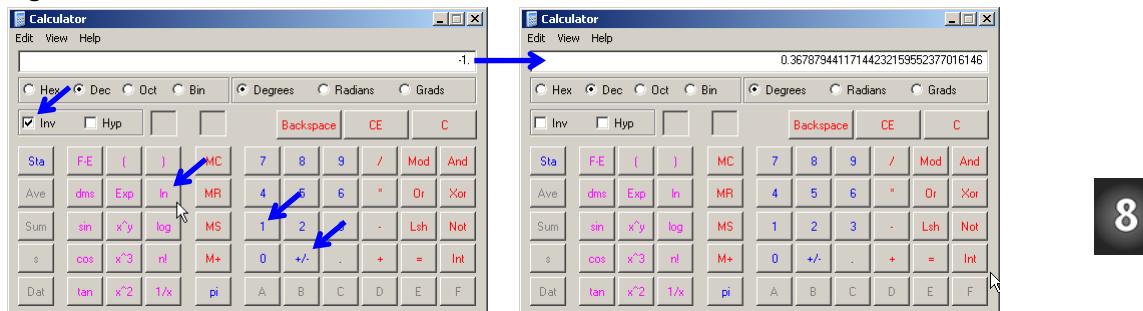
- ✓ Run Windows Calculator by clicking Start → All Programs → Accessories → Calculator.
- ✓ If your calculator looks like the one on the left in Figure 8-2, click View and select Scientific.

**Figure 8-2:** Windows Calculator



Most calculators have an  $e^x$  button you can use to calculate the points on  $y = e^{-x}$  graphs, and it's usually shared with the  $\ln$  function, which tells you what  $x$  is in  $e^x$  for a given value. To save button space, the Windows Calculator has the  $\ln$  key and an inverse (Inv) checkbox that you can click to make the  $\ln$  key calculate  $e^x$ . Here is how to calculate  $e^{-1}$  with the Windows calculator's  $\ln$  button:

- ✓ Click the 1 button.
- ✓ Click  $+/ -$  to make it  $-1$ .
- ✓ Click the Inv checkbox.
- ✓ Click the ln button.
- ✓ The calculator will display the result of  $e^{-1}$ . 
- ✓ Calculate the value of  $e^{-5}$ .
- ✓ Try  $e^{-2}$ ,  $e^{-3}$  and  $e^{-4}$ , and compare them to the points in the graph on the left hand side of Figure 8-1.

**Figure 8-3:** Calculate  $e^{-1}$  with the Windows Calculator

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You can create similar graphs to predict a voltage ( $v$ ) as it decays from a certain starting value down to zero volts over time ( $t$ ) with this version of the RC decay equation:

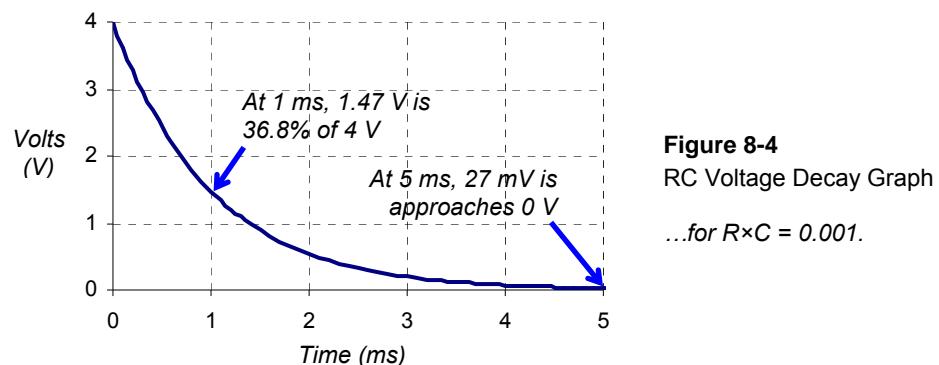
$$v = V_I \times e^{-t/RC}.$$

$V_I$  is the initial or starting voltage, and  $R$  and  $C$  are the values of the resistor and capacitor. The value  $RC$  in  $v = V_I e^{-t/RC}$  is called the  $\tau$  time constant, and is expressed as the Greek letter tau ( $\tau$ ), which is pronounced, “taw.” So, you may see the decay expressed as  $v = V_I e^{-t/\tau}$ . A factoid to memorize is that the voltage decays to about 36.8% of its initial value in one  $\tau$  time constant, and for a reminder, just calculate  $e^{-1}$  with your calculator.

Let's say that  $C = 1 \mu\text{F}$  and  $R = 1 \text{k}\Omega$ . Then,  $R \times C = 1 \text{k}\Omega \times 1 \mu\text{F}$ , which is  $1,000 \times 0.000001 = 0.001$ . If we assume the capacitor gets charged to 4 V before being allowed to decay through the resistor, that would make  $V_i = 4 \text{ V}$ , and the equation would be:

$$v = 4 \times e^{-t/0.001}$$

Figure 8-4 shows a graph of this equation. At 1 ms, the voltage has decayed to  $4 \times e^{-0.001/0.001} = 4 \times e^{-1} = 4 \times 36.8\% = 1.47 \text{ V}$ . By the time the decay reaches the 5 ms mark, it's close enough to its final voltage to consider completely discharged.



**Figure 8-4**  
RC Voltage Decay Graph  
...for  $R \times C = 0.001$ .

In this activity, you will measure RC decay time and use it to verify the values of R and C in a circuit. You will also compare the decay time at the 36.8% decay point to the circuit's RC time constant.

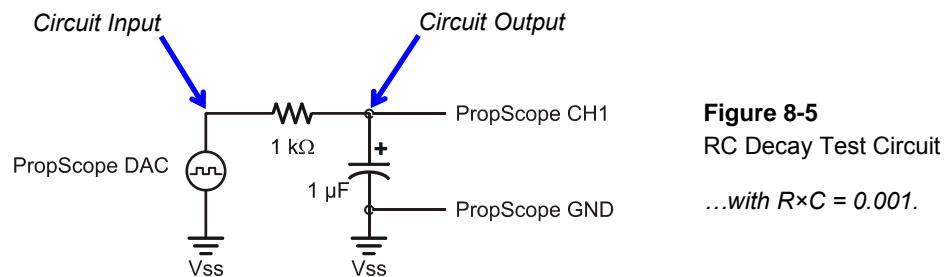
### **RC Time Constant Test Circuit Parts**

- (1) Resistor – 1 kΩ (brown-black-red)
- (1) Capacitor – 1 μF
- (misc) Wires

### **RC Time Constant Test Circuit**

Figure 8-5 shows a schematic of the RC decay test circuit and Figure 8-6 shows an example wiring diagram.

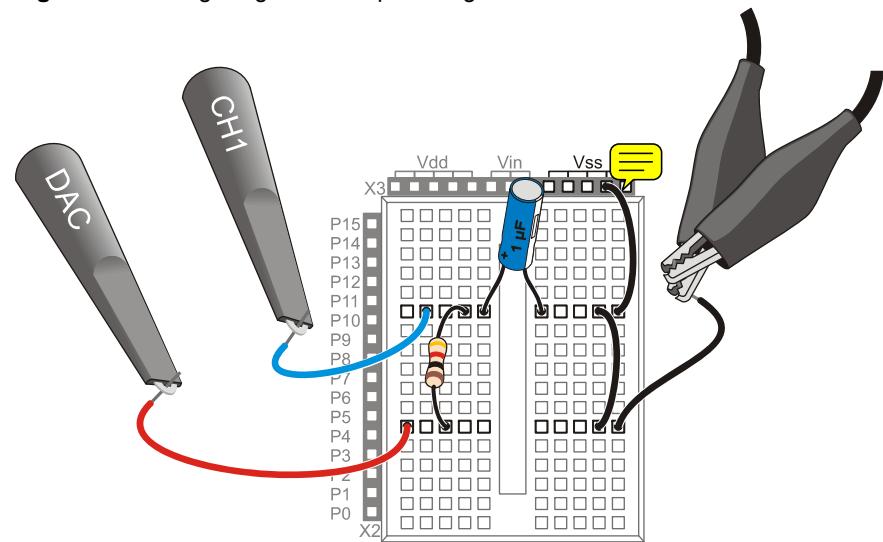
- ✓ If your probe with the red indicator band is not already connected to the DAC CARD's function generator BNC connector, do that now. (For a refresher on the locations of these connectors, see Figure 2-14, page 44.)
- ✓ Connect the DAC probe (with the red indicator band) to the circuit input as shown in Figure 8-5 and Figure 8-6.
- ✓ Connect the CH1 probe (with the blue indicator band) to the RC circuit's output.



**Figure 8-5**  
RC Decay Test Circuit  
...with  $R \times C = 0.001$ .

**Figure 8-6:** Wiring Diagram Example of Figure 8-5

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### **RC Time Constant Predictions**

The decay time tests involve a square wave that will charge and discharge the RC circuit's capacitor. The first task is to  out a good frequency for the square wave. ~~Each high/low time needs to be at least 5 RC time constants.~~ Since  $R = 1 \text{ k}\Omega$ , and  $C = 1 \mu\text{F}$ , the RC time constant  $\tau$  is:

$$\begin{aligned}\tau &= R \times C \\ &= 1 \text{ k}\Omega \times 1 \mu\text{F} \\ &= 1,000 \times 0.000001 \text{ s} \\ &= 0.001 \text{ s} \\ &= 1 \text{ ms}\end{aligned}$$

The square wave's high signal has to last at least 5 time constants ( $5\tau$ ) for the capacitor to charge, and the low signal also needs to last  $5\tau$  for the capacitor to discharge. So, the minimum value of one signal cycle period ( $T_{\min}$ ) to the RC circuit's input has to last for a total of ten RC time constants:

$$T_{\min} = 10\tau = 10 \times 1 \text{ ms} = 10 \text{ ms}$$

This means the input frequency has to be at most the reciprocal of  $T_{\min}$ :

$$\begin{aligned}f_{\max} &= 1 \div T_{\min} \\ &= 100 \text{ Hz}\end{aligned}$$

For a first view, it's always good to see at least two full cycles, which means that the display has to be two cycles wide:

$$\text{Oscilloscope Screen Width}_{\min} = 2 \times T_{\min} = 2 \times 10 \text{ ms} = 20 \text{ ms}$$

Remember that the Horizontal dial specifies the width of a time division, which is  $1/10^{\text{th}}$  of the oscilloscope screen's width, so:

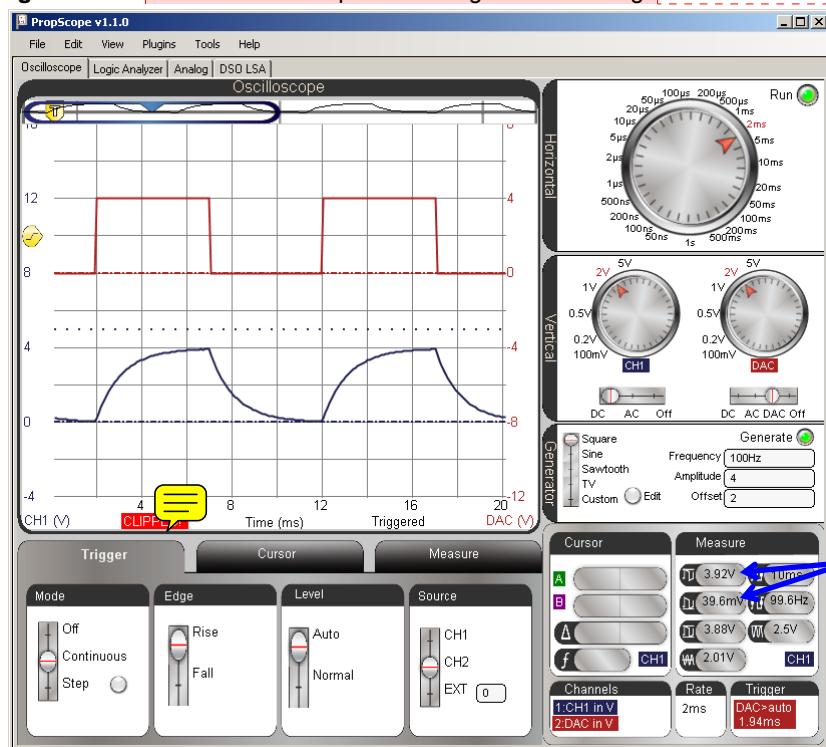
$$\text{Horizontal Dial Setting}_{\min} = \text{Oscilloscope Screen Width}_{\min} \div 10 = 20 \text{ ms} \div 10 = 2 \text{ ms}$$

### Examine the Capacitor Voltage as it Charges and Discharges

Figure 8-7 shows two cycles of the square wave the function generator applies to the RC circuit along with the RC decays at the circuit's output.

- ✓ Generator panel: Function switch = Square, Frequency = 100 Hz, Amplitude = 4 V, Offset = 2 V.
- ✓ Dials: Horizontal = 2 ms/div, Vertical CH1 = 1 V/div, CH2 = 1 V/div.
- ✓ Vertical coupling switches: CH1 = DC, CH2 = DAC
- ✓ Trigger tab: Mode = Continuous, Edge = Rise, Level = Auto, Source = CH2.
- ✓ Trigger Time Control: Set to 1<sup>st</sup> time division line
- ✓ Position the red CH2/DAC trace above the blue CH1 positive/negative RC decay trace.

**Figure 8-7: 5 Time Constant Capacitor Charge and Discharge**



**Comment [AL77]: Retake pending CLIPPED message goes away.**

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High and low peak voltages

In Figure 8-7 the upper, red CH2/DAC trace shows a square wave that spends 5 ms at 4 V, then 5 ms at 0 V. This is the signal the function generator applies to the RC circuit's input. With each stage level, current flows through the resistor and either charges or discharges the capacitor during each 5 ms time period. The lower, blue CH1 trace shows the capacitor voltage's response, which alternates directions of RC decay curves. Since the function generator voltage spends 5 ms, which is  $5 \times \tau$ , in each state, the capacitor should charge to almost 4 V and discharge to almost 0 V.

In the oscilloscope screen, the CH1 voltage charges so close to 4 V and discharges so close to 0 V that it's difficult to tell it hasn't actually reached those values. Since the rule of thumb for practical applications is that 5 time constants is enough to consider the capacitor fully charged or discharged, the fact that the signal looks so close to its final voltages is a good sign. We can see from the high and low peak voltages in the Measure display that the capacitor charged to 3.92 V, then discharged to 39.6 mV. Although these measurements aren't exactly the predicted 27 mV, they are in the right ballpark to confirm that the circuit is working properly. A few hundredths of a volt off is fine. If it were instead a few tenths of a volt, it would be time to go searching for sources of error other than propagated errors from supply noise and small function generator output + CH1 input errors.

- ✓ Click the CH2 trace  the Measure panel to display its values. (Or click the CH1/CH2 label in the Measure display to toggle between measurements for the two traces.)
- ✓ Make a note of the CH2/DAC high and low peak voltages.
- ✓ Click the CH1 trace (or the CH2 label in the Measure display) to switch to displaying values for CH1, and make notes of the high and low peak voltages. Examples are shown in Figure 8-7.
- ✓ Compare them to the predicted  $5\tau$  values of 0.674% and 99.32%. For example, 0.674% of 4 V is  $4 \times 0.00674 = 0.02696 \approx 27$  mV.
- ✓ Optional: The CH2/DAC signal is an ideal value. You can probe the CH2 probe with the CH1 probe to find the actual measured voltage the function generator applies to the circuit's input, and then compare those to the measured peak voltages at the circuit's output.

Let's try adjusting to cycle high/low times that last  $10\tau$  (ten RC time constants) instead of  $5\tau$  to see if anything interesting happens. For this, we'll want twice the signal period, which would be half the frequency. To maintain two cycles in the Oscilloscope display, the time per division will also have to be doubled, or in the case of the PropScope,

adjusted from 2 ms/div to the next larger increment, which is 5 ms/div. Figure 8-8 shows the new view. In this particular example, the high peak in the Measure display is now about 3.98 V, which is 20 mV from 4 V, and the low peak is at almost –10 mV. As before, these values are still “in the right ballpark.”

- ✓ Adjust the Horizontal dial to 5 ms/div.
- ✓ Adjust the Generator panel’s Frequency field to 50 Hz.
- ✓ Adjust the Trigger Time Control to the 2<sup>nd</sup> time division line.
- ✓ Repeat the input output signal high and low peak measurement comparisons. How different are your results after ten RC time constants ( $10\tau$ )?

