Lab 1: Observing Analog-to-Digital and Digital-to-Analog Conversion Using the Agilent 54622D Digital Oscilloscope

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Equipment Required

- Agilent 54622D Mixed-Signal Oscilloscope with two 10X attenuating probes and digital input harness
- Agilent E3631A DC Power Supply
- Agilent 34401A Digital Multimeter to measure DC base current
- Agilent 33250A or 33120A Function Generator to create sine waves
- Components: ADC0804 ADC IC, MC1408 DAC IC, Eight LEDs, Resistors: eight 1.3k Ω; two 2.7 k Ω, one 2.2k Ω, three 10k Ω, 100k Ω potentiometer
- Capacitors: one 150 pF, one 47 pF, two 0.1 µF, one 10 µF tantalum, two 220 µF
- Optional: Audio Amplifier with Speaker, to listen to output signal

Introduction:

Our technological world is full of analog parameters (time, temperature, sounds including music and speech, speed, etc.) which are increasingly being turned into digital formats (digital clocks, digital thermometers, audio CDs and MP3 players, digital dashboards).
For example, body temperature used to be measured with a glass capillary tube connected to a reservoir of mercury. Put under the tongue of a person, the mercury reservoir warmed up, and expanded in volume. This expansion pushed the column of mercury up the thin hollow channel in the glass, and a calibrated scale etched in the glass allowed a temperature to be read by the length of the mercury column. These parameters (temperature and length of mercury column) are pure analog. Mercury is dangerous, glass can easily break, and most homes now depend on a digital thermometer to read body temperature. A sensor in the tip changes resistance based on temperature, which creates a voltage proportional to temperature. This voltage is the input to a analog-to-digital converter, the output of which is converted to base ten and fed to a liquid crystal display (LCD). Nobody has to "read" a glass thermometer analog scale; the LCD clearly says "102.6 °F or 39.2 °C", so the sick child gets to stay home from school today.

Analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) play key roles in the digitizing of analog parameters and the subsequent restoration of digital information to its analog form.

In this experiment you will:

- construct an analog-to-digital converter circuit, with an LED indicating the logic level of each digital output
- use a potentiometer with DC to verify its correct operation
- measure the DC input voltage required to produce turn on each "bit" of the ADC output
- construct a digital-to-analog converter circuit, and confirm that it works correctly
- connect the ADC output to the DAC input, and examine the input and output analog signals
- observe the phenomenon of "aliasing", the creation of false frequencies in a sampled system by using an input signal containing frequencies greater than the conversion frequency/2.

Basic Settings of Your Oscilloscope:

1) Turn the oscilloscope ON by pressing the white button at the lower right corner of the CRT screen (the ***graticule*** of the cathode-ray tube). At this time, don't connect anything to Channel 1 or Channel 2 vertical inputs, or to the **Ext Trigger** input.

2) You probably weren't the last person to use the oscilloscope, and it's probably NOT set up to do the measurements you want to make. A good way to start is to return the oscilloscope to its "Default" condition by pressing the **Save/Recall** ***Hardkey*** in the **File** area of the front panel, then pressing the **Default Setup** softkey. Do this now.