**Figure 8-8:** Square Wave Input and Increasing/Decreasing RC Decay Output

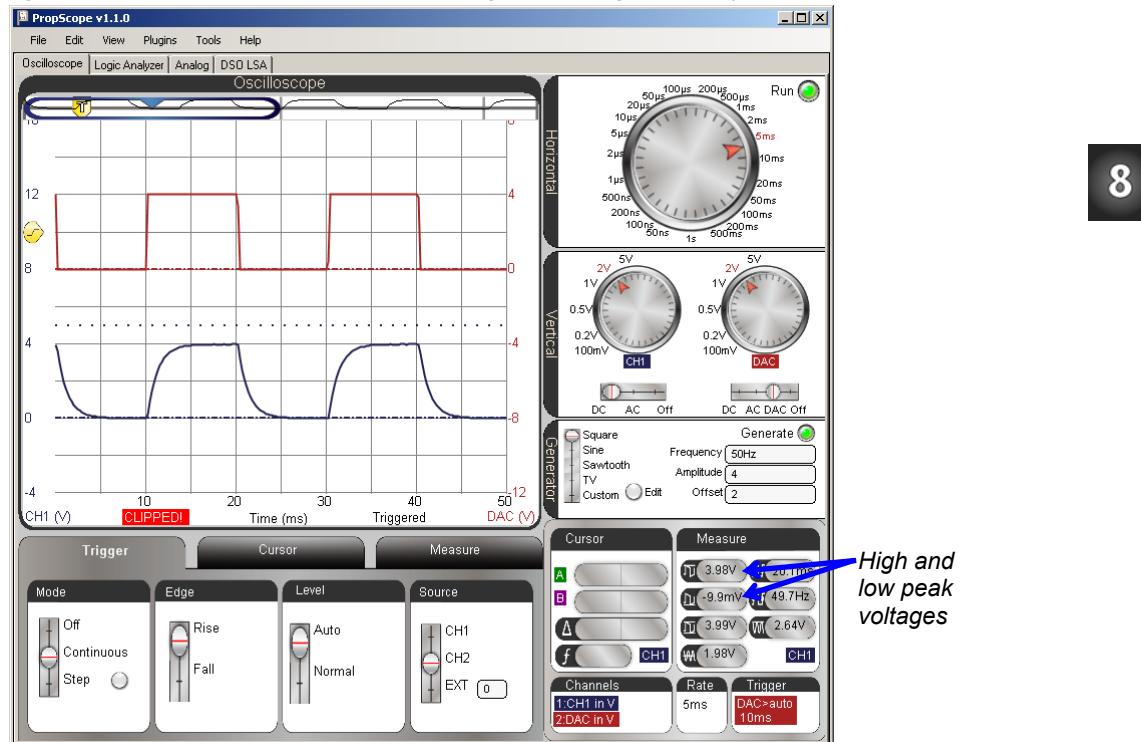


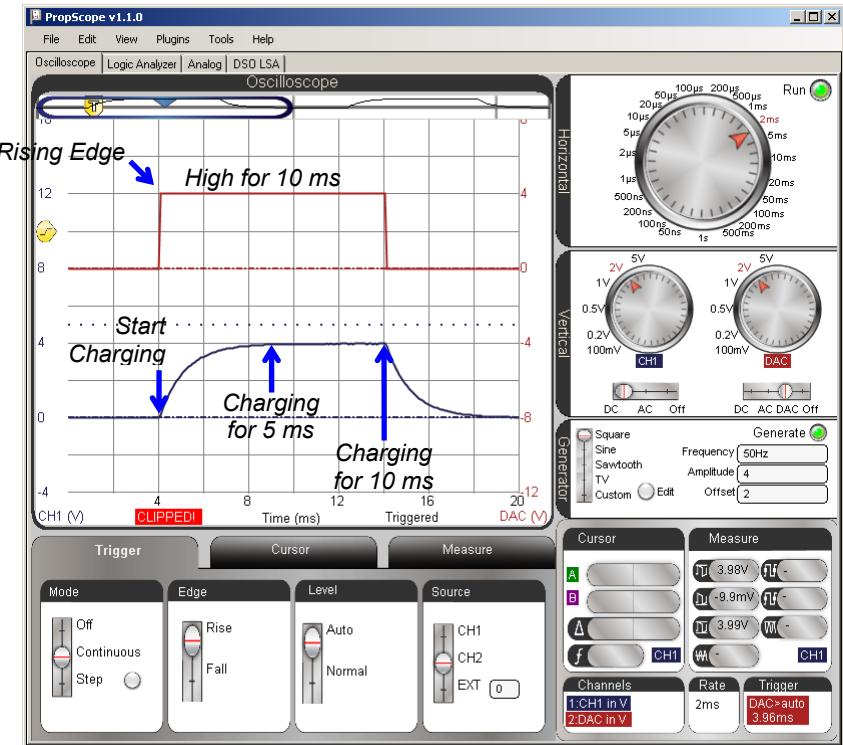
Figure 8-9 zooms in to 2 ms/division with the horizontal scale for a closer look at voltage as the capacitor charges. Since the trigger time control is set to the 2<sup>nd</sup> time division line,

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the positive edge of the CH2 function generator signal lines up with that division line, and its negative edge lines up with the 7<sup>th</sup> time division line. Between 5 and 10 ms into the high signal, the CH1 RC circuit output voltage changes very little, if any. This makes sense since  is the 5  $\tau$  mark, and the capacitor should be charged to 99.32% of the applied voltage.

- ✓ Change the Horizontal dial to 2 ms/div for the view in Figure 8-9.

**Figure 8-9:** Charging the Capacitor for 10 ms

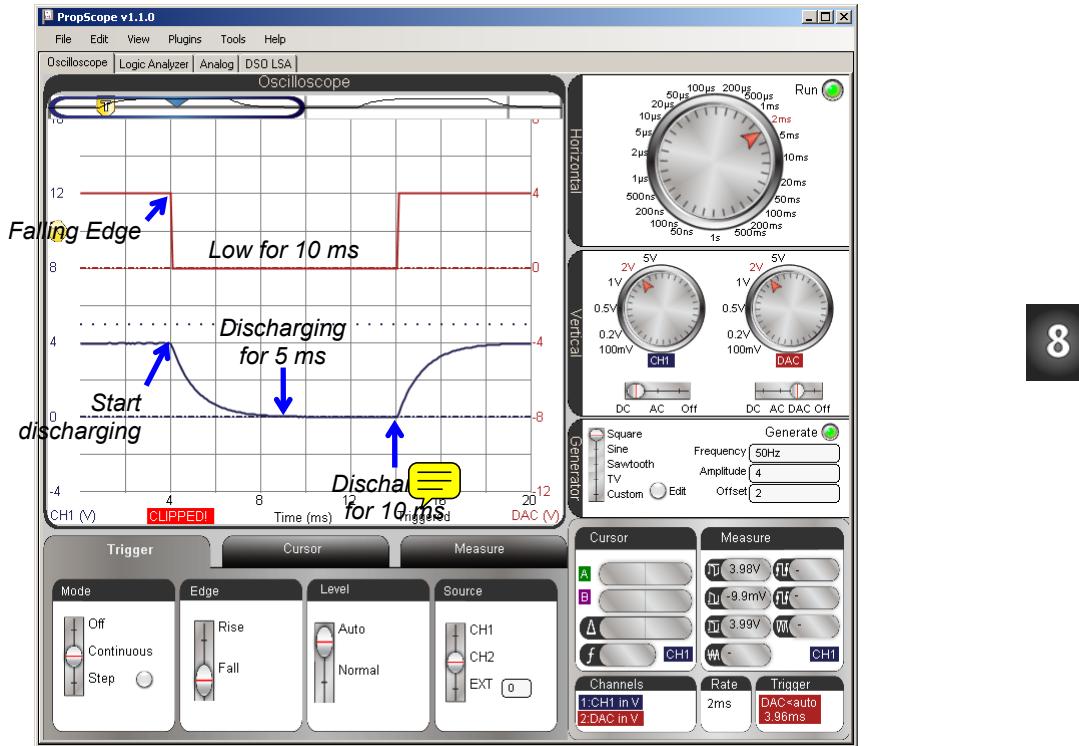


Here is a trick to remember. You don't have to move the screen back and forth to switch from the view of the capacitor's voltage response as it charges to its voltage response as it discharges. Instead, just change the Trigger Edge from Rise to Fall. Your display should then resemble Figure 8-10. With that change, it causes the function generator signal's negative edge to line up with the 2<sup>nd</sup> time division. The 10 ms of function generator's

low signal becomes visible in CH2, and the RC circuit's output voltage response as the capacitor discharges becomes visible in CH1.

- ✓ Change the Trigger Edge setting from Rise to Fall. Your view should now resemble Figure 8-10.

**Figure 8-10:** Toggle Trigger Edge from Rise to Fall to See the 10 ms Discharge



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### RC Time Constant Measurements

In an RC decay, if 1 time constant has elapsed, the voltage will have decayed from 100% to 36.8%. The converse is also true, if the voltage has decayed to the 36.8% level, one time constant has elapsed. With this in mind, the trick to measuring an RC circuit's time constant from its decay response is to set a horizontal voltage cursor at a level that's 36.8% above the final voltage. Then, use the time cursors to measure from the start of

the decay to the point where the voltage cursor that's at the 36.8% level intersects with the trace.

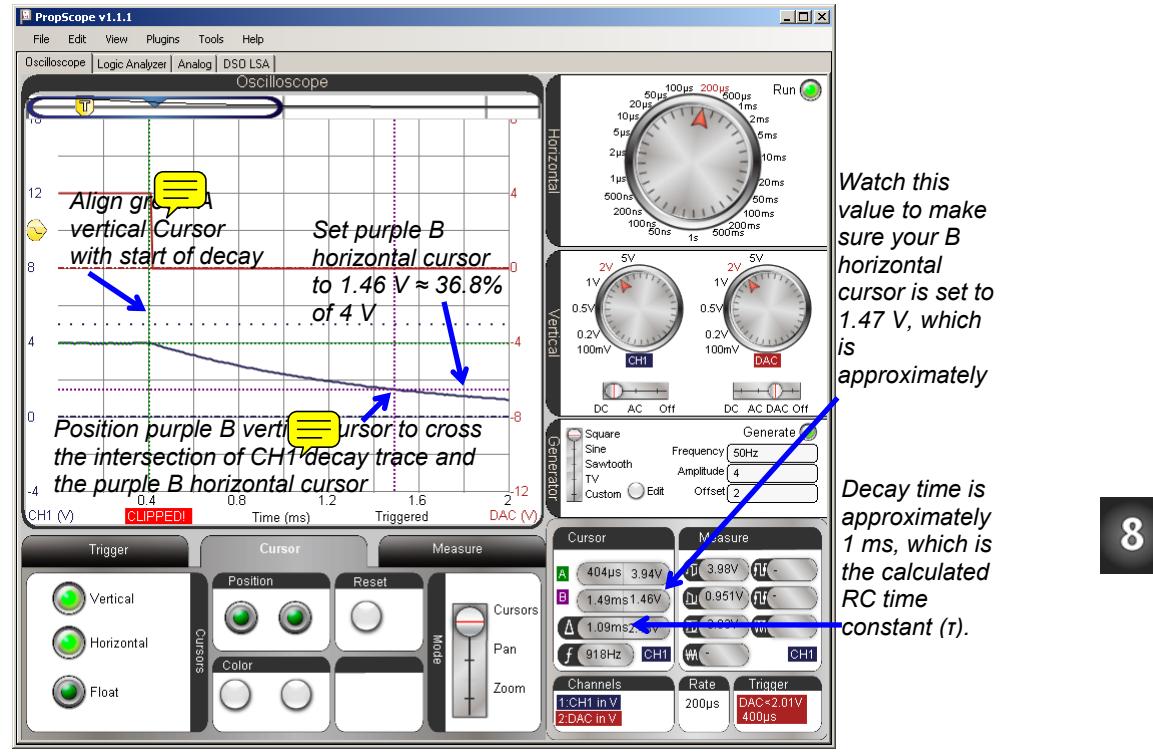
Figure 8-11 shows an example with the Horizontal dial adjusted to 200  $\mu\text{s}/\text{div}$  for a zoomed in view of that first one millisecond time constant's worth of decay. The vertical A time cursor is lined up with the start of the decay. Then, the horizontal B voltage cursor is set to as close as possible to 1.47 V, which is 36.8% of 4 V. You can use the B voltage level measurement in the Cursor display to know the cursor's voltage as you position it to 1.47 V. Next, the time from the start of the decay to the 36.8% level is measured by aligning the vertical B time cursor with the intersection of the decay trace and the horizontal B voltage cursor. The time measurement result will appear in the Measure Display's  $\Delta$  field.



**Horizontal Cursors** are positioned at voltage levels and measure voltage differences. They are commonly referred to as "voltage cursors."

**Vertical Cursors** are positioned at times and measure time differences. They are commonly referred to as "time cursors."

- ✓ Set the trigger Level to Normal.
- ✓ Make sure the Trigger Voltage control is 2 V on the CH2 vertical scale. (In the middle of the CH2/DAC square wave in Figure 8-11.)
- ✓ We want to take a close look at that first millisecond of decay, so adjust the Horizontal dial to 200  $\mu\text{s}/\text{div}$ .
- ✓ Multiply 4 V by 36.8%, the result should be about 1.47 V.
- ✓ Line the green A vertical cursor up with the start of the decay.
- ✓ Set the purple B horizontal cursor as close as possible to 1.47 V. Use the B cursor voltage measurement in the Cursor display as a guide.
- ✓ Position the purple B vertical cursor so that it crosses the intersection of the B vertical cursor and the CH1 trace.
- ✓ The Cursor display's  $\Delta$  field will show the time difference between the two vertical cursors, which is  $\tau$  for your circuit.

**Figure 8-11:** Measuring the RC Time Constant**Predicted vs. Measured Differences**

In Figure 8-11, the measured RC Time constant is 1.09 ms, which is within 9% of the calculated  $\tau$  value of 1 ms. Since the electrolytic capacitor's tolerance is  $\pm 20\%$ , a difference of up to 20% between the measured and predicted values would still be reasonable.

**Your Turn: Repeat for RC Decay from 0 to 4 V**

For RC decay from 0 to 4 V, all you have to do is toggle the Trigger Edge from Fall to Rise, and then use cursors to measure the time difference between when the capacitor starts charging and when it passes 63.2% of the way to its final voltage level.

- ✓ Try it.

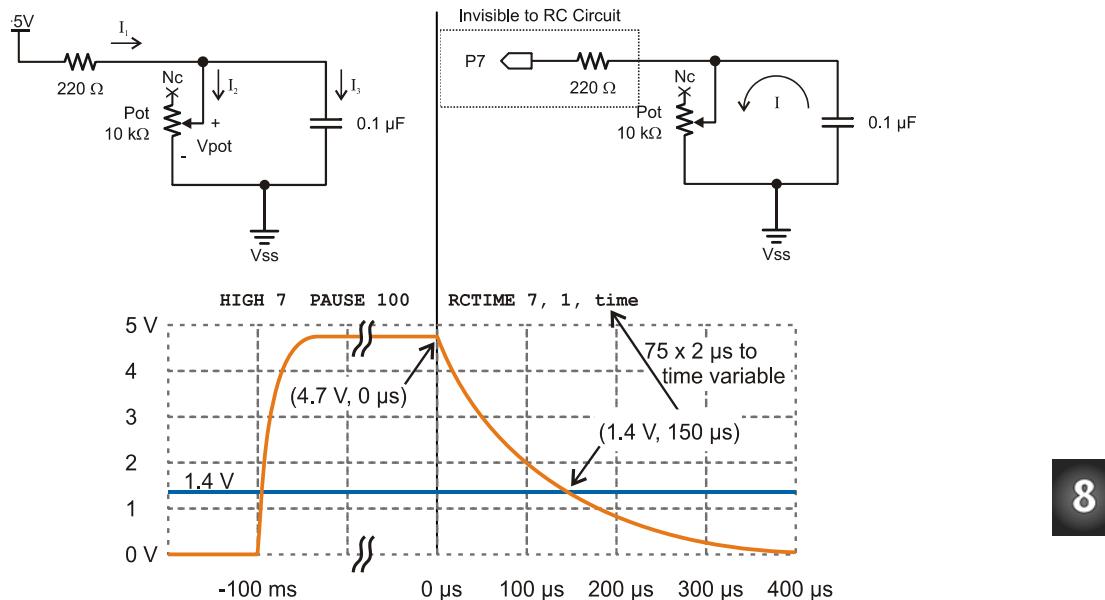
Your value should be almost identical to your decay time since it's a measurement of the RC time constant for the same circuit.

## ACTIVITY #2: RC SENSOR MEASUREMENTS WITH A POTENTIOMETER

The BASIC Stamp can measure RC decay with a command called RCTIME. Since a wide variety of sensors either vary in resistance or capacitance, it's an extremely useful feature. It can also be used with sensors that vary in conductance, allowing more or less current to flow with changes in the physical property the sensor measures. Examples of physical properties the BASIC Stamp can measure with sensors and RCTIME include: visible light, infrared light, humidity, potentiometer knob position, temperature, presence or absence of a flame, and the presence of certain gasses. Those are also just a few entries in a larger list; if the sensor varies in either resistance, capacitance, or conductivity, it's a candidate for the techniques you will examine in this activity.

Figure 8-12 shows how the BASIC Stamp's RCTIME command works with a potentiometer. With its B and W terminals connected as shown, the pot functions as a variable resistor. The adjusting knob can be turned to vary the resistance from  $0\ \Omega$  to  $10\ k\Omega$ . On the left side of Figure 8-12, the microcontroller sets its I/O pin high. The resulting 5 V signal charges the capacitor through the  $220\ \Omega$  resistor. After a brief pause, the RCTIME command sets the I/O pin to input, and the circuit and voltage behave as shown on the right side of the figure. As an input, the I/O pin is invisible to the circuit, and it's like the voltage source just disappeared. So, the capacitor starts losing its charge through the potentiometer. As it loses its charge, the capacitor's voltage decays. So, the BASIC Stamp's RCTIME command measures the time between when it changed its I/O pin to input and when the capacitor's voltage decays to the I/O pin's 1.4 V logic threshold.

**Figure 8-12:** Voltage at P7 through HIGH, PAUSE, and RCTIME Commands  
(Excerpt from *What's a Microcontroller, Chapter 5*)



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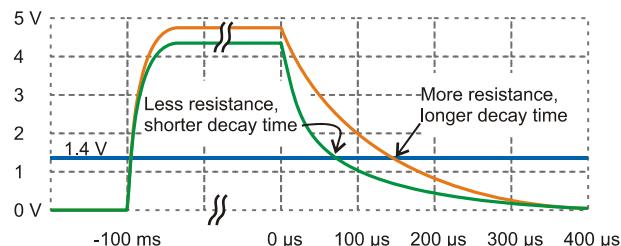
#### Different RC Time Constants for Charging and Discharging

The RC time constant for the circuit on the left side of Figure 8-12 is  $220 \Omega \times 0.1 \mu\text{F} = 22 \mu\text{s}$ . So only a tiny delay is needed while the capacitor charges. The RC time constant for the decay is the potentiometer's resistance  $R_{pot} \times 0.1 \mu\text{F}$ .  $R_{pot}$  could be as large as  $10 \text{ k}\Omega$ . Assuming the  $1.4 \text{ V}$  threshold is less than 2 time constants into the decay, an estimate for the longest possible time measurement (with generous padding) would be:

$$2 \times \tau = 2 \times 10,000 \times 0.1 \times 10^{-6} = 2 \text{ ms.}$$

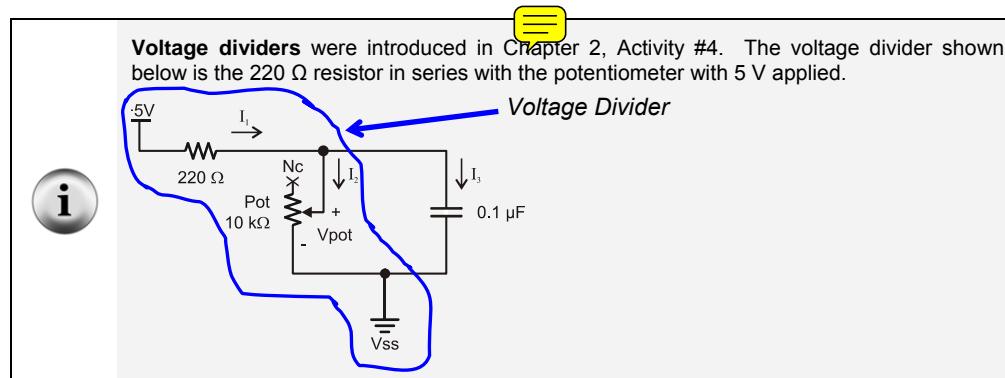
Keep in mind that different potentiometer knob positions result in different resistances. In an RC circuit, different resistances result in different decay times  the BASIC Stamp can measure and use to infer the potentiometer knob's position. This is useful for making the potentiometer and adjusting knob in microcontroller applications. Figure 8-13 shows examples of how two different potentiometer resistances result in two different decay times, which the BASIC Stamp's RCTIME command would record as two different time measurements. If the pot's knob has been adjusted to make the

resistance larger, the RC time constant will also be larger, which means the capacitor will take longer to decay from its starting voltage to 1.4 V. If the pot's knob has been adjusted to make the resistance smaller, the RC time constant is smaller, and the voltage will take less time to decay.



**Figure 8-13**  
How Potentiometer Resistance  
Affects Decay Time  
*(Excerpt from What's a  
Microcontroller, Chapter 5)*

The voltage the capacitor charges to also changes slightly in Figure 8-13. The  $220\ \Omega$  resistor in Figure 8-12 protects the I/O pin from current surges as the capacitor starts charging, and it also protects the I/O pin if the potentiometer's knob is turned to the limit of its range of motion that gives it  $0\ \Omega$  of resistance. Since the BASIC Stamp sends a high signal to the circuit to charge the capacitor, that high signal would be shorted to ground if the potentiometer is set to  $0\ \Omega$ . So the  $220\ \Omega$  resistor protects the I/O pin from this condition. However, there is a price for the resistor protection. In the case of the RC decay measurement, the resistor forms a voltage divider with the potentiometer's resistance. That voltage divider limits the final voltage the potentiometer can charge up to. This shows in the graph as the capacitor charging up to a lower value when the potentiometer's resistance is less, which in turn reduces the decay time slightly more than the smaller RC time constant would on its own.



### Potentiometer Sensor Test Parts

(1) Potentiometer – 10 kΩ (103)

(1) Capacitor – 0.1 μF (104)

(1) Resistor – 220 Ω (red-red-brown)

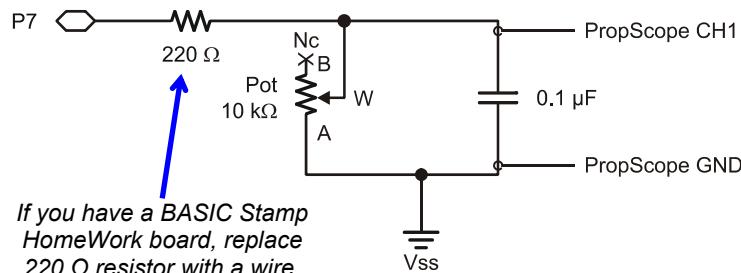
If you have a BASIC Stamp HomeWork board, use a wire instead of the 220 Ω resistor.

(Misc) Wires

### Potentiometer Sensor Test Circuit

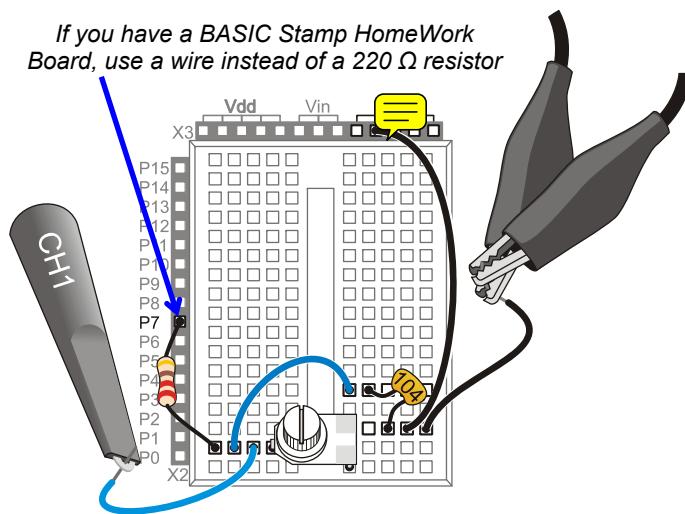
Figure 8-14 shows the potentiometer decay test circuit, and Figure 8-15 shows an example wiring diagram.

- ✓ Build the circuit shown in Figure 8-14 and Figure 8-15.



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**Figure 8-14**  
Pot Schematic



**Figure 8-15**  
Example Wiring for  
Figure 8-14.

### Potentiometer Sensor Test Code

ReadPotWithRcTime.bs2 is an example program from What's a Microcontroller. Its DO...LOOP has code that sets P7 high and then waits for 100 ms, which is way more time than necessary for charging capacitor. The main reason for the long PAUSE command is to slow down the ~~messages~~ the BASIC Stamp sends to the Debug Terminal to a rate of 10 Hz. After the PAUSE, the RCTIME command sets the I/O pin to input and then waits for the voltage at I/O pin P7 to decay to 1.4 V. Then, it stores the time measurement in terms of 2  $\mu$ s units in a variable named time. Before it repeats the DO...LOOP, the DEBUG command displays the time variable's measurement result in the Debug Terminal.

- ✓ Enter ReadPotWithRcTime.bs2 into the BASIC Stamp Editor and run it.

```
' What's a Microcontroller - ReadPotWithRcTime.bs2
' Read potentiometer in RC-time circuit using RCTIME command.

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

time          VAR      Word                  ' For storing decay times
```

```

PAUSE 1000          ' 1 s before sending messages

DO
    HIGH 7           ' Main Loop
    PAUSE 100
    RCTIME 7, 1, time
    DEBUG HOME, "time = ", DEC5 time
    ' Set P7 high
    ' Wait 0.1 seconds
    ' RC Decay time measurement
    ' Display time in 2 us increments

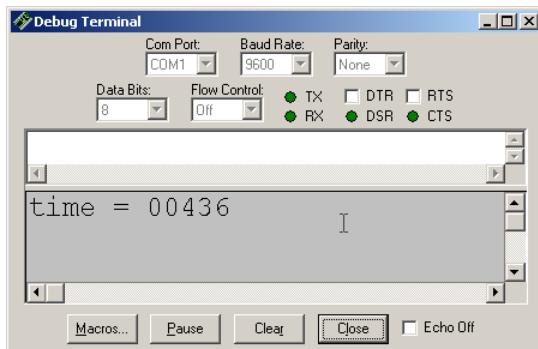
LOOP
    ' Repeat main loop

```

Figure 8-16 shows the decay measurement, which again is the number of 2  $\mu$ s units it took the capacitor voltage to decay from its starting voltage down to 1.4 V. Since the time displayed in Figure 8-16 is 436, it means that the decay took  $436 \times 2 \mu\text{s} = 872 \mu\text{s}$ .

- ✓ Maintain downward pressure on the potentiometer knob as you adjust it to keep it in contact with the breadboard connections.
- ✓ Turn the potentiometer knob to a point about  $\frac{3}{4}$  of the way counterclockwise in its range of motion, then make fine adjustments for a Debug Terminal value of 436.

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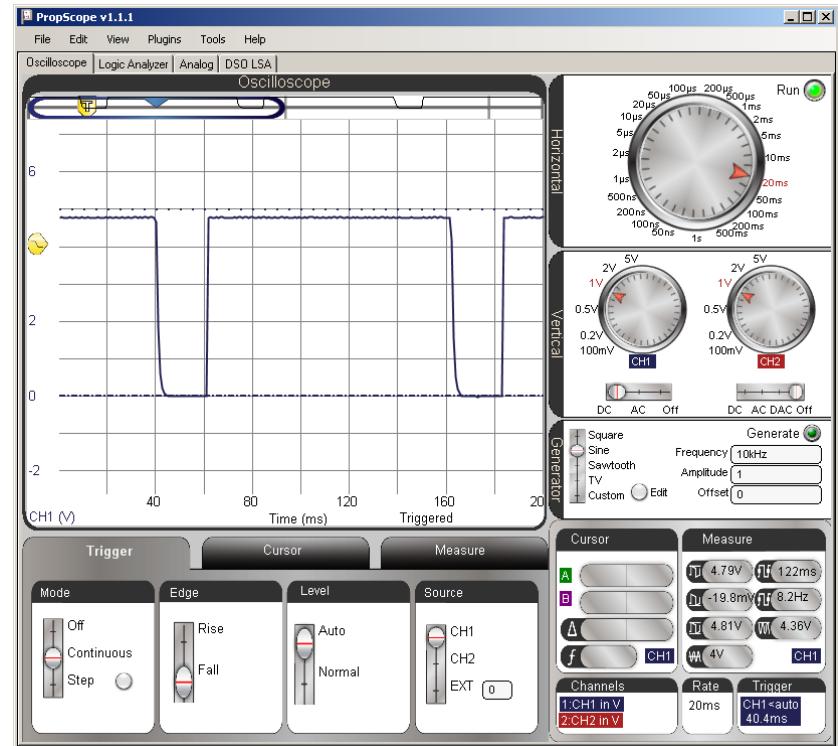
**Figure 8-16**  
Debug Terminal Pot  
Measurement  
*...in 2  $\mu$ s units.*

### Potentiometer Sensor Test Measurements

Each repetition of ReadPotWithRcTime.bs2 takes at least 100 ms because of the PAUSE 100 command. In addition, there's the time it takes for the RC decay measurement, the DEBUG command, and some time to process all the commands in the loop. All that said, 200 ms is a reasonable estimate for a first look at two cycles of the measurement, so the Horizontal dial is set to 20 ms/div in Figure 8-17.

- ✓ Dials: Horizontal = 20 ms/div, Vertical CH1 = 1 V/div.
- ✓ Vertical coupling switches: CH1 = 1 V, CH2 = Off.
- ✓ Trigger tab switches; Mode = Continuous, Edge = Fall, Level = Auto, Source = CH1.
- ✓ Trigger Time Control: Adjust vertical crosshair to 2<sup>nd</sup> Time division line.

**Figure 8-17: Two Decay Measurements Separated by a 100 ms Pause**

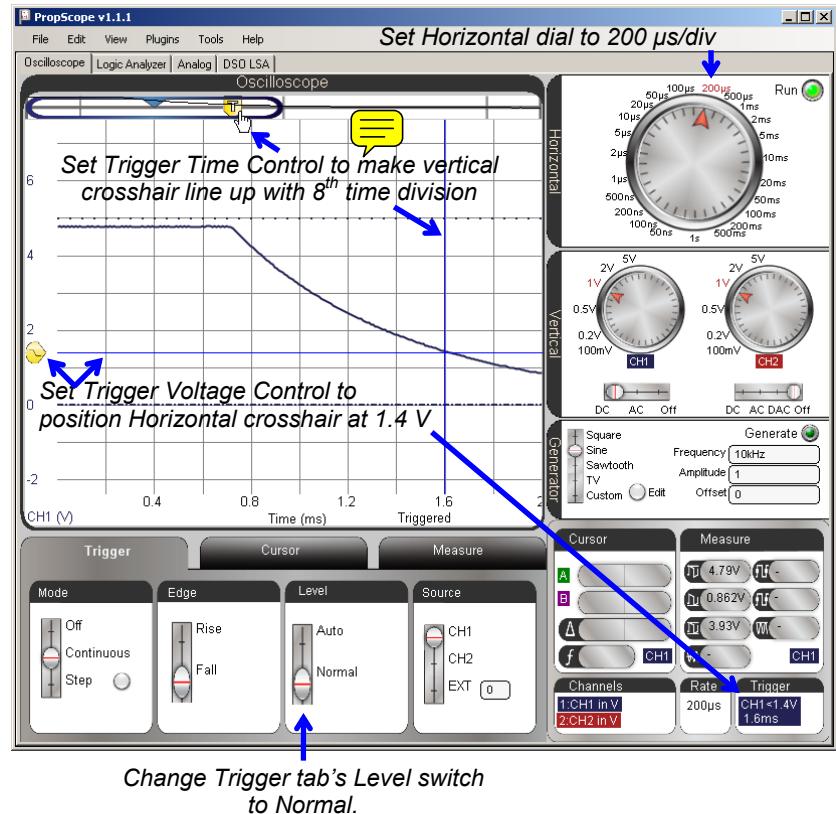


In Figure 8-17, it's difficult to see any of the decay measurement because the PAUSE command is 100 ms, but the decay is only 872  $\mu$ s. That's less than 1/100<sup>th</sup> of the PAUSE time! Figure 8-19 shows an example of a closer look at the decay portion of the signal. The fact that the Trigger Edge was set to Fall made it so that reducing the Horizontal dial to 500  $\mu$ s/div zoomed right in on the decay measurement. With this view, the cursors can be used to measure the decay time and verify the BASIC Stamp's measurement.

The PropScope uses a full cycle to calculate average voltage. When the Trigger tab's Level switch is set to Auto, it uses this level for positioning the Trigger Voltage Control. When you zoom in on decay times to take cursor measurements, there's no full cycle, so it's hard for the PropScope to know what the automatic trigger level should be. Also, since we are measuring the time it takes the voltage to decay to the BASIC Stamp's 1.4 V logic threshold, it's a good idea to set the Trigger tab's Level setting to Normal, and then manually adjust the Trigger Voltage Control to 1.4 V. The trace will cross this at the end of the measurement, so it's also a good idea to adjust the Trigger Time Control to somewhere near the right of the oscilloscope display, like maybe the 8<sup>th</sup> time division line.

- ✓ Change the Trigger tab's Level switch from Auto to Normal.
- ✓ Slide the Trigger Voltage Control to 1.4 V. The Trigger display in the bottom-right corner of the window shows your manually adjusted trigger voltage value. Watch it as you adjust the Trigger Voltage Control's horizontal trigger crosshair to get as close as possible to 1.4 V.
- ✓ Slide the Trigger Time Control to align the vertical trigger crosshair with the 8<sup>th</sup> time division line.
- ✓ Adjust the Horizontal dial to 500  $\mu$ s/div.
- ✓ Check your display against Figure 8-18.

**Figure 8-18:** Adjustments for Verifying BASIC Stamp RC Decay Measurements

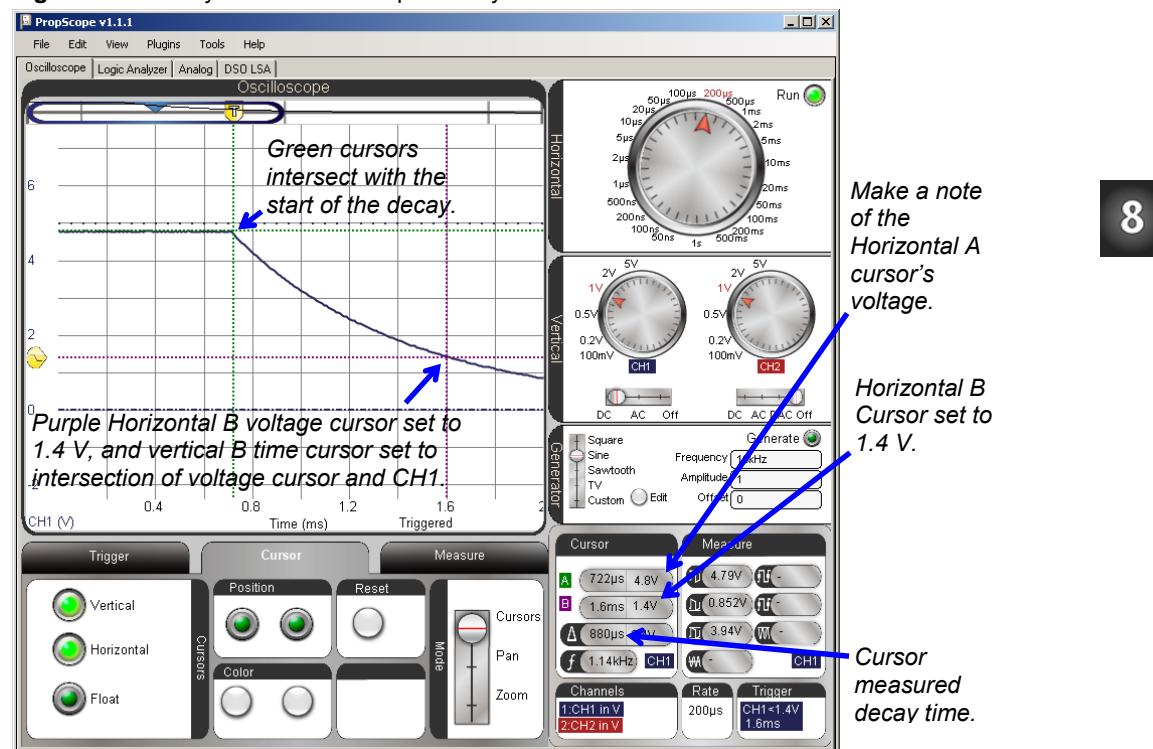


The display is now ready for verifying the BASIC Stamp's 872  $\mu$ s decay time measurement with a cursor measurement. Figure 8-19 shows how the purple B cursor's were adjusted to intersect with the CH1 decay trace at 1.4 V. (Keep in mind that 1.4 V is not 36.8%, it's the BASIC Stamp's threshold voltage.) Then, the Green A cursors were adjusted to intersect at the start of the decay. The time measurement in the Cursor display's  $\Delta$  field turns out to be 880  $\mu$ s, which is close enough to the BASIC Stamp's  $436 \times 2 \mu\text{s} = 872 \mu\text{s}$  time measurement for verification purposes.

- ✓ Set the purple horizontal B voltage cursor to 1.4 V using the Cursor display's B voltage measurement as a guide.

- ✓ Line the vertical B time cursor so that it crosses the intersection of the horizontal B voltage cursor and the CH1 trace.
- ✓ Position the green A cursors up to intersect with the start of the decay.
- ✓ The Cursor display's  $\Delta$  field shows the difference between the two time cursors, which should be fairly close to twice the value displayed in by the BASIC Stamp in the Debug Terminal.
- ✓ Make a note of the Horizontal A cursor's voltage level. We'll compare the voltage the capacitor charged to in Figure 8-19 against that voltage with a lower potentiometer resistance.