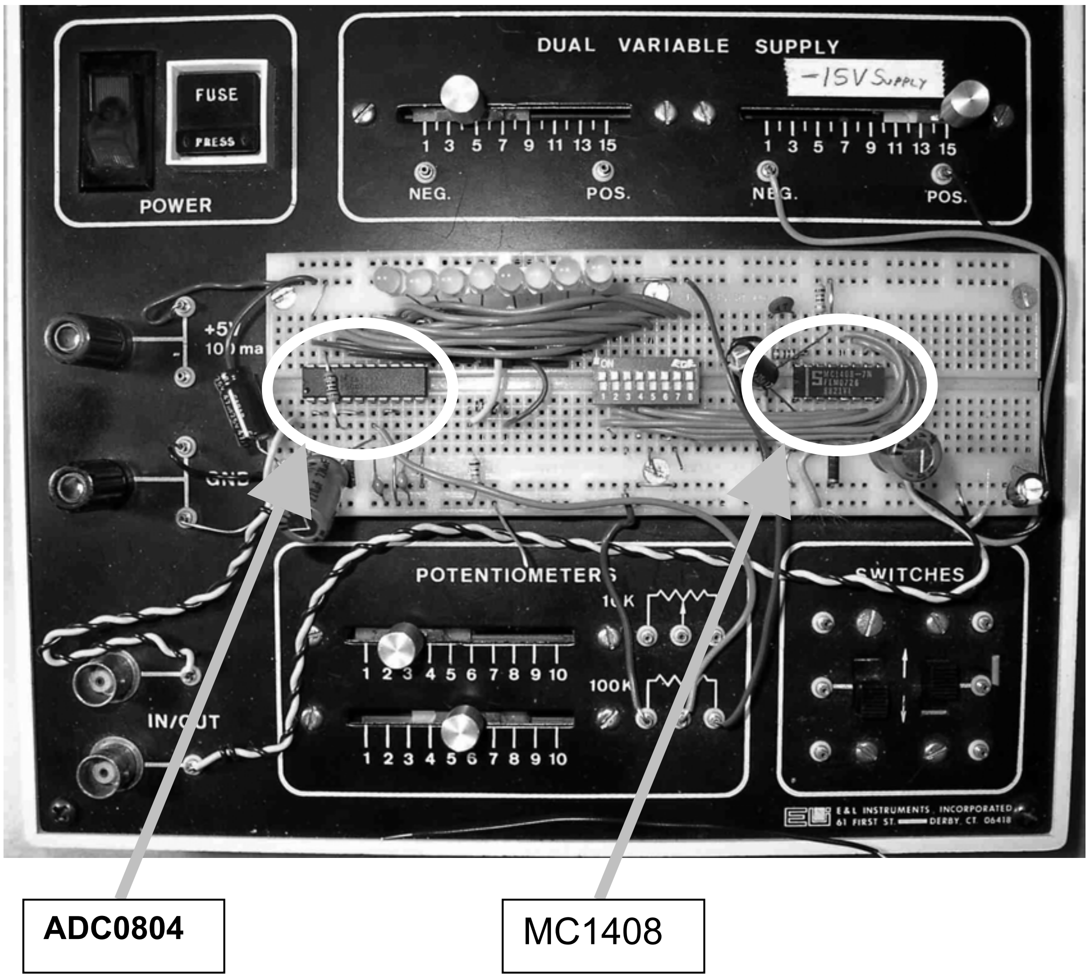
   You will see a horizontal line in the middle of the display (CRT graticule), and at the top right is a blinking "**Level**". This area of the display is telling you that the oscilloscope is configured to trigger its sweep on **Channel 1**, using **positive edge** triggering in **Auto Level** mode, and it's NOT finding a signal at the trigger **Level** of **0.00 V**. This makes sense, as there is no input signal at this time.

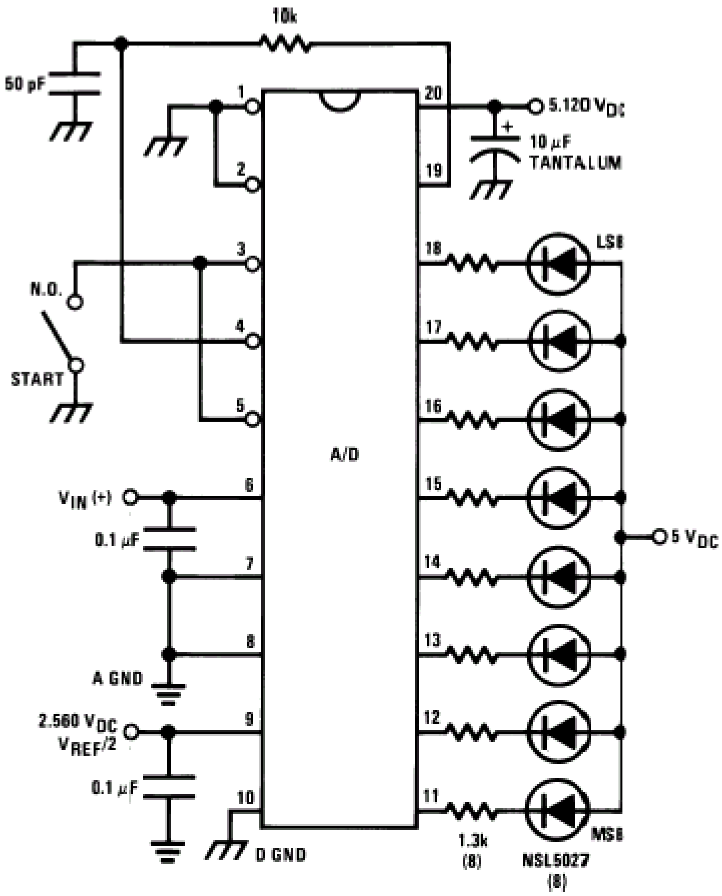
3) Connect two 10X attenuating probes to Channel 1 and Channel 2. Set the **Probe Factor** for both channels to 10:1.

4) Compensate both probes (using the **Probe Comp** output on the front panel), making sure the square wave compensation waveform looks "square".

REMEMBER: Pressing **and holding** ANY key (hardkey or softkey) will bring up a help screen on the display. What a handy way to learn about its features!

One layout of the circuits for this experiment is shown below. Note the +5 V supply (on the left), the -15 V supply (top right), the 8 LEDs and the 100 k Ω potentiometer (bottom center).