**Figure 8-19:** Verify the BASIC Stamp's Decay to 1.4 V Measurement



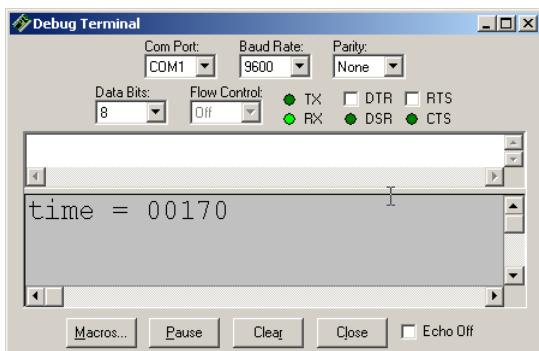
In Figure 8-19, the cursor A voltage measurement is close to 5 V (4.8 V), which indicates that the potentiometer's resistance is large compared to the  $220\ \Omega$  resistor. For example,

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if you substitute  $7000\ \Omega$  into the voltage divider equation from Chapter 2, the result would be:  $V_o = 5\text{ V} \times 7000\ \Omega \div (7000\ \Omega + 220\ \Omega) \approx 4.84\text{ V}$

Figure 8-20 shows an example the BASIC Stamp's measurement in the Debug Terminal when the pot is turned to about  $\frac{3}{4}$  of the way clockwise in its range of motion. The decay time is  $170 \times 2\ \mu\text{s} = 340\ \mu\text{s}$ .

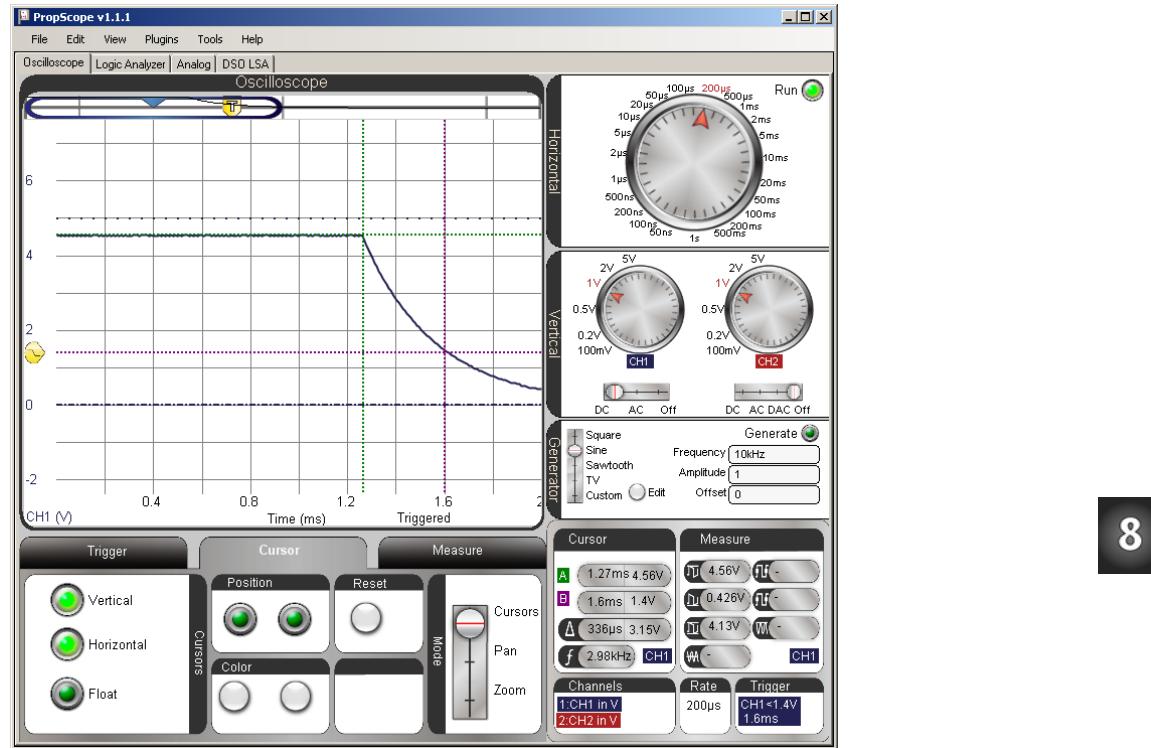
- ✓ Turn the potentiometer knob clockwise until the Debug Terminal reports a value in the neighborhood of 170.



**Figure 8-20**  
Shorter Decay  
Measurement

Figure 8-21 shows the corresponding Oscilloscope decay time measurement. The main change is that the potentiometer's resistance is smaller, so the decay time is shorter for a shorter RCTIME measurement. A secondary change is that the capacitor charges to a slightly lower voltage. That's because the  $220\ \Omega$  protection resistor value didn't change, but the potentiometer is now a smaller value. As the BASIC Stamp charges the circuit, the slightly lower voltage divider level between the pot and  $220\ \Omega$  resistor limits the capacitor to charging to a slightly lower level (4.56 V instead of 4.8 V).

- ✓ Repeat the decay cursor time measurement with the vertical cursors. It should be in the neighborhood of  $340\ \mu\text{s}$ .
- ✓ Also, repeat the voltage measurement before the decay starts with the green horizontal A cursor, and compare it to the level you measured with the other potentiometer setting.

**Figure 8-21:** Shorter Decay, Lower Starting Voltage

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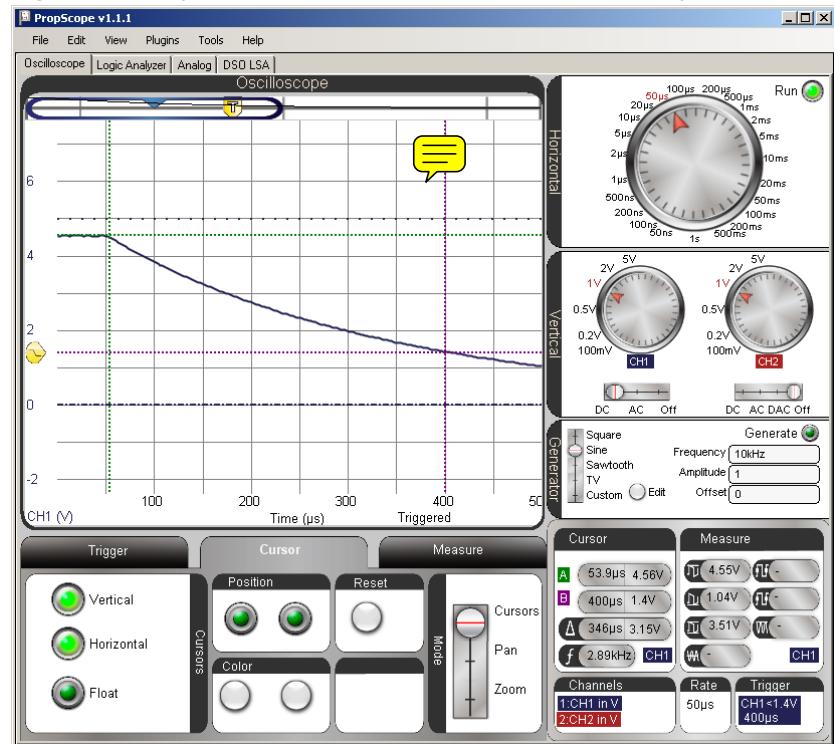
### Zoom in on the Shorter Time Value

Figure 8-22 shows how reducing the Horizontal dial to a smaller time/division makes it possible to zoom in and get a more precise measurement. Take a look at the time  $\Delta$  value in the Cursor panel. Ironically, it's 346  $\mu$ s, is a little further off than the 336  $\mu$ s from Figure 8-21. Still, the PropScope is now reporting a more precise measurement with the higher Horizontal time/division setting. Furthermore, a 6  $\mu$ s difference is not cause for concern. It's only 1.76% off the BASIC Stamp measurement, which can be attributed to a combination of possible differences in the two devices' clock frequencies, slight alignment errors with the cursors, and slight deviations of the actual threshold voltage from the 1.4 V level.

- ✓ Carefully adjust the pot's knob to make the Debug Terminal report 170.

- ✓ Try reducing your time division to 50  $\mu$ s and repeat the cursor time and voltage measurements.

**Figure 8-22:** Adjust the Horizontal Dial to Zoom in on the Decay Time



### Your Turn: Pick a Decay Time and Test

- ✓ Pick a different potentiometer knob adjustment for a different Debug Terminal decay time and use the PropScope to verify the BASIC Stamp's measurements.

### **ACTIVITY #3: RC CIRCUIT'S ROLE IN D/A CONVERSION**

In Chapter 4, Activity #2, the relationship between duty cycle and DAC voltage was introduced. In this activity, you will repeat some of those measurements, and then make

the average voltage calculation that the RC circuit performs on the duty cycle signal that results in the DAC voltage across the capacitor.

### DAC Test Parts

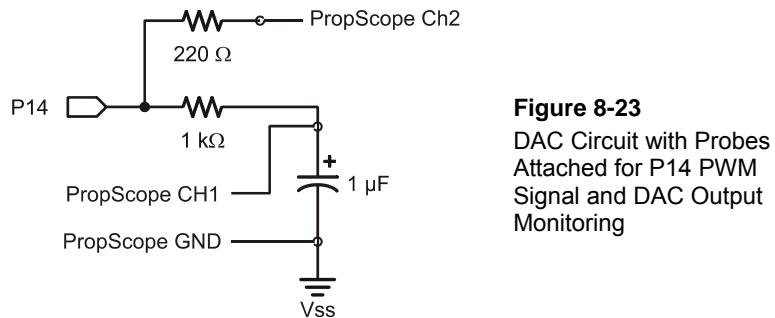
- (1) Resistor – 220 Ω (red-red-brown)
- (1) Resistor – 1 kΩ (brown-black-red)
- (1) Capacitor – 1 μF
- (misc.) Jumper wires

### DAC Test Circuit

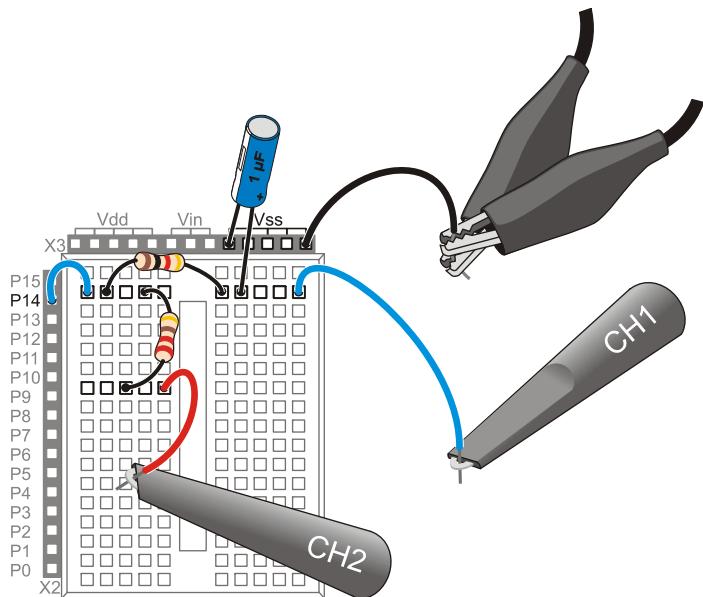
The circuit in Figure 8-23 and Figure 8-24 should be familiar from the duty cycle measurements in Chapter 4, Activity #2.

- ✓ **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 8-23 and Figure 8-24.

**Comment [AL78]:** Do we need to repeat electrolytic cap warnings here?



**Figure 8-23**  
DAC Circuit with Probes  
Attached for P14 PWM  
Signal and DAC Output  
Monitoring



**Figure 8-24**  
Example Wiring  
Diagram for Figure 8-23

### DAC Test Program

This program was introduced in Chapter 2, Activity #3. It repeatedly sets the voltage across the RC circuit's capacitor to 1.25 V.

- ✓ Enter Test 1 Channel Dac.bs2 into the BASIC Stamp Editor and run it.

```
' Test 1 Channel Dac.bs2
' Set P14 capacitor to 1.25 V.
' {$STAMP BS2}                                ' Target module = BASIC Stamp 2
' {$PBASIC 2.5}                               ' Language = PBASIC 2.5

PAUSE 1000                                     ' 1 ms before first DEBUG command
DEBUG "Program running..."                      ' Debug Terminal message

DO
    PWM 14, 64, 1                             ' Main Loop
                                                ' 1.25 V to P14 capacitor
LOOP                                         ' Repeat main loop
```

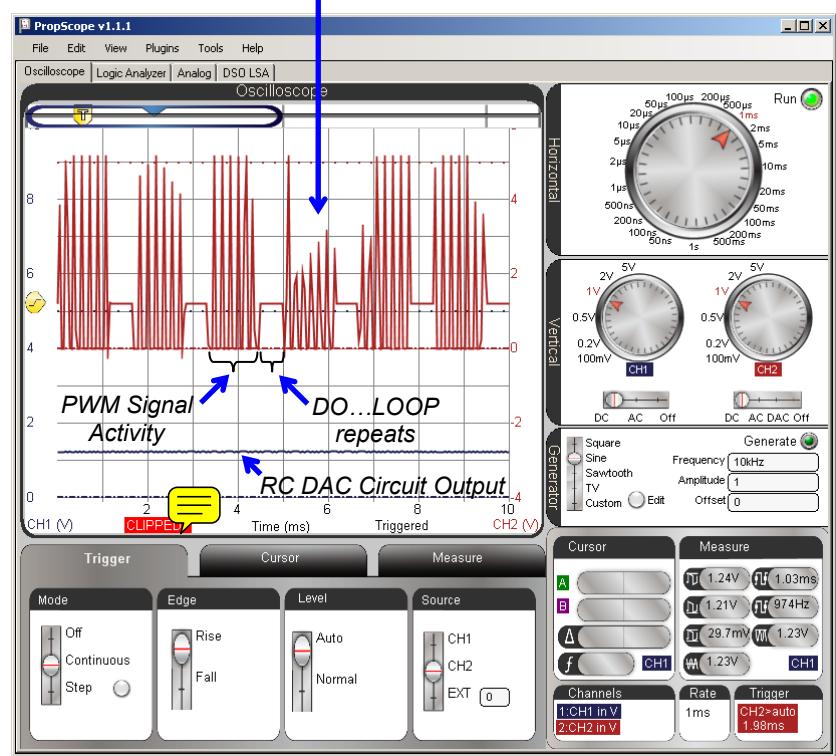
### **DAC Test Measurements**

In Figure 8-25, the lower, blue CH1 trace shows the DC voltage the PWM signal establishes across the capacitor. The upper, red CH2 trace shows signal activity during six repetitions of the DO...LOOP in Test 1 Channel Dac.bs2. This Horizontal dial setting gives an overview of the program running with 1 ms periods of PWM activity followed by about  $\frac{1}{2}$  ms of delay between DO...LOOP repetitions. Since we would expect 5 V high PWM pulses, the sporadic pulse heights are a clue that there isn't enough room in the display to view all the signal activity. So after this quick check, we'll use smaller settings to zoom in on the PWM signal activity.

- ✓ Dial adjustments: Horizontal = 1 ms/div, Vertical CH1 = 1 V/div, CH2 1 V/div.
- ✓ Vertical coupling switches: CH1 = DC, CH2 = DC.
- ✓ Trigger tab switches: Mode = Continuous, Edge = Rise, Level = Auto, Source = CH2.
- ✓ Trigger Time Control: adjust vertical crosshair to second time division.
- ✓ If the label in the lower-right Measure display reads CH2, click it to toggle to display the CH1 measurements.

**Figure 8-25: Overview of Signal Activity**

Since we expect PWM to be a series of 5 V high/low signals, these sporadic voltage levels are a clue that the Horizontal time/division setting can be reduced for more signal detail.



**Oversampling vs. Aliasing**

The PropScope takes a series of  measurements called samples, and sends them to the PropScope software to be displayed. When there are more than enough samples to represent the signal being measured, it is called oversampling. If there are not enough samples to properly display the waveform, it is under-sampled. If there are so few samples compared to the frequency that one voltage measurement is from one cycle of the signal and the next is from a later cycle, the result is often a signal that looks very different from the actual signal being measured. This is called aliasing, and the PropScope displays a signal that's standing in as an alias for the actual signal.



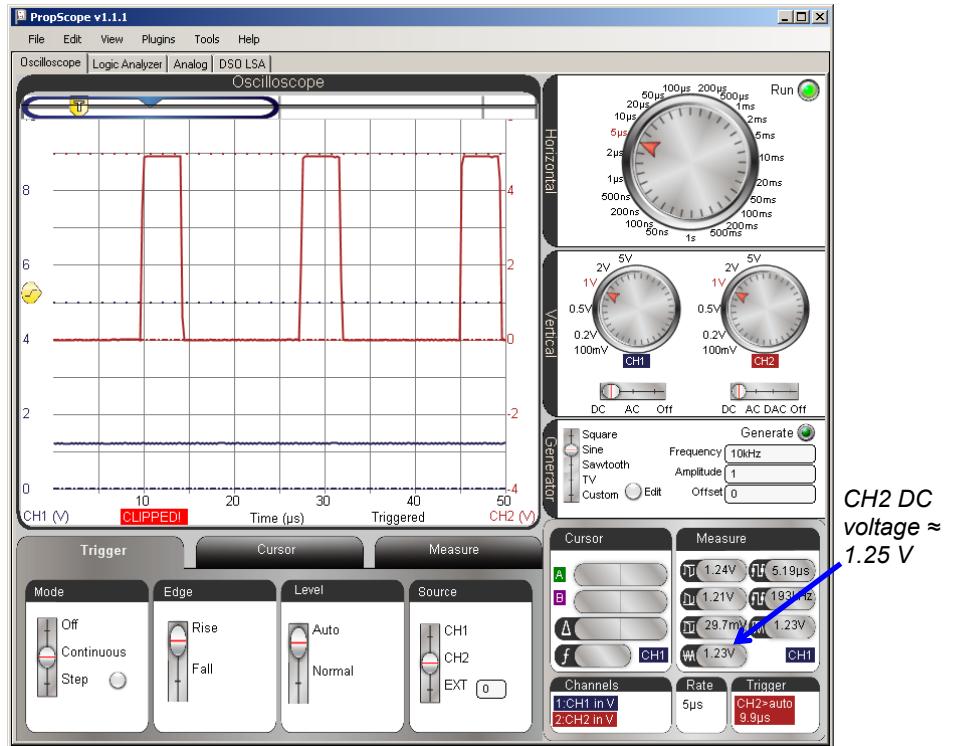
The theoretical minimum sampling rate needed to reconstruct a signal is two samples per cycle, and it's called the Nyquist rate. In practice, systems are usually designed to oversample, meaning they take many times the Nyquist rate. For example, it takes 536 voltage samples to construct all the activity in a trace as it crosses the PropScope's Oscilloscope screen.

The Horizontal dial in  Figure 8-26 is adjusted to 5  $\mu$ s/division for a detailed view of the PWM signal's binary pulses. Since the PWM signal is 5 V for  $\frac{1}{4}$  of its cycle, it sets a voltage across the capacitor that's 1.25 V, which is  $\frac{1}{4}$  of the 5 V high pulses. In review of Chapter 4, Activity #2 the duty cycle is the percent ratio of  $t_{high}$  to  $t_{cycle}$ . The PWM signal in Figure 8-26 is high for  $\frac{1}{4}$  of its cycle, so the duty cycle is 25%. Applied to the RC circuit, it establishes a voltage that's 25% of the 5 V high signal (assuming the low signal is at ground = 0 V the other 75% of the time.)

**8**

- ✓ Adjust the Horizontal dial to 5  $\mu$ s/div.
- ✓ Check the CH2 signal to verify that it is high for  $\frac{1}{4}$  of the time.
- ✓ Check the CH1 average voltage in the Measure display and verify that it is about 1.25 V. (You can either click the CH1 trace, or click the CH1/CH2 label in the Measure display's lower-right corner to toggle between displaying CH2 and CH1 values.)

**Figure 8-26:** RC Circuit Converts Signal High  $\frac{1}{4}$  of the time to 1.25 V ( $\frac{1}{4}$  of 5 V)



CH2 DC  
voltage  $\approx$   
1.25 V

#### PWM Pin, Duty, Duration



Pin is the I/O pin the BASIC Stamp sends the PWM signal to. Duty is the number of 256ths of a cycle the signal is high, and Duration is the time the BASIC Stamp transmits the PWM signal.

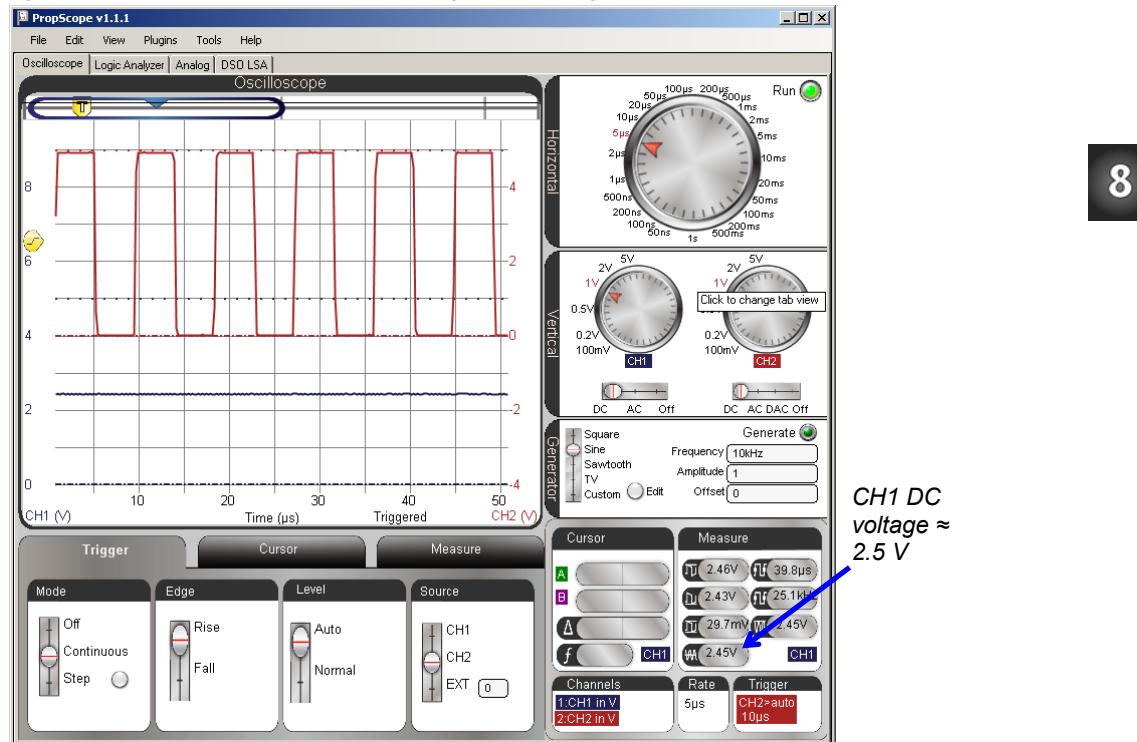
Example: PWM 14, 64, 1 sends a PWM signal that's high 64/256ths of the time for 1 ms. 64/256ths is  $\frac{1}{4}$ , so that's why the signal is high  $\frac{1}{4}$  of the time.

For now, all we want to do is be sure that there really is a relationship between the ratio of high time to cycle time ( $t_{high}/t_{cycle}$ ) that controls the voltage across the capacitor. You can do this by varying the PWM command's Duty argument in Test 1 Channel Dac.bs2 and checking the duty cycle and CH1 voltage between each adjustment. For example,

Figure 8-27 shows the binary signal for PWM 14, 128, 1. Now, the signal is high for half the time, and the voltage across the capacitor is 2.5 V, which is about half of 5 V.

- ✓ In Test 1 Channel Dac.bs2, change the PWM command to PWM 14, 128, 1
- ✓ Load the modified program into the BASIC Stamp.
- ✓ Check the CH2 signal to verify that it is high for about half the time.
- ✓ Click the CH1 signal and check its average voltage in the Measure display to verify that it is about 2.5 V. Remember, you can either click the CH1 trace, or click the CH1/CH2 label in the Measure display's lower-right corner to toggle between displaying CH2 and CH1 values.

**Figure 8-27:** RC Circuit Converts PWM Signal that's High  $\frac{1}{2}$  of the time to 2.5 V ( $\frac{1}{2}$  of 5 V)

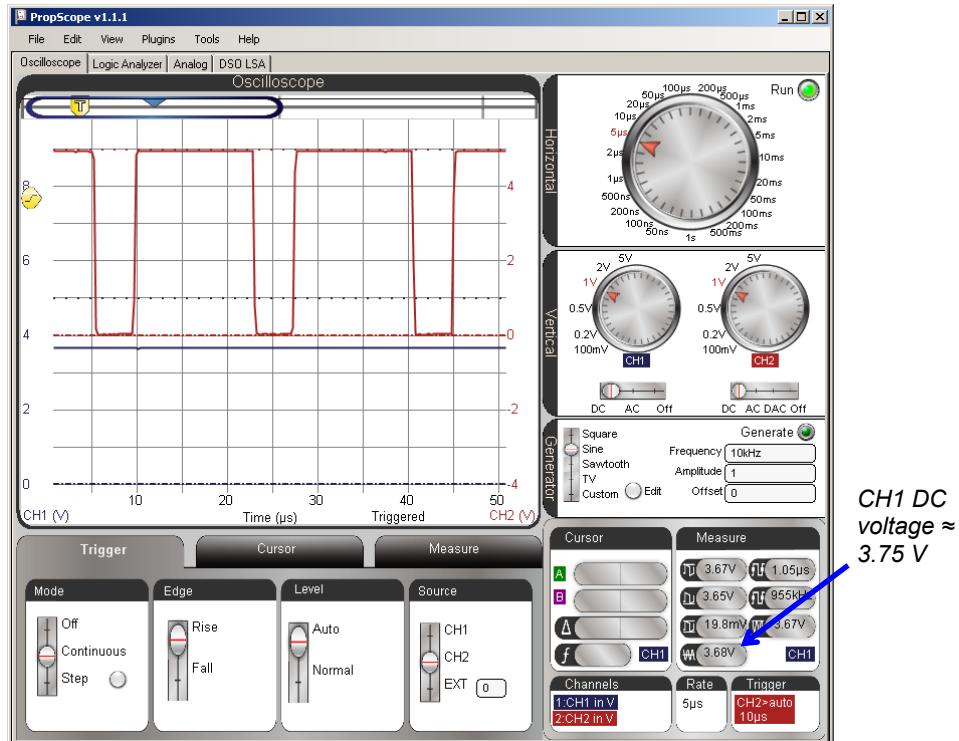


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Figure 8-28 shows the Oscilloscope display with the command PWM 14, 192, 1. Now, the CH2 signal is high about  $\frac{3}{4}$  of the time, and CH1 shows that the voltage across the capacitor is now about 3.75 V, which is  $\frac{3}{4}$  of 5 V.

- ✓ In Test 1 Channel Dac.bs2, change the PWM command to PWM 14, 192, 1
- ✓ Load the modified program into the BASIC Stamp.
- ✓ Check the CH2 signal to verify that it is high for about  $\frac{3}{4}$  of the time.
- ✓ Check the average voltage of the CH1 signal in the Measure display to verify that it is about 3.75 V.

**Figure 8-28:** RC Circuit Converts PWM Signal that's High  $\frac{3}{4}$  of the time to 3.75 V ( $\frac{3}{4}$  of 5 V)



### Verifying the RC Circuit's "Average" Voltage Output

When a duty cycle signal's period is much smaller than the RC time constant ( $T \ll \tau$ ) the RC circuit's output transmits the average of the voltage input. With the BASIC Stamp's

PWM signal, calculating the average is simple because the signal spends its low time at ground. So, the average voltage is  $5\text{ V} \times t_{\text{high}} \div t_{\text{cycle}}$ . More generally, the average voltage of a signal is the area between the trace and ground during a cycle, divided by the time of a cycle.

$$\text{Average Voltage} = \frac{\text{Area between signal and ground during a cycle}}{\text{Cycle Time}}$$

For example, the average voltage in Figure 8-28 is:

$$\text{Average Voltage} = \frac{5\text{ V} \times 15\text{ }\mu\text{s}}{20\text{ }\mu\text{s}} = 3.75\text{ V}$$

- ✓ Apply the average voltage calculation to Figure 8-27 and Figure 8-26.

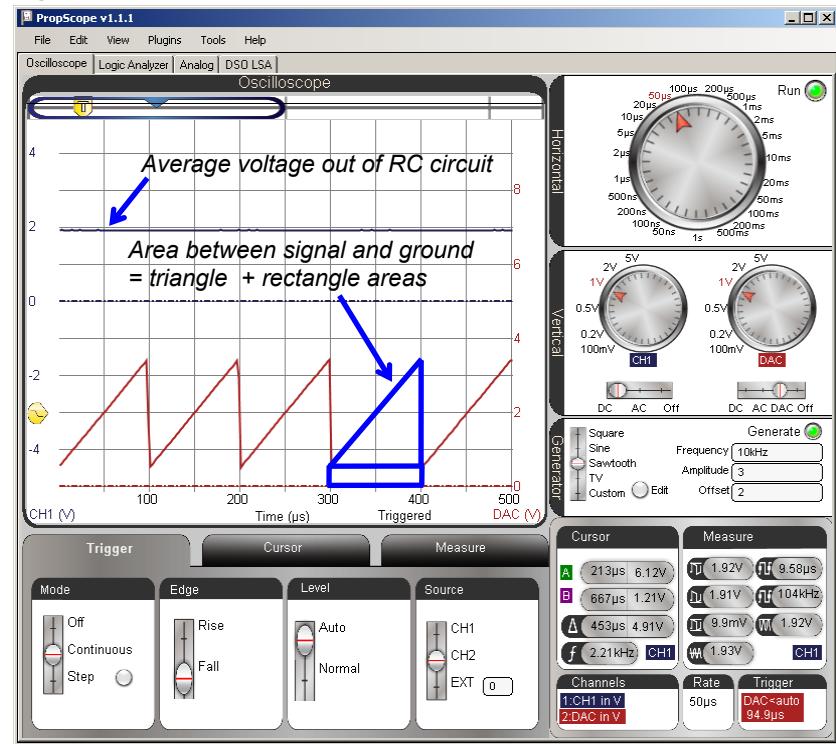
### **Your Turn: Average Voltage for a Different Signal**

The average voltage of the lower, red CH2 trace in Figure 8-29 is the area between one of the triangles in the sawtooth wave and the Ground line, divided by the time of one cycle. To calculate the area between the trace and the ground line for a cycle, calculate the area of the triangle (half a rectangle), and add the area of the rectangle below it.

8

- ✓ Calculate the average voltage by dividing the time of a cycle into the area for Figure 8-29.
- ✓ Set up an experiment that sends the signal in Figure 8-29 to the RC DAC circuit.
  - Disconnect the I/O pin P14 from the circuit.
  - Move the CH2 probe's BNC connector to the DAC CARD's Function generator output.
  - Configure the PropScope's function generator to transmit a 10 kHz, 3 Vpp, 2 VDC offset Sawtooth wave.
  - Swap the vertical positions of CH1 and CH2. In other words, position the Blue CH1 trace in upper region of Oscilloscope and ground line for red CH2 trace just above the horizontal time axis values.
  - Compare your calculated average voltage to the Measured average voltage for both CH1 and CH2.

**Figure 8-29: Function Generator Sawtooth into RC Circuit**



#### ACTIVITY #4: RC D/A CONVERTER DECAY FROM LOAD

The DAC circuit needs an op amp buffer before a microcontroller application can use the voltage ~~to~~ drive a load. The op amp buffer circuit will be introduced in Chapter 9, Activity #2. In the meantime, this activity examines what placing a load across the RC circuit does without the op amp buffer.

#### Extra Parts for Load Test

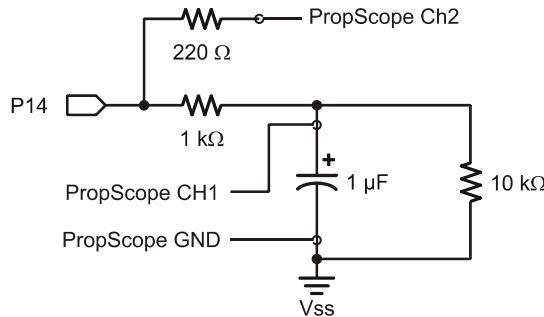
- (1) Resistor – 10 kΩ (brown-black-orange)
- (1) Resistor – 2 kΩ (red-black-red)

### Load Test Circuit

Figure 8-30 shows a 10 kΩ load applied to the previous activity's RC DAC circuit's output, and Figure 8-31 shows an example wiring diagram.

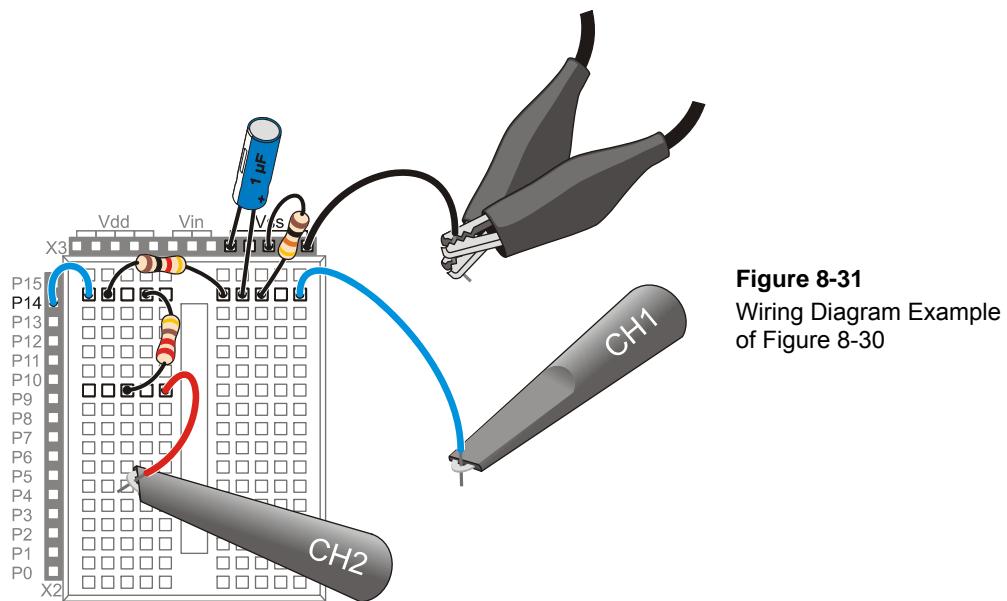
- ✓ **STOP:** Disconnect the CH2 probe's BNC plug from the DAC CARD and reconnect it to the PropScope's CH2 BNC jack before continuing here.
- ✓ Modify the circuit from the previous activity by adding the 10 kΩ resistor shown in Figure 8-30 and Figure 8-31.

**Comment [AL79]:** Apply plug to jack rules to all chapters.



**Figure 8-30**  
PWM DAC Test Circuit  
with 10 kΩ Resistor Load

8



**Figure 8-31**  
Wiring Diagram Example  
of Figure 8-30

### DAC Load Test Program

Instead of applying the PWM repeatedly at top speed like the example program from the previous activity, Test 1 Channel Dac with Delay.bs2 applies the PWM signal and then delays for 5 ms before repeating. This makes it convenient to use the PropScope to examine what happens with the 10 k $\Omega$  resistor attached.