This circuit is from page 24 of National Semiconductors document : *http://www.national.com/ds/AD/ADC0801.pdf*

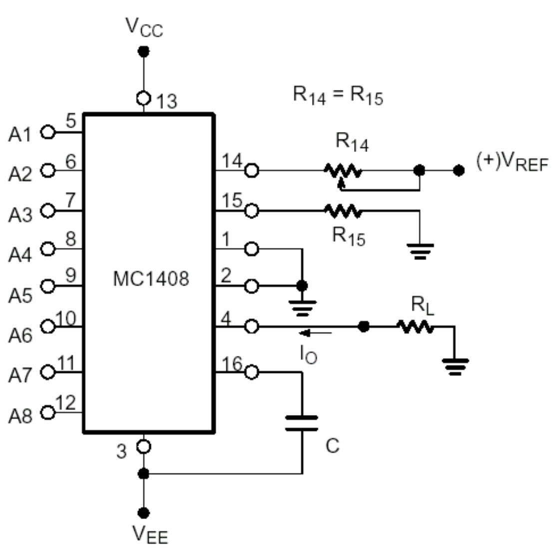
IMPORTANT NOTES for the ADC0804:

1. Separate grounds must be used: one for analog, and one for digital. This is a VERY important concept, to avoid digital noise from getting into the analog input circuit. Use a separate bus for each ground, and bring them together only at a single point: the negative terminal of the 5 V power supply.

2. A "START" switch *may* be needed. As shown, the ADC is in "free-running" mode. At the end of one conversion, another starts. Under certain conditions, the circuit may not begin the analog-to-digital conversion process unless pins 3 & 5 are momentarily grounded. This may be done manually, or may be done with a series R-C circuit (a power-on "start" circuit): 10k Ω to =5 V, 0.1µF to ground, junction to pins 3 & 5. Every time power is applied, the 0.1µF will hold pins 3 & 5 low, until it charges through the 10k Ω.

This experiment requires that you tie these two circuits together (i.e. the 8-bit output of the ADC, above, gets connected to the 8-bit input of the MC1408 DAC, below). Do this as follows: connect the MSB of the ADC (pin 11 of the ADC0804) above, to the MSB of the DAC (pin 5 = A1 of the MC1408) below. Next, connect pin 12 above to pin 6 below. Do this for each bit, ending with the LSB, so that pin 18 above (LSB output of the ADC) is connected to to pin 12 below (LSB input of the DAC).

Note the inconsistency in notation: Pin 11= DB7 of the ADC above is the MSB, while Pin 5= A1 of the DAC below is the MSB. The ADC notation uses DB0 - DB7 (DB0 is the LSB, DB7 is the MSB). The DAC notation uses A1 - A8 (A1 is the MSB, A8 is the LSB).



This circuit is from page 5 of Phillips Semiconductor document: *http://www.semiconductors.philips.com/acrobat/datasheets/MC1408-8_3.pdf*

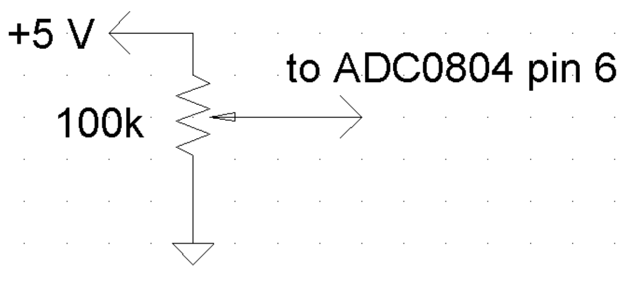
R14 = R15 = 2.7k Ω (fixed resistors)
RL = 2.2 k Ω
C = 47 pF

V_{CC} = + 5 V, and V_{EE} = -15 V.
V_{REF} = V_{CC} = + 5 V

Because of this DAC's architecture, the output voltage (at pin 4) will always be a negative voltage.

Procedure One - Testing the ADC and DAC With DC Input:

1. Construct the ADC circuit shown at the top of page 3. Do not connect the circuit to the DC power supply, or to an input signal at this time. Make the MSB LED on the left, and the LSB LED on the right.



Be VERY careful to include all needed components and wires, and to NOT put in wires that aren't needed. It's much easier to build it correctly, even if it takes a bit longer to do so, than it is to make a mistake and have to troubleshoot it later.

2. Now build the DC input circuit shown below. The value of the potentiometer is quite unimportant; anything from a 1k Ω to a 100k Ω will be fine.
3. Set the current limit controls on both of your power supplies to about 50 mA *(proper use of current limiting can prevent an LED from becoming an SED [smoke-emitting diode])*. Now turn on the DC power (for the +5 V and the -15 V supply).

4. With the wiper of the input circuit potentiometer at ground (analog Vin = 0 V), the 8-bit output of the ADC should be all zeros ($0000\ 0000_2$). The way the LEDs are connected, each LED will light up when the bit it represents is ***low* = *0*$_2$**. So, all LEDs should be lit at this time.

5. Now move the wiper slowly from 0 V to +5 V, while observing the LEDs. The LEDs should turn on and off in a binary counting order. For example, the LED pattern should follow the following pattern:

MSB							**LSB**	
ON	ON	ON	ON	ON	ON	ON	ON	$= 0000\ 0000_2 = 000_{10}$
ON	ON	ON	ON	ON	ON	ON	**off**	$= 0000\ 0001_2 = 001_{10}$
ON	ON	ON	ON	ON	ON	**off**	ON	$= 0000\ 0010_2 = 002_{10}$
ON	ON	ON	ON	ON	ON	**off**	**off**	$= 0000\ 0011_2 = 003_{10}$
ON	ON	ON	ON	ON	**off**	ON	ON	$= 0000\ 0100_2 = 004_{10}$
ON	ON	ON	ON	ON	**off**	ON	**off**	$= 0000\ 0101_2 = 005_{10}$

etc.

This counting pattern will progress in 255 steps from $0000\ 0000_2$ (all LEDs ON) until, with the wiper at +5 V, the pattern should be: $= 1111\ 1111_2$ (all LEDs OFF):

off	**off**	**off**	**off**	**off**	**off**	**off**	**off**	$= 1111\ 1111_2 = 255_{10}$

6. Now construct the DAC circuit shown at the bottom of page 3. Connect the eight bits at the output of the ADC to the eight-bit input of the DAC. Be sure to read the explanation of ADC output bit nomenclature, and DAC input bit nomenclature, between the schematics on page 3.

7. We will now test the ADC and the DAC as a system, using different DC input voltages (set by you using the potentiometer) so that one bit at a time is tested.

MSB LED	**LED**	**LED**	**LED**	**LED**	**LED**	**LED**	**LSB LED**	**Vin (V)** to the ADC	**Vout (V)** from the DAC
Off	Off	Off	Off	Off	Off	Off	Off		
Off	ON	ON	ON	ON	ON	ON	ON		
ON	Off	ON	ON	ON	ON	ON	ON		
ON	ON	Off	ON	ON	ON	ON	ON		
ON	ON	ON	Off	ON	ON	ON	ON		
ON	ON	ON	ON	Off	ON	ON	ON		
ON	ON	ON	ON	ON	Off	ON	ON		
ON	ON	ON	ON	ON	ON	Off	ON		
ON	ON	ON	ON	ON	ON	ON	Off		
ON	ON	ON	ON	ON	ON	ON	ON		

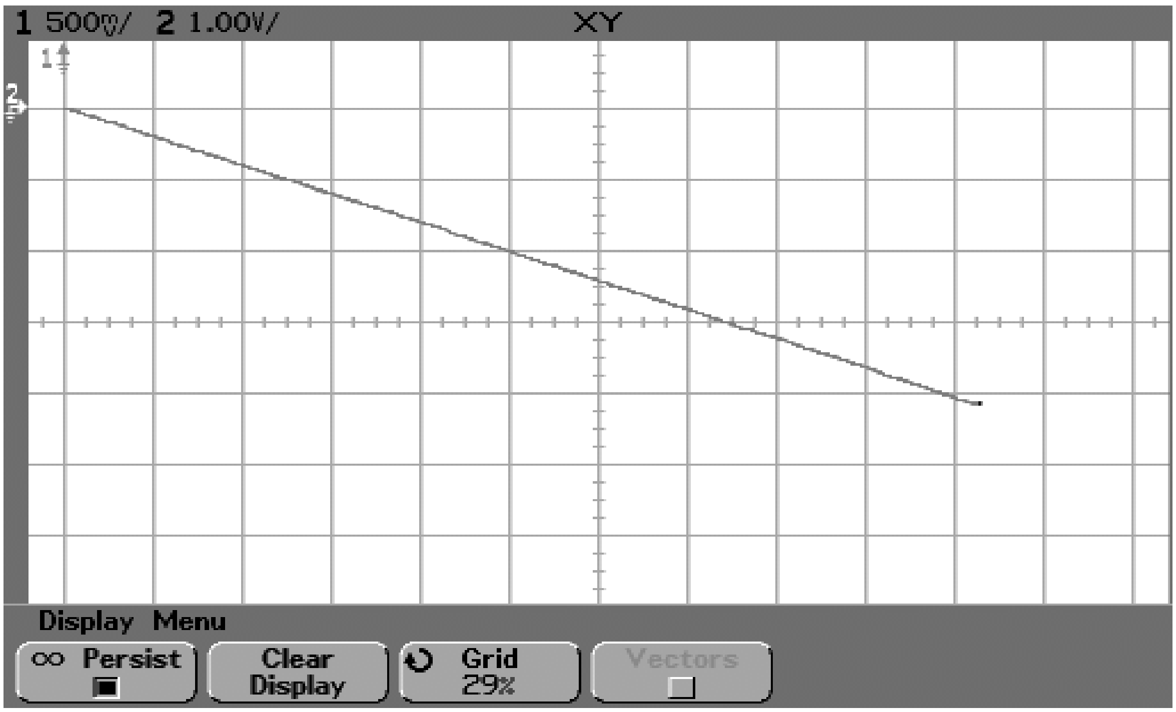
In the table above, you should see that the input voltage to the ADC decreases from about 5 V to 0 V as you go from the top row to the bottom row. Likewise, the output voltage from the DAC changes from about -4.2 V to 0 V as you go from the top row to the bottom row.