- ✓ Enter and run Test 1 Channel Dac with Delay.bs2.

```
' Test 1 Channel Dac with Delay.bs2
' Set P14 capacitor to 1.25 V.
' {$STAMP BS2}
' {$PBASIC 2.5}

DEBUG "Program running..."           ' Target module = BASIC Stamp 2
                                ' Language = PBASIC 2.5

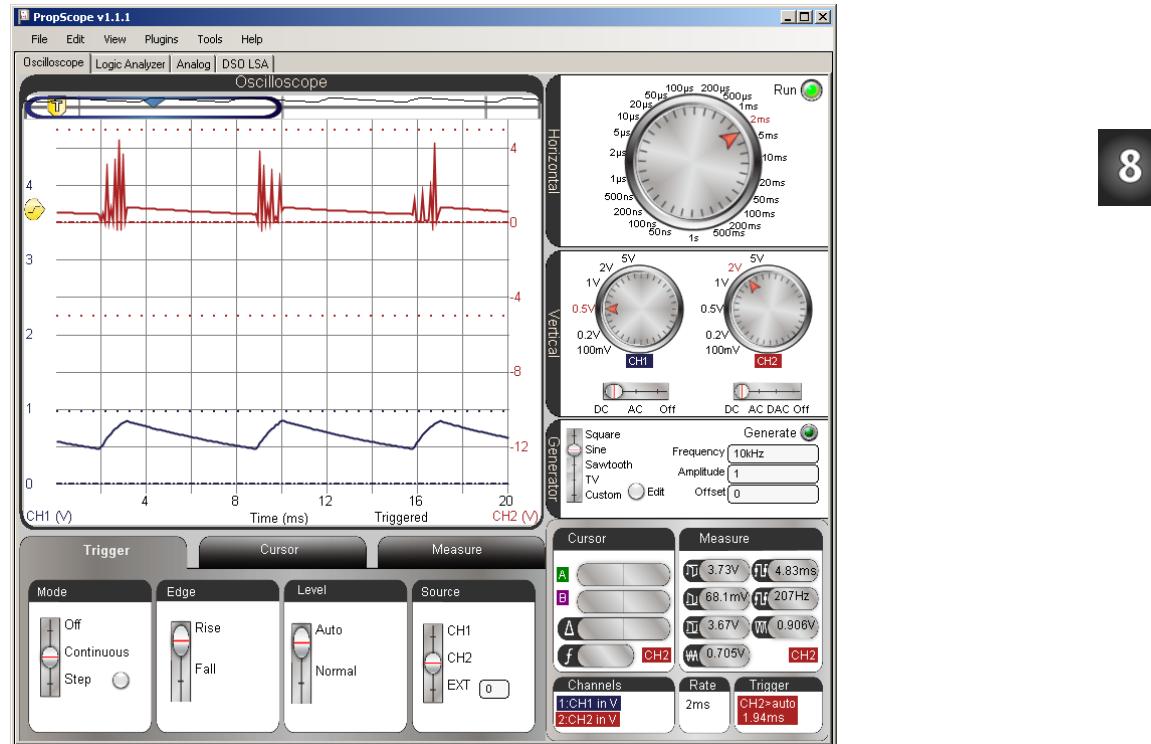
DO
    PWM 14, 32, 1                 ' Main Loop
    PAUSE 5                         ' 1.25 V to P14 capacitor
                                    ' Delay for 5 ms
LOOP                                ' Repeat main loop
```

### DAC Load Test Measurements

Figure 8-32 shows the decays that result as the capacitor loses its charge through the 10 kΩ resistor. Again, an op amp buffer will solve this problem in Chapter 9, Activity #2.

- ✓ Dial adjustments: Horizontal = 2 ms/div, Vertical CH1 = 0.5 V/div, CH2 = 2 V/div.
- ✓ Vertical coupling switches: CH1 = DC, CH2 = DC.
- ✓ Trigger tab switches: Mode = Continuous, Edge = Rise, Level = Auto, Source = CH2.
- ✓ Trigger Time Control: adjust vertical crosshair to first time division line.

**Figure 8-32:** Voltage Across Capacitor Decays through 10 kΩ Resistor between PWM Signals



8

### Your Turn: Compare to Increased Load and No Load

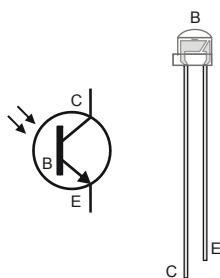
A 2 k $\Omega$  resistor has less resistance, so it conducts more current. As a result, it drains the capacitor more quickly, and can be termed a “heavier” current load on the capacitor.

With the resistor removed, the capacitor should lose its charge very slowly. The rate the capacitor loses its charge depends on the insulator that keeps the two metal plates that hold charge apart. This insulator is called a dielectric, and the small current that flows through the dielectric is called leakage current.

- ✓ Replace the 10 k $\Omega$  resistor with a 2 k $\Omega$  resistor.
- ✓ Check the voltage output results with the PropScope.
- ✓ ~~Disconnect the load resistor, the decay should be very small in comparison. With a low leakage current capacitor, it would be even smaller.~~

### **ACTIVITY #5: PHOTOTRANSISTOR LIGHT SENSOR EXAMPLE**

The phototransistor shown in Figure 8-33 is a light sensor that is also compatible with RCTIME measurements. C, B, and E stand for the phototransistor’s terminals, which are named collector, base, and emitter. Brighter light shining on the phototransistor’s base causes it to conduct more current, dimmer light results in less current. By measuring how quickly the phototransistor allows the capacitor to discharge in an RC circuit, a microcontroller can detect light levels. In this activity, you will test BASIC Stamp light measurements with the BASIC Stamp, and verify the time measurements with the Oscilloscope.



**Figure 8-33**  
Phototransistor Schematic Symbol  
and Part Drawing

### Phototransistor Light Sensor Parts

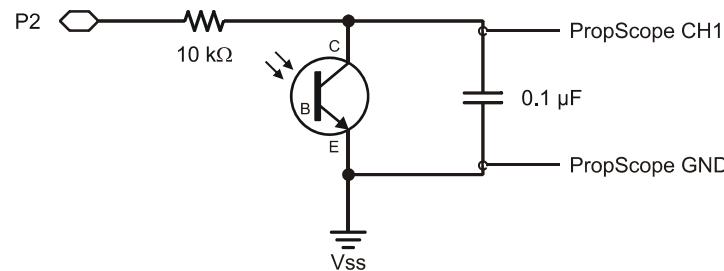
- (1) Phototransistor
- (1) Capacitor – 0.1  $\mu$ F (104)
- (1) Resistor 10 k $\Omega$  (brown-black-orange)

(misc) Jumper wires

**Phototransistor Light Sensor Circuit**

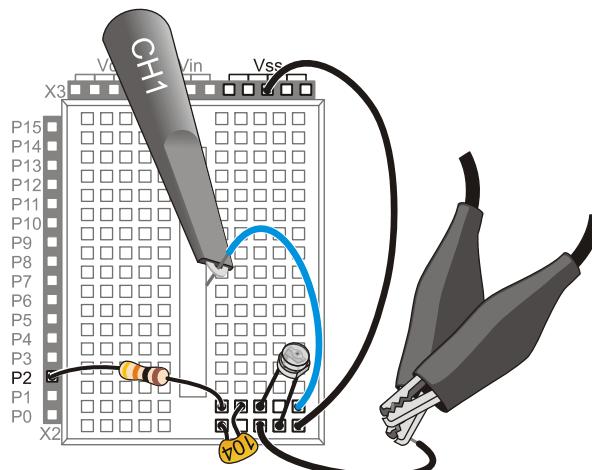
Figure 8-34 shows a schematic of the phototransistor in an RC decay circuit, and Figure 8-35 shows a wiring diagram example. Although this is still an RC decay circuit, there are several differences. First, the pot has been replaced with a phototransistor. Second, the I/O pin assignment is different, P2 instead of P7. Third, the capacitor is ten times the value that was used with the previous circuit. Fourth and finally, this circuit has a  $10\text{ k}\Omega$  resistor instead of a  $220\text{ }\Omega$  resistor. This is not for increased I/O pin protection; it's for a light level compensation feature that will be examined after the basic measurements.

- ✓ Build the circuit shown in Figure 8-34 and Figure 8-35.



**Figure 8-34**  
Phototransistor  
Schematic

8



**Figure 8-35**  
Wiring Diagram  
Example for Figure  
8-34

TestPhototransistor.bs2 is an excerpt from What's a Microcontroller, Chapter 7. It tests the phototransistor in much the same fashion as the previous example program tested the photoresistor.

- ✓ Enter TestPhototransistor.bs2 into the BASIC Stamp Editor and run it.
- ✓ Make sure the lighting conditions are low. No bright lights or sunlight from a nearby window.
- ✓ If the measurement is 0, it indicates that the time measurement exceeded the RCTIME command's 65535 maximum value, which in turn indicates that it's either too dark, or there is a wiring mistake.

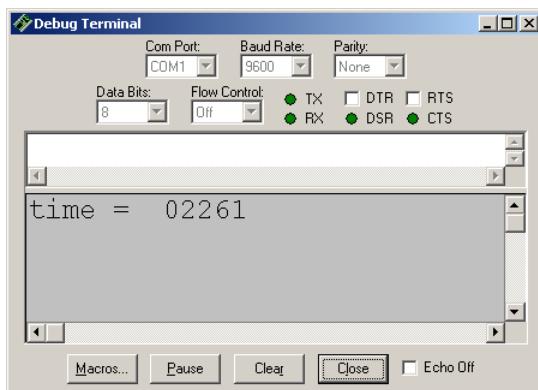
```
' What's a Microcontroller - TestPhototransistor.bs2
' Read phototransistor in RC-time circuit using RCTIME command.
' {$STAMP BS2}                                ' Target module = BASIC Stamp 2
' {$PBASIC 2.5}                               ' Language = PBASIC 2.5

time      VAR     Word          ' For storing decay times
PAUSE 1000                           ' 1 s before sending messages

DO
    HIGH 2                            ' Main Loop
    PAUSE 100                          ' Set P2 high
    RCTIME 2, 1, time                 ' Wait 0.1 seconds
    DEBUG HOME, "time = ", DEC5 time ' RC Decay time measurement
    DEBUG HOME, "time = ", DEC5 time ' Display time in 2 us increments
LOOP                                ' Repeat main loop
```

Figure 8-36 shows the Debug Terminal display for the phototransistor test. This measurement should get larger with less light and smaller with more light. This circuit was designed for indoor lighting, so make sure to stay out of really bright light conditions, especially sunlight streaming in through a window.

- ✓ Test your phototransistor by casting a shadow over it with your hand; the measurement should increase.
- ✓ Remove the shadow, and the measurement should decrease again.



**Figure 8-36**  
BASIC Stamp  
Phototransistor Decay  
Measurement

Figure 8-37 shows an example of the decay measurement. It utilizes the same procedure as the potentiometer decay measurement. The only differences is that the Horizontal dial is adjusted to a coarser time scale of 500  $\mu$ s/div to accommodate the decay time. Your lighting conditions may be different, and you may end up having to choose a different Horizontal dial setting. In this example, the BASIC Stamp RCTIME measurement is  $2261 \times 2 \mu\text{s} = 4522 \mu\text{s}$ . The PropScope  $\Delta$  measurement is 4.52 ms, which is 4520  $\mu\text{s}$ . Especially since the light sensor measurement fluctuates, we are not expecting an exact match, just oscilloscope verification that the BASIC Stamp measurement is in the right neighborhood. So this might be somewhat of a closer match than a typical measurement.

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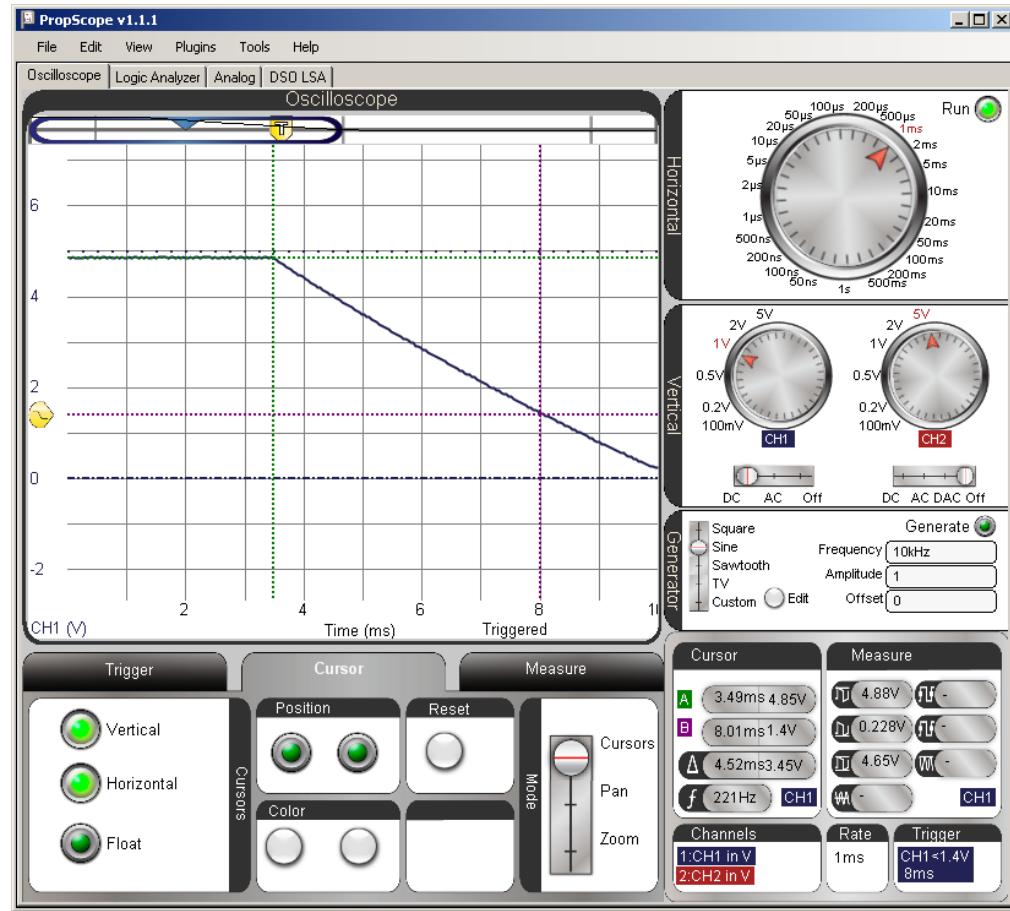
- ✓ Use your Debug Terminal time measurement to figure out approximately what Horizontal dial setting will suit your lighting conditions/decay times. Remember to multiply by 2 to get the number of microseconds.
- ✓ Use the PropScope to verify the BASIC Stamp's time measurements in your lighting conditions. Depending on your lighting conditions, your time scale may have to be significantly different from what's in the figure.

#### From RC Decay to Linear Decay



The shape of the trace no longer matches the RC decay curve. In fact, the decay looks almost linear, and that's because it is almost linear. The transistor is like a current valve, and the light level controls how much current it allows through, which in turn controls the rate the capacitor discharges. The light level is more or less constant during the measurement, so the capacitor loses its charge at a linear rate, which results in a linear voltage decay.

**Figure 8-37:** Examine BASIC Stamp's Phototransistor Decay Measurement with PropScope



### Automatic Lighting Condition Adjustments

One important difference with the phototransistor is it is a current conducting device that does not create a voltage divider. So the capacitor will charge up to the about the same value regardless of the light level. If you take the phototransistor out of the circuit, you have an RC DAC circuit for setting voltages. With the phototransistor in the circuit, you can actually use the PWM command to charge up the capacitor to a certain level, followed by the RCTIME command to measure the decay time. This makes it possible

for the program to adjust to lighting conditions by charging the capacitor to higher or lower voltages before the measuring the decay time. For example, Test Phototransistor Adjustment.bs2 uses the PWM command to charge the capacitor up to about 3.34 V (instead of 5 V) before starting the RCTIME measurement. The result will be a lower light measurement value because the voltage before the decay is lower.

- ✓ Enter Test Phototransistor Adjustment.bs2 into the BASIC Stamp Editor and Run it.

```
' What's a Microcontroller - Test Phototransistor Adjustment.bs2
' Read phototransistor in RC-time circuit using RCTIME command.

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

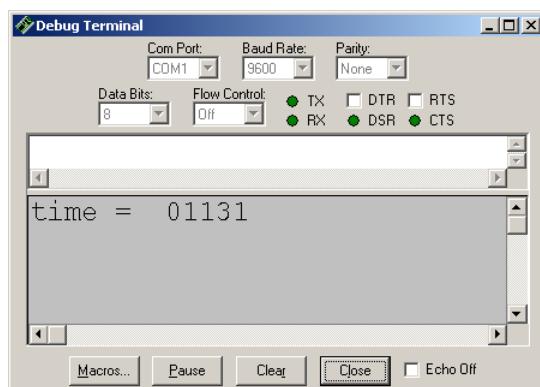
time      VAR      Word          ' For storing decay times

PAUSE 1000                            ' 1 s before sending messages

DO
  PAUSE 100                           ' Main Loop
  PWM 2, 171, 10                      ' Wait 0.1 seconds
  RCTIME 7, 1, time                   ' Charge to 171/256 of 5 V
  DEBUG HOME, "time = ", DEC5 time   ' RC Decay time measurement
  ' Display time in 2 us increments
LOOP                                ' Repeat main loop
```

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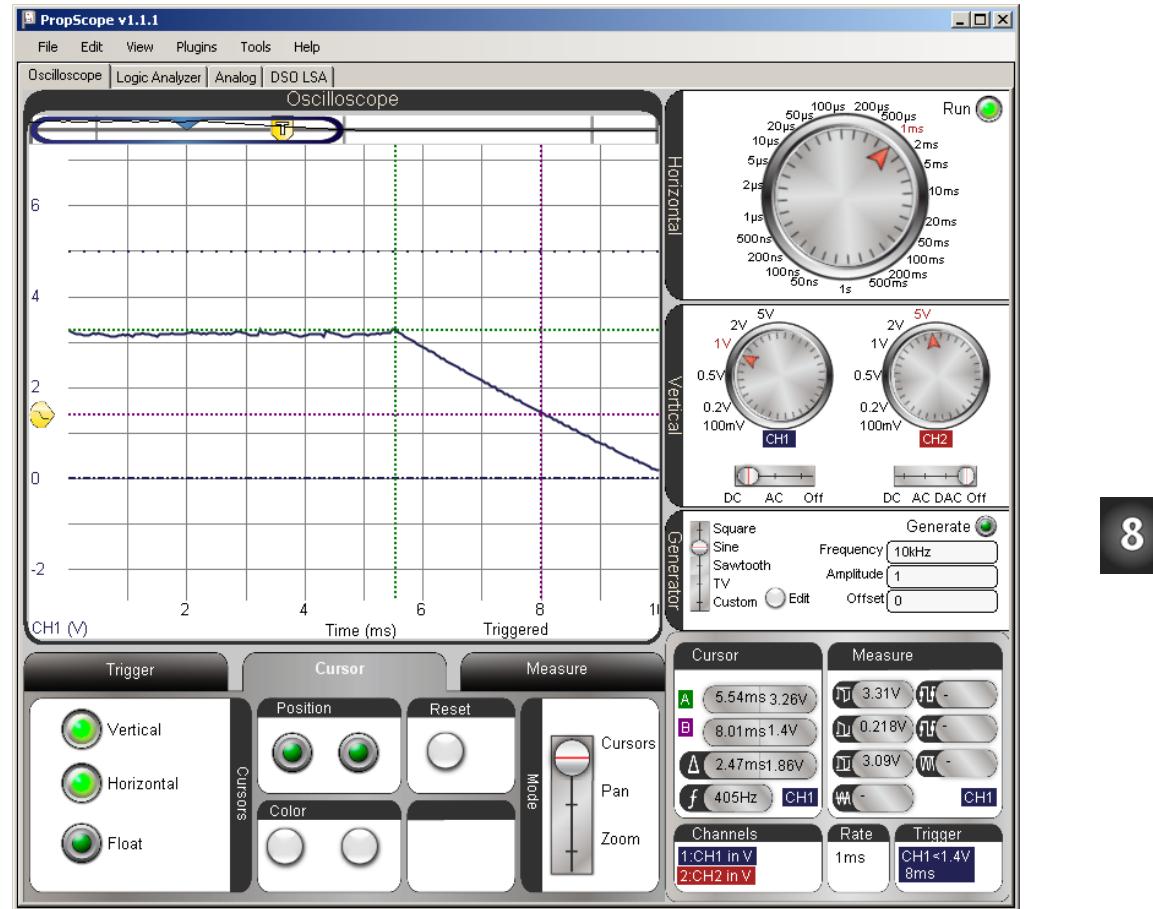
Figure 8-38 shows a light measurement in roughly the same lighting conditions as the previous measurement. However, the result is only half the value, with a decay time of  $1131 \times 2 \mu\text{s} = 2262 \mu\text{s}$ .