Based on the data in the table above, what is the "resolution", in volts, of the ADC? Show how you determine the answer (there are several ways).

Based on the data in the table above, what is the "resolution", in volts, of the DAC? Show how you determine the answer (there are several ways).

8. The next step is a dynamic test of the ADC/DAC system. You will move the wiper of the potentiometer from 0 V to +5 V, and the output voltage will vary from about 0 V to -4.2 V. The graph of Vout vs. Vin will be displayed, and recorded, on the digital oscilloscope.

9. Connect analog Channel 1 to the ADC input (ADC0804 pin 6), and analog Channel 2 to the DAC output (MC1408 pin 4). Put the MSO into X-Y mode by pressing the **Main/Delayed** hardkey in the **Horizontal** section, and then pressing the **X-Y** softkey under the display.



Analog output voltage (y-axis), channel 2 versus analog input voltage (x-axis), channel 1. This is done using the infinite (∞) persistence feature. A potentiometer is manually moved so that the ADC input voltage is varied from 0 VDC to +5 VDC (10 divisions @ 500 mV/div); the DAC output voltage varies from 0 VDC to -4.17 VDC (4.17 divisions @ 1.00 V/div).

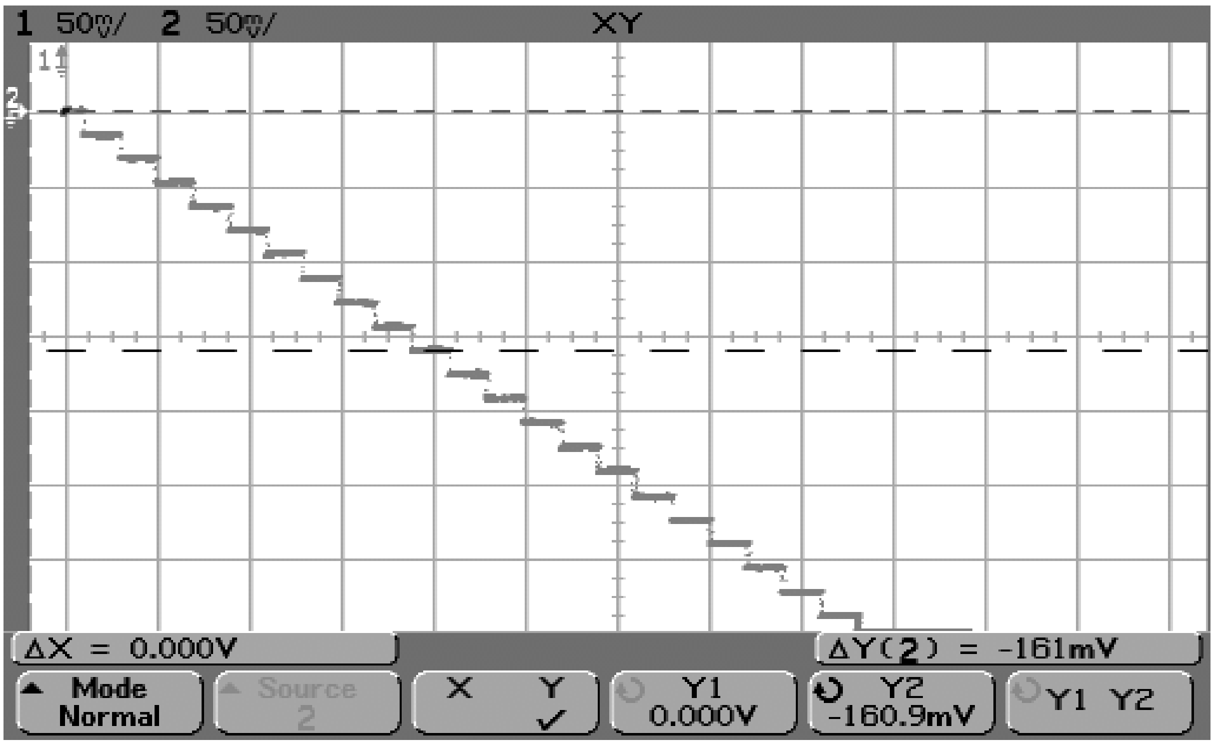
Although it can't be seen here, the "line" is really a staircase, with 2^8-1 = 255 "steps" of height 4.17V/255 = 16.4 mV. Each vertical division (@ 1V/div) has 1V/16.4mV = 61 steps.

10. Set the volts/div controls as shown above, and the position controls to place the ground symbols for both channels as shown.

11. Turn on the "infinite persistence" (found under the **Display** menu) so that you see a line (as shown above) instead of a dot, as you move the wiper from one extreme to the other.

12. Record the graph of Vout vs. Vin, using the **Quickprint** feature (saves the display to a graphics file on a 1.44 Mbyte floppy disk).

13. Now return the potentiometer wiper to 0 V, which should make the dot be in the upper left corner of the display. Change the volts/div controls so that both channels are 50 mV/div, and readjust the position controls as needed to keep the dot in the upper left corner. This will "zoom in" on the graph, and allow us to clearly see the individual steps in the output voltage, and to measure the step height (resolution).



This is an expanded view of the display at the top of the page. DAC analog output voltage (y-axis), on Channel 2 versus analog input voltage (x-axis) on Channel 1.

Here the scale for both axes has been changed to 50 mV/div, so that the individual steps can be seen. Instead of measuring the height (in mV) of one step, greater accuracy was achieved by measuring the voltage difference of 10 steps, and dividing the result by 10: (160.9 mV)/(10 steps) = 16.1 mV/step. Thus, this DAC has a resolution (smallest possible change in output voltage) of 16.1 mV.

14. Make sure that "infinite persistence" is still turned on. Press "Clear Display", to erase the earlier display. (found under the **Display** menu) so that you see a staircase display (as shown above) instead of a dot, as you move the wiper only a small amount (not from one extreme to the other).

15. Record the expanded graph of Vout vs. Vin, using the **Quickprint** feature (saves the display to a graphics file on a 1.44 Mbyte floppy disk).

16. Based on the data in the graph above, the resolution of the DAC is 16.1 mV. What is the "resolution", in volts, of the ***your*** DAC? Show how you determine the answer.

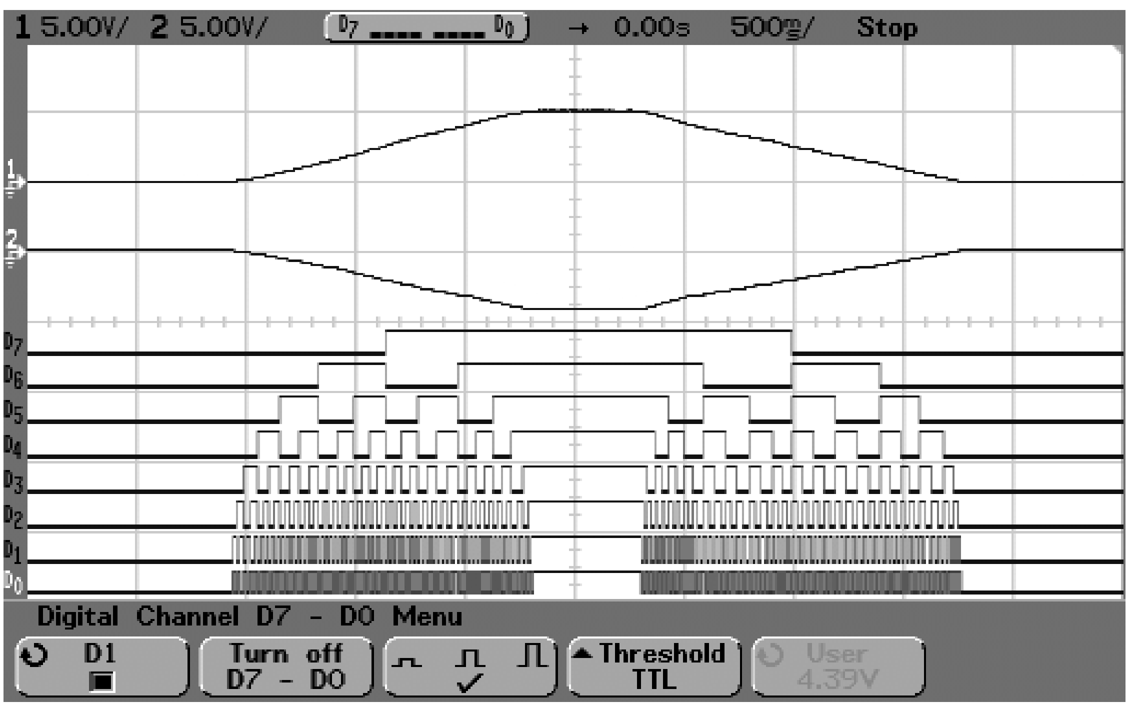
17. Now we will use the mixed-signal oscilloscope to look at the 8-bit digital output of our ADC. Turn the DC power supply off, to prevent damage while connecting the digital harness.

18. Connect one half of the 16-bit digital input harness, using the 8 bits labeled D0 – D7, to the digital outputs of the ADC. Make sure D0 (the LSB) is connected to pin 18 (the LSB output of the ADC). Use short pieces of bare wire in the breadboard slots, and be sure that the digital harness connectors don't touch each other or cause short circuits on the data bus.