**Figure 8-38**  
Same Light Level, PWM  
Reduced Sensitivity

Figure 8-39 shows an example of the lower starting voltage, which contributes to a smaller decay time, but there appears to be something more than just lower starting voltage that's reducing the BASIC Stamp's decay time measurement, which is 2262  $\mu$ s. In contrast, the oscilloscope measurement is 2.47 ms = 2470  $\mu$ s. That's more than 200  $\mu$ s difference between the BASIC Stamp and PropScope measurement. Unlike previous measurement differences, which were small, this is a definite indicator that something is not performing as expected.

- ✓ Try comparing your BASIC Stamp's measurements using `Test Phototransistor Adjustment.bs2` against the PropScope decay measurements. See the difference between BASIC Stamp and PropScope measurement here?

**Figure 8-39:** How PWM Determines the Starting Voltage

8

It turns out that the cause of the measurement difference is the fact that the PWM command changes the I/O pin direction to input when it's done. In D/A conversion with no circuit load, that change from output to input allows the capacitor to hold its charge (and voltage). However, our light sensor circuit has the phototransistor that starts draining the capacitor as soon as the PWM command is done. So, after the PWM command finishes, we can infer from the measurement that there's about 200  $\mu$ s of capacitor voltage decay time before the RCTIME command starts.

The PWM-before-RCTIME technique is still useful, because it does make it possible to adjust the system's light sensitivity. With additional testing, a better estimate of time between PWM and RCTIME can be determined. Then, the program can just add that value to the measurements. In other applications, this time difference doesn't even matter. For example, there's an application for the Boe-Bot Robot that makes it compare two of these light sensor measurements to figure out which one detects brighter light. This works well for light source following activities. The Boe-Bot's program doesn't care about precise measurements, it just wants to know which measurement is larger. Since the extra time would be identical for both sensors, the comparison of the two measurements still supplies the information the BASIC Stamp needs for determining the direction of the light source.

**A current load on a DAC circuit without an op amp has its uses; this is one of them.**

The previous activity demonstrated how a resistive load prevented the capacitor in a DAC circuit from holding its charge, which in turn prevented it from maintaining an output voltage. If the goal is to maintain an output voltage under load, the load poses a problem that an op amp will be used to fix in the next chapter.



In this automatic light level adjustment activity, the goal was not to maintain a voltage output; it was to charge a capacitor with a light sensor load to a certain voltage before measuring the decay. With control over the voltage, it makes it possible to adjust a system to adapt to different light levels. So this is an application where placing a load ~~across~~ the DAC circuit without the op amp buffer is useful.

Think about how a property that's considered "bad" for one application can be "good" for another. Try to keep it in mind as you learn more about how circuits interact with each other. Applying an element that's considered "bad" for one circuit or application might just solve a thorny design problem for a different one.

## ACTIVITY #6: LOW PASS FILTER

Chapter 7, Activity #6 introduced a low pass filter example, and tests demonstrated that higher frequency sine waves applied to the circuit's input resulted in lower amplitude sine waves with more phase shift at the output. In contrast, lower frequency sine waves were allowed to "pass" through the filter with less attenuation and phase shift.

The value of  $R \times C$  that we've been using to characterize RC decay is also a key value for a low RC pass filter. You can use it to get the value of the filter's cutoff frequency, which is the point at which the output sine wave amplitude is reduced to 70.7% of the input sine wave, and the phase is shifted by 45°. Another way to say this is that the

output signal amplitude, divided by the input signal amplitude is 0.707. This value is the reciprocal of the square root of two.

$$\frac{v_{out}}{v_{in}} = 0.707 = \frac{1}{\sqrt{2}}$$

In this activity, you will calculate the cutoff frequency for a low pass RC filter, and apply that frequency to the filter's input with the PropScope's function generator. You will then test the amplitude and phase of the circuit's output to verify the frequency calculation.



**Corner frequency** is another common expression for cutoff frequency. When the amplitude response of a filter is plotted over frequency, the amplitude turns a corner and starts declining at the cutoff frequency. These graphs are common in the analysis of filters and amplifiers, and they are called Bode plots. The name Bode is pronounced "bo-dee".

### Low Pass Filter Test Parts List

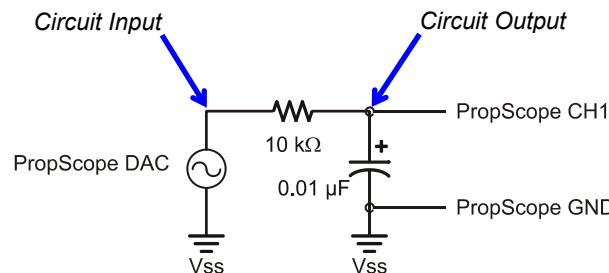
- (1) Resistor – 10 kΩ (brown-black-orange)
- (1) Capacitor – 0.01 μF
- (misc) Jumper wires

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### Low Pass Filter Test Circuit

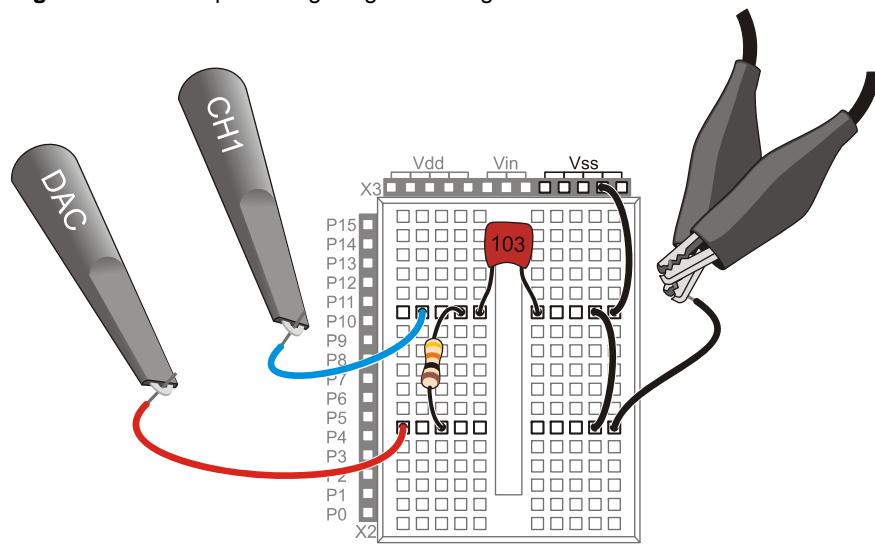
The circuit schematic in Figure 8-40 and wiring diagram example in Figure 8-41 are repeats of the circuits from Chapter 7, Activity #6.

- ✓ Unclip the CH2 probe tip from whatever it's connected to.
- ✓ Disconnect the CH2 probe from the PropScope at its BNC connector and connect it to the DAC CARD's function generator output.
- ✓ Build the RC circuit shown in Figure 8-40 and Figure 8-41.
- ✓ Connect the function generator output to the RC low pass filter input.
- ✓ Connect the CH1 probe to the filter's output.



**Figure 8-40**  
Schematic for RC Low Pass Filter Amplitude and Phase Angle Test Measurements

**Figure 8-41:** Example Wiring Diagram for Figure 8-40



### Calculate the Cutoff Frequency and Phase Shift

The three values we need to know for verifying the filter's behavior are output amplitude, frequency, and phase shift in terms of time. This activity started by mentioning that the output sine wave amplitude will be  $0.707 \times$  the input sine wave amplitude and that the phase delay will be  $45^\circ$ . The cutoff frequency still needs to be calculated, and then that has to be used to calculate a  $45^\circ$  phase delay time.

The equation for cutoff frequency is:

$$f_C = \frac{1}{2\pi RC}$$

Substituting our  $R = 10 \text{ k}\Omega$  and  $C = 0.01 \mu\text{F}$  values, the cutoff frequency is:

$$f_C \approx \frac{1}{2 \times 3.1416 \times 10,000 \times 0.00000001} \approx 1,591.5 \text{ Hz}$$

Next, we need to figure out what the phase shift time is for  $45^\circ$  at 1591.5 Hz. To do this, all we need to do is rearrange the terms in one of the two phase angle equations from Chapter 7, Activity #6, and solve for  $\Delta t$ . Since we now know the frequency, we can use the phase angle equation with the frequency term and save the  $1/T$  calculation:

$$\theta = \Delta t \times f \times 360^\circ \rightarrow \Delta t = \frac{\theta}{f \times 360^\circ}$$

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Next, solve for  $\Delta t$  when  $\theta = 45^\circ$ .

$$\Delta t = \frac{45^\circ}{1591.5 \text{ Hz} \times 360^\circ} \approx 78.5 \mu\text{s}$$

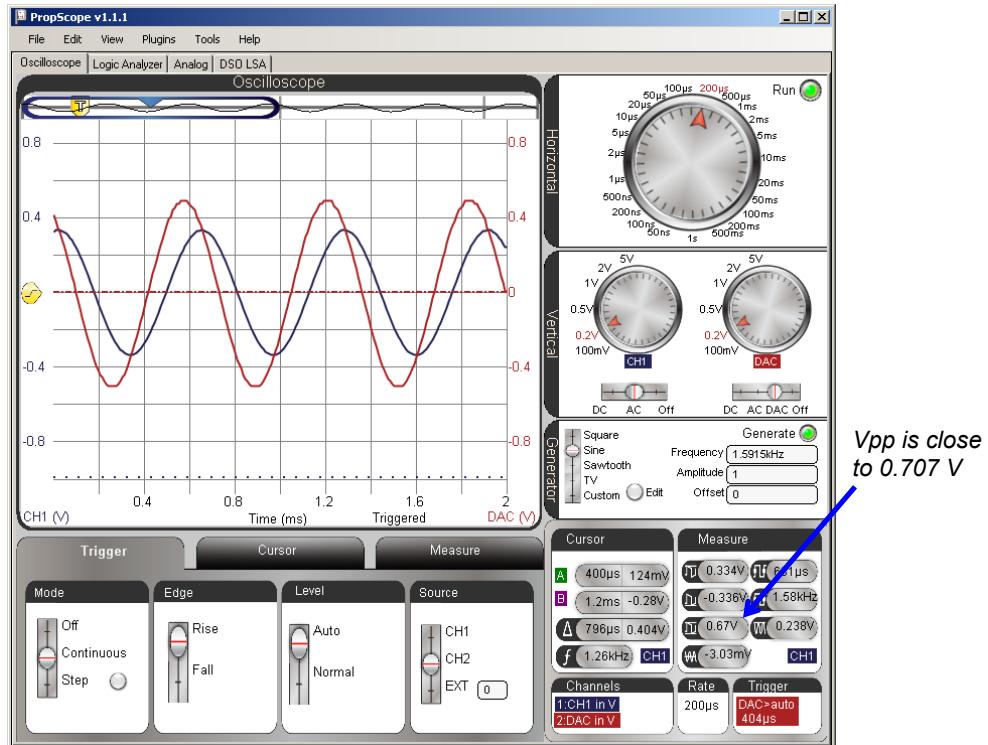
Now we know that the cutoff frequency for our **RC Filter** is 1591.5 Hz. If we supply the filter with a sine wave at this frequency, we'll expect the output to be 70.7% of the input signal amplitude, with a phase shift of  $45^\circ$ , which corresponds to a time shift of 78.5  $\mu\text{s}$ .

### Test the Amplitude and Cutoff Frequency

First let's check to find out if the filter's output signal is about 70.7% of the input signal from the function generator. To make this measurement easy, the PropScope's function generator can supply the RC circuit's input with a 1.5915 kHz sine wave that's 1 Vpp. Then, the output signal's amplitude should be about 0.707 Vpp. Figure 8-42 shows an example.

- ✓ Set the Generate switch to Sine, with a Frequency of 1591.5Hz, an Amplitude of 1 V, an Offset of 0 V, and remember to click the Generate button.
- ✓ Adjust the dials, coupling switches and Trigger tab settings to match Figure 8-42.
- ✓ Adjust the trace positions as shown in the Oscilloscope display, with both the CH2/DAC trace and CH1 circuit output trace in the middle of the screen. Their ground lines should be right on top of each other.
- ✓ Set the Measure display to CH1. If its channel indicator is set to CH2, click it to toggle back to CH1.
- ✓ Use the Measure display to verify that the CH1 measurement of the output sine wave's amplitude is in the 0.707 V neighborhood.

Figure 8-42: Amplitude Output/Input Comparison



In Chapter 7, the output sine wave from the circuit was positioned below the input sine wave, and cursors were used to make the comparisons. Since the Measure display's amplitude value always closely matched the horizontal voltage cursor measurements, we'll rely on it instead of the cursors for amplitude measurements. Chapter 7 also mentioned another common technique of displaying the sine waves with both the CH1 and CH2 ground lines set to the same level. It superimposes the sine waves for improved visual comparison. So, in this chapter we'll rely on that approach.

#### How close should the measurement be?

The tolerances of the resistor and capacitor are 5%, meaning that each one's actual value could be 5% smaller or larger than its nominal (named) value. Other sources of error might include the capacitance inside the breadboard clips and the PropScope's 2% voltage measurement tolerance. All told,  $\pm 7\%$  error is reasonable. The percent error equation is:



$$\% \text{error} = \frac{\text{measured} - \text{predicted}}{\text{predicted}} \times 100\%$$

With the measurement of 0.682 V<sub>pp</sub> from Figure 8-42, the percent error is:

$$\% \text{error} = \frac{0.67 \text{ V}_{\text{pp}} - 0.707 \text{ V}_{\text{pp}}}{0.707 \text{ V}_{\text{pp}}} \times 100\% \approx -5.23\%$$

See Appendix C: Error Propagation Example for more information.

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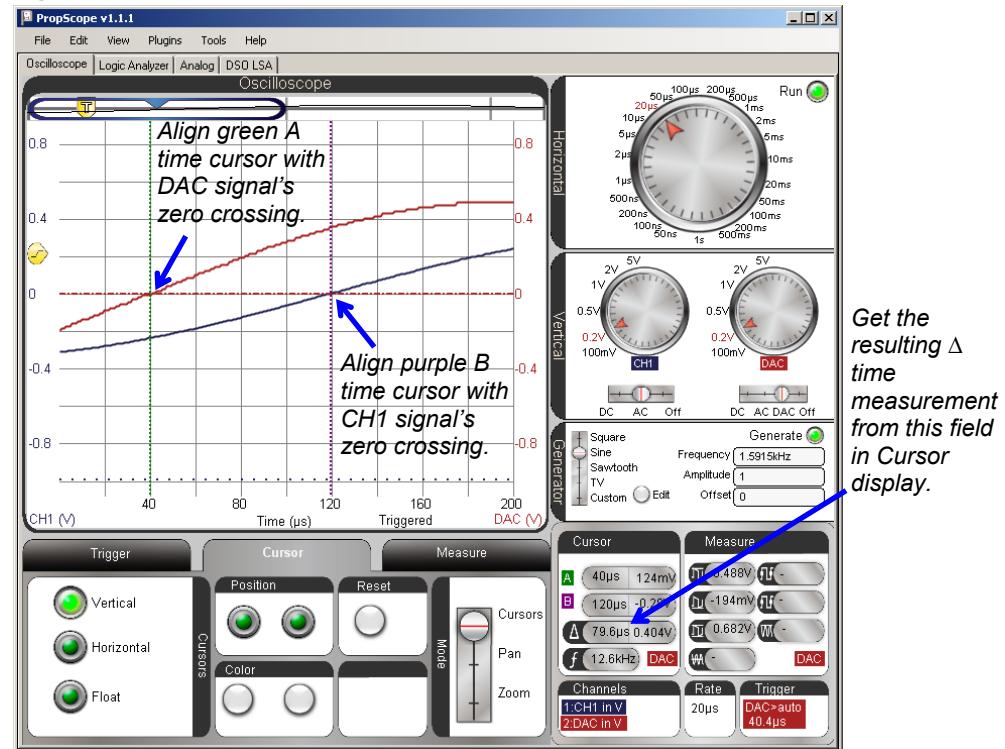
Although the horizontal voltage cursors were not necessary for amplitude measurements, the vertical time cursors are still essential for the phase delay measurement. Figure 8-43 shows an example. The Horizontal time/division setting is reduced for a more precise time difference measurement. As in Chapter 7, each signal's 0 V crossing is a reference point for the beginning of each sine wave's cycle. To measure the time difference between the beginning of each sine wave's cycle, each vertical time cursor is positioned to intersect with a channel trace where it crosses the 0 V ground line. This provides a delay measurement that can be compared to our calculated  $\Delta t$  value of 77.8  $\mu\text{s}$ .

- ✓ Adjust the Horizontal dial to 20  $\mu\text{s}/\text{div}$ .
- ✓ Go to the Cursors tab and turn the Vertical cursors on and the other cursors off.
- ✓ Position the green vertical A time cursor so that it intersects with the CH2/DAC trace as it crosses the 0 V ground line.
- ✓ Position the purple vertical B time cursor so that it intersects with the CH1 trace as it crosses the CH1 0 V ground line.

- ✓ Check the  $\Delta$  measurement in the Cursors display, and compare to the calculated 78.5  $\mu$ s value.



**Figure 8-43:** Phase Output/Input Comparison



**Again, how close should the measurement be?**

For the phase delay,  $\pm 6\%$  is reasonable. Comparing the  $79.6 \mu s$  measurement from Figure 8-43 against the predicted value of  $78.5 \mu s$ , we have:



$$\begin{aligned}\%error &= \frac{\text{measured} - \text{predicted}}{\text{predicted}} \times 100\% \\ &= \frac{79.6 \mu s - 78.5 \mu s}{78.5 \mu s} \times 100\% \\ &= 1.4\%\end{aligned}$$

**Your Turn: Test Other Frequencies and Time Constants**

Keep in mind that a “low-pass” filter lets low frequency sine waves through, and “filters out” higher frequency sine waves. If the DAC is set to  $1/10^{\text{th}}$  the cutoff frequency, the RC circuit’s output signal on CH1 should be almost the same amplitude as the input signal on the DAC/CH2. In contrast, if you make the DAC send a frequency that’s ten times the cutoff frequency, the RC circuit’s output signal on CH1 should be much lower in amplitude.