19. Turn on the D0 - D7 inputs of the MSO, using the hardkey on the front panel.

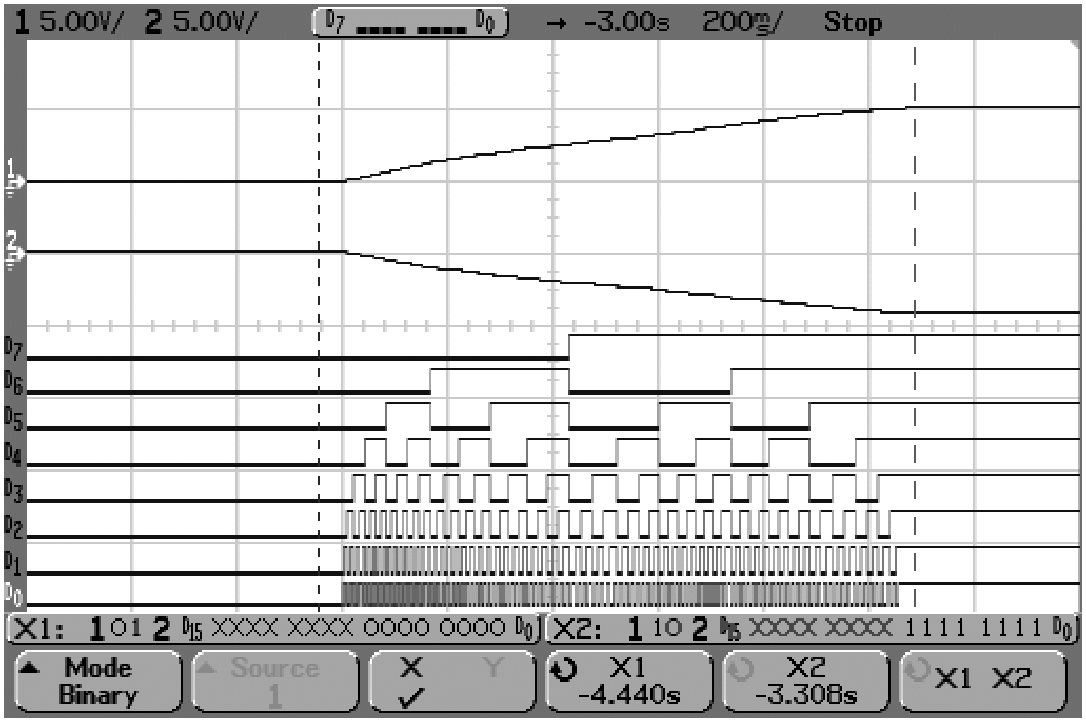
20. Turn on the power supply, and move the slide potentiometer from 0 VDC to +5 VDC, and back to 0 VDC again. Change the oscilloscope **horizontal mode** from X-Y to **ROLL**. This provides a slow sweep speed, and allows you to see instantaneous voltages as they occur. Once you have a reasonable display, freeze the screen by pressing the **STOP** hardkey.

21. Your display should look like the one below. The 8-bit digital output can be seen to go from all low levels (0000 0000) to all high levels (1111 1111) in binary, and back .



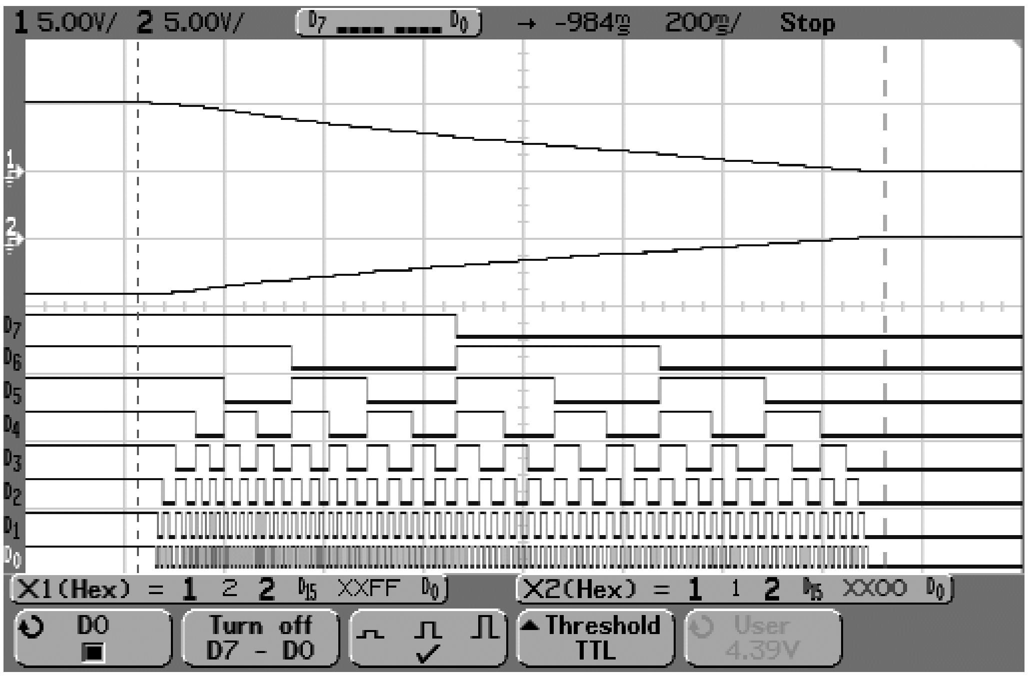
The analog display of Channel 1, at top, shows the input to the ADC ramping from 0 V to +5 V, and then back down to 0 V in a time period of about 3 seconds. Channel 2 shows the DAC output ramping from 0 V to -4 V, and then back up to 0 V.