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- ✓ Try setting the Generate panel’s Frequency field to 159 Hz, and compare the RC circuit’s output amplitude on CH1 to the DAC/CH2 signal amplitude. Adjust the oscilloscope disp is needed.
- ✓ Repeat for 15.9 kHz; the signal’s amplitude should be much lower (attenuated).

You can increase the cutoff frequency by decreasing the value of  $RC$ . If you do this, the filter will not reduce the amplitude until the input frequency is higher. For example, decreasing the resistor by a factor of 10, increases cutoff frequency by a factor of 10. So, the value of the  $10 \text{ k}\Omega$  resistor is changed to  $1 \text{ k}\Omega$  in these cutoff frequency calculations:

$$\begin{aligned}f_C &= \frac{1}{2\pi RC} \\ &= \frac{1}{2 \times 3.1416 \times 1,000 \times 0.00000001} \\ &\approx 15,915 \text{ Hz}\end{aligned}$$

- ✓ Replace the 10 k $\Omega$  resistor in Figure 8-40 and Figure 8-41 with a 1 k $\Omega$  resistor and repeat the calculations and tests in this activity for the higher cutoff frequency.

You could also reduce the capacitor's value for the same effect, except that the Understanding signals kit does not contain a 0.001  $\mu\text{F}$  = 1 nF capacitor. You could however, leave the resistor alone and swap out the 0.01  $\mu\text{F}$  capacitor for a 0.1  $\mu\text{F}$  capacitor for a cutoff frequency that's ten time lower (instead of higher).

## SUMMARY

This chapter introduced a variety of RC circuit measurements, including RC time constants and resistive and capacitive sensors. The RC DAC's role in D/A conversion was examined, along with its susceptibility to resistive loads. The low pass filter was also revisited, this time, with attention to testing its cutoff frequency.

## Questions

1. What does a resistor resist?
2. How far does a capacitor discharge after 1 RC time constant?
3. What is  $\tau$ ?
4. How do you measure an RC time constant given an oscilloscope decay measurement?
5. How do you line up the start of an RC decay with the Oscilloscope screen's 2<sup>nd</sup> time division line?
6. Does the PropScope have an automated RC time constant feature?
7. In an RC decay circuit that measures a resistive sensor, what else affects the decay time in addition to the RC time constant?
8. What property of the potentiometer does the RC decay measurement measure?
9. What voltage does the BASIC Stamp allow an RC circuit to decay to for its time measurement?
10. Which of a phototransistor's terminals accepts light as an input?
11. How can the BASIC Stamp control the voltage the capacitor charges to before the RC decay measurement?
12. For binary signals to set a DC voltage at a capacitor in an RC circuit, how does the period have to compare to the time constant?
13. How do you calculate the area under a binary signal?
14. If a 5 V PWM signal is high for 3/11ths of the time, what will the voltage across the capacitor be?

15. What happens to the voltage across the capacitor after PWM charges it if it's connected to a resistor load?
16. What ratio of output to input amplitude would you expect from a sine wave output from an RC low pass filter at the cutoff frequency?
17. If you need to increase an RC filter's low pass cutoff frequency by 10, could you change to make it so?

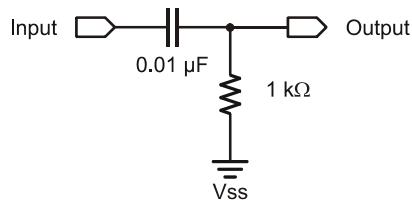
### **Exercises**

1. Calculate the points for 1, 2 and 3 in the  $y = 1 - e^{-x}$  graph in Figure 8-1.
2. Assume  $R \times C = 0.5$ ,  $V_I = 5$  V, and  $V_F = 0$  V. Calculate the decay at  $t = 0.5$  s.
3. Calculate the RC time constant  $\tau$  for  $R = 2$  kΩ and  $C = 10$  μF.
4. Calculate a good square wave input frequency for viewing decay with  $R \times C = 100$  μs.
5. A decay measurement is 650 in terms of 2 μs units. Calculate the time measurement.
6. Calculate how long an RCTIME command would have to take to charge a capacitor in an RC circuit with  $R = 220$  Ω and  $C = 0.1$  μF. Write the HIGH, PAUSE and RCTIME commands that would be needed for this job on P7.
7. In the command PWM 14, 32, 1, predict the ratio of high/to low signal.
8. In the command PWM 14, 224, 1, predict the ratio of high/to low signal.
9. Calculate the area under a 1 Hz square wave that's 5 V high 1/3 of the time and 0 V low the other 2/3 of the time.
10. Calculate the area under a 10 Hz square wave that's 5 V high 2/3 of the time and 0 V low the other 2/3 of the time.
11. Calculate the cutoff frequency of a low pass filter with  $R = 2$  kΩ and  $C = 0.01$  μF.
12. Calculate the cutoff frequency of a low pass filter with  $R = 22$  kΩ and  $C = 0.1$  μF.

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### **Projects**

1. Test the PWM command for its smallest high time.
2. Figure 8-44 shows a high pass filter. It allows high frequencies to pass, and cuts off frequencies below the  $f_C = 1/2\pi RC$  cutoff frequency by attenuating them. Test amplitude outputs at  $10 \times f_C$ ,  $f_C$ , and  $0.1 \times f_C$ . Test the phase at  $f_C$ . Hint: The phase measurements will have to show how the output sine wave's phase delay leads (not lags) the input signal by 45°.



**Figure 8-44**  
High Pass Filter

## Solutions

- Q1. Current flow.  
Q2. To about 36.8% of its original value.  
Q3. The Greek letter Tau, an abbreviation for the RC time constant.  
Q4. Find the point 36.8% from the final voltage, and then measure the time between the start of the decay and that point.  
Q5. By adjusting the trigger time control to make the vertical crosshair line up with the 2<sup>nd</sup> division line.  
Q6. No, but it does have cursors, which are useful for measuring the time from the start of a decay to 36.8% of its final value.  
Q7. The resistor in series with the circuit forms a voltage divider that prevents the capacitor from charging up to ~~it's the~~ the voltage the I/O pin supplies. Lower initial voltage, smaller decay time.  
Q8. Resistance that varies with the knob's position.  
Q9. I → 4 V logic threshold.  
Q10. Its base.  
Q11. Use PWM to set an initial voltage.  
Q12. The period must be much smaller than the time constant ( $T \ll RC$ ).  
Q13. By multiplying the area between signal voltage and the ground line by the amounts of time they last.  
Q14.  $3/11 \times 5 \text{ V} = 1.3636\ldots$   
Q15. The capacitor's voltage decays through the resistor load.  
Q16. 70.7% of the input sine wave.  
Q17. Reduce either R or C by a factor of 10. (The RC term is in the cutoff frequency equation's denominator, so reducing R or C by 10 increases the frequency result by 10.)
- E1. Values to 3 significant figures: 0.632, 0.865, 0.950.  
E2.  $v = 5 \times e^{-(0.5/0.5)} = 5 \times e^{-1} \approx 1.84 \text{ V}$ .

E3.  $2,000 \Omega \times 0.00001 \mu\text{F} = 0.2 \text{ s}$ .

E4.  $t_{\text{high}}$  and  $t_{\text{low}}$  should be  $5\tau$  each.  $5 \times \tau = 5 \mu\text{s}$ . Period  $T = t_{\text{high}} + t_{\text{low}} = 500 \mu\text{s} + 500 \mu\text{s} = 1 \text{ ms}$ .  $f = 1/T = 1/0.001 = 1000 \text{ Hz}$

E5.  $650 \times 0.000002 \text{ s} = 0.0013 \text{ s}$

E6.  $5\tau = 5 \times 220 \times 0.1 \times 10^{-6} = 110 \mu\text{s}$ . Smallest PAUSE Duration argument is 1, so:  
HIGH 7: PAUSE 1: RCTIME 7, 1, time

E7.  $32/256 = 1/8$

E8.  $224/256 = 7/8$

E9.  $(5 \text{ V} \times 1/3 \text{ s}) + (0 \text{ V} \times 2/3 \text{ s}) \approx 1.67 \text{ Vs}$

E10.  $(5 \text{ V} \times 0.0667 \text{ s}) + (0 \text{ V} \times 0.0333 \text{ s}) \approx 0.3335 \text{ Vs}$

E11.  $f_C = 1/2\pi RC \approx 1 \div (2 \times 3.1416 \times 2,000 \times (0.01 \times 10^{-6})) \approx 7957.7 \text{ Hz}$

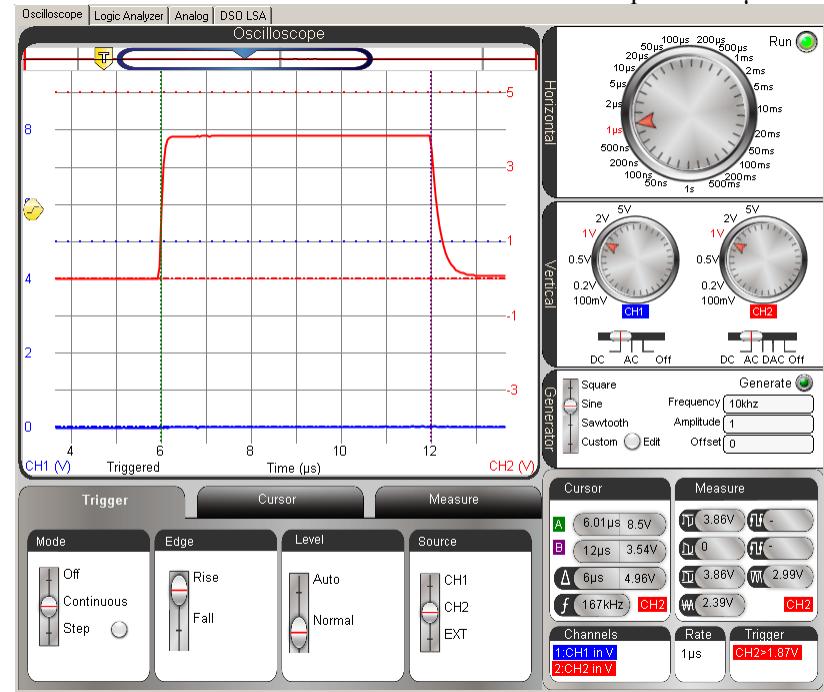
E12.  $f_C = 1/2\pi RC \approx 1 \div (2 \times 3.1416 \times 22,000 \times (0.1 \times 10^{-6})) \approx 72.34 \text{ Hz}$

P1. First, modify Test 1 Channel Dac.bs2 so that it sends the smallest possible pulse by setting the PWM command's Duty argument to 1.

```
' Test 1 Channel Dac for CH5P1.bs2
' Set P14 capacitor to 1.25 V.
' {$STAMP BS2}                                ' Target module = BASIC Stamp 2
' {$PBASIC 2.5}                               ' Language = PBASIC 2.5
DEBUG "Program running..."                      ' Debug Terminal message
DO
    PWM 14, 1, 1                                ' Main Loop
                                                ' 5 V x 1/256th
LOOP                                         ' Repeat main loop
```

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Vertical time cursors on CH2 indicate that the shortest pulse is 6  $\mu$ s.

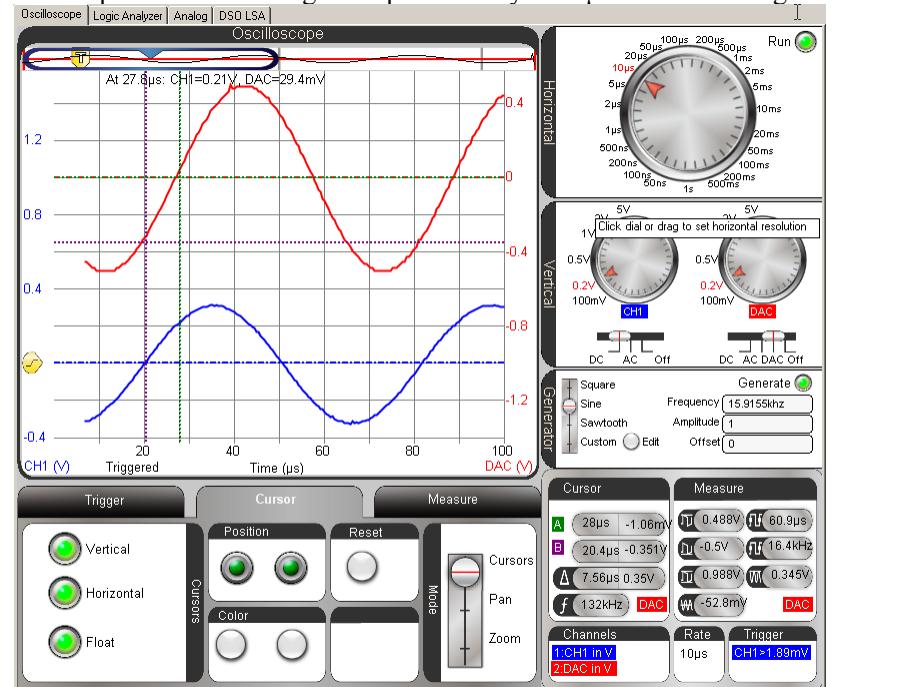


P2.

$$F_C = 1/(2\pi RC) = 1/(2 \times 3.1416 \times 1,000 \times 0.01 \times 10^6) \approx 15915.5 \text{ Hz}$$

$$\Delta t = \theta/(f \times 360^\circ) = 45^\circ/(15915.5 \text{ Hz} \times 360^\circ) \approx 7.85 \mu\text{s}$$

The output wave is leading the input wave by 7.56  $\mu\text{s}$  → close enough.



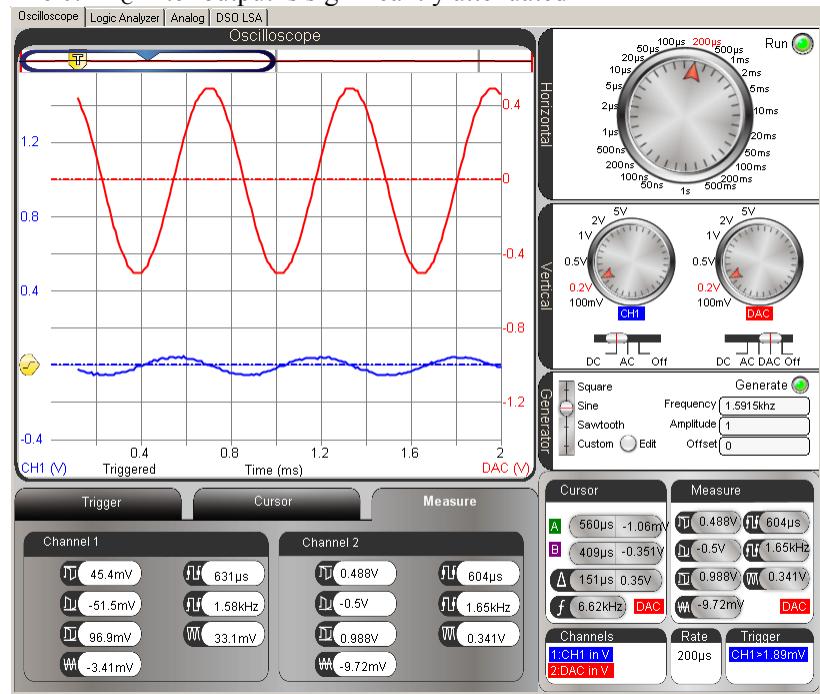
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The output wave is 0.629 Vpp, which is somewhat less than 0.707. %error =  $(0.629 - 0.707) / 0.707 = -11\%$ .

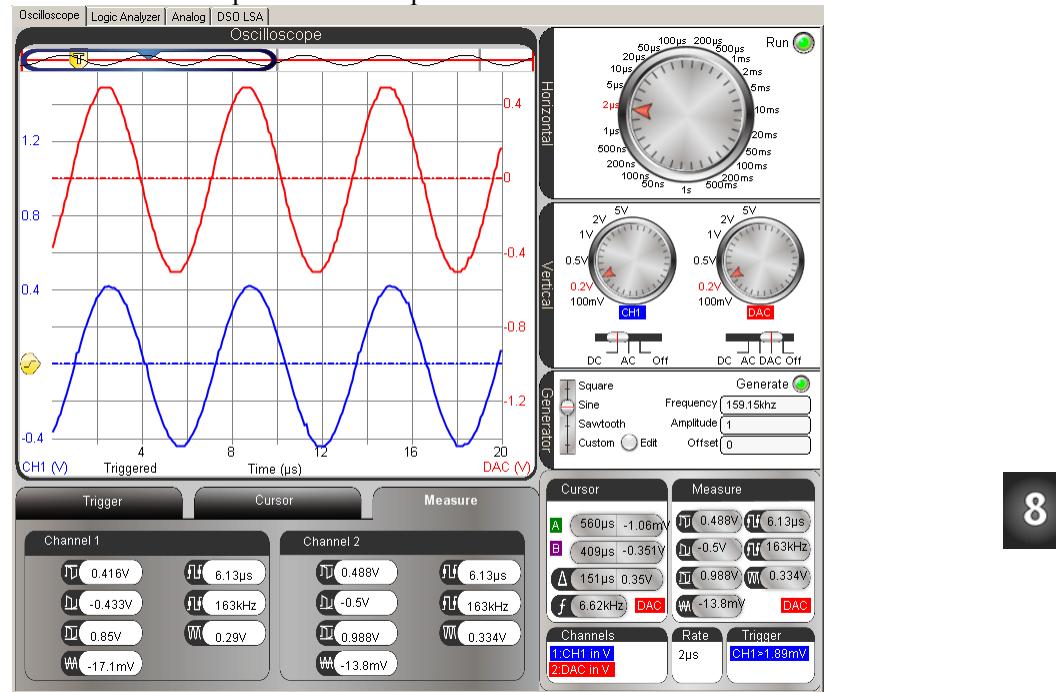


**Comment [AL80]:** Some amplitude measurement corrections are still pending as of v1.1.1. Update when corrected.

The  $0.1 \times f_C$  filter output is significantly attenuated



...and the 10x frequency is almost the same amplitude as the input wave is almost the same amplitude as the input wave.



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