The digital display, bits D0 - D7 at bottom, go from a digital value of $0000\ 0000_2$ to $1111\ 1111_2$, and then back down to $0000\ 0000_2$. D0 is the LSB, and D7 is the MSB.



The analog display of Channel 1, at top, shows the input to the ADC ramping up from 0 V to +5 V. Channel 2 shows the DAC output ramping down from 0 V to -4 V.

The digital display goes from a digital value of $0000\ 0000_2$ to $1111\ 1111_2$. D0 is the LSB, and D7 is the MSB. The cursors (X1 & X2) are in **Binary** mode, and show all 16 bits. Bits D8-D15 show as **X = Don't Care**, since D8-D15 are turned off.



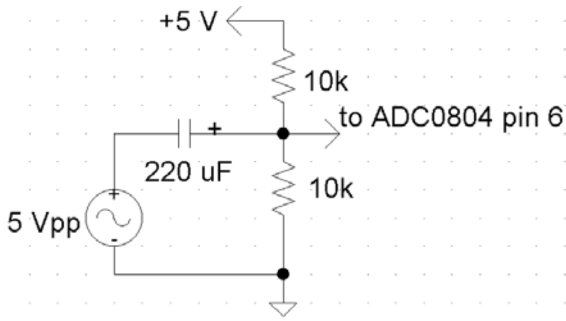
The analog display of Channel 1, at top, shows the input to the ADC ramping down from +5 V to 0 V. Channel 2 shows the DAC output ramping up from -4 V to 0 V.

The digital display goes from a digital value of $1111\ 1111_2$ to $0000\ 0000_2$. The cursors (X1 & X2) are in **Hex** mode, and show all 16 bits. Bits D8-D15 show as **X = Don't Care**, since D8-D15 are turned off. The digital value of $1111\ 1111_2 = XXFF_H$ (the X meaning D8-D15 are not used, X = don't care), and the digital value of $0000\ 0000_2 = XX00_H$.

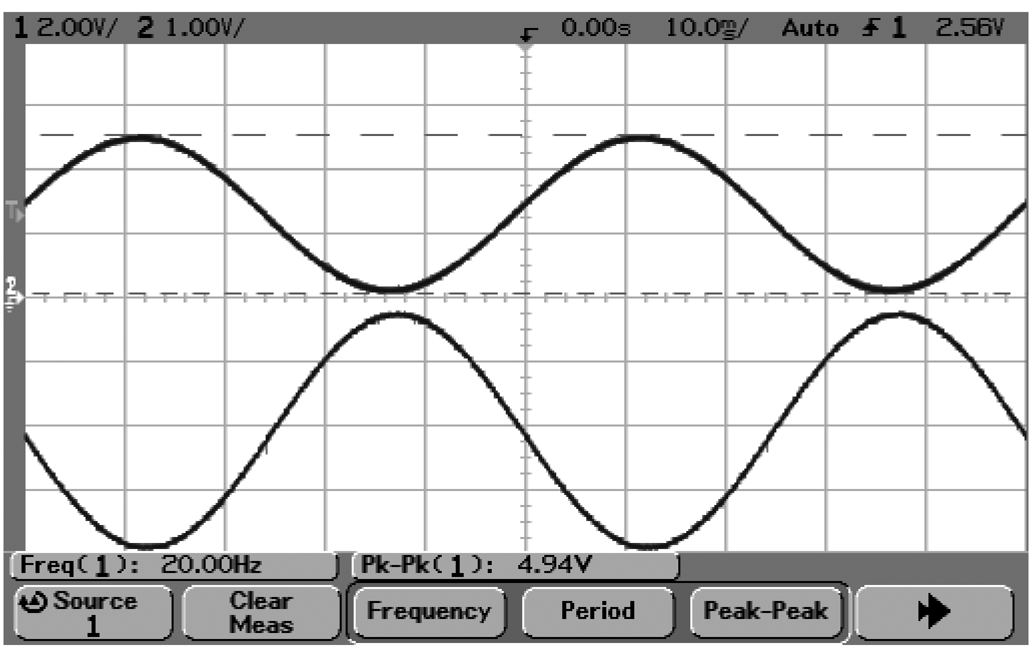
Procedure Two - Testing the ADC and DAC with A Sinusoidal Input:

1. Don't connect the function generator to the circuit yet. Set it to produce a sinusoid as follows: 2.5 Vp = 5.0 Vpp, at 20 Hz. Do this with only the generator connected to the oscilloscope.

2. Turn off the power to the ADC/DAC circuit. Now build the input circuit shown below, so that a sinusoid can be the input signal to the ADC. Be sure to put the positive (+) end of the coupling capacitor as shown. This circuit offsets the DC voltage at the ADC input pin to 1/2 of 5 V, or 2.5 V. This allows an external signal (from the function generator) to move the ADC input and down from this voltage, not to exceed 2.5 Vp of signal.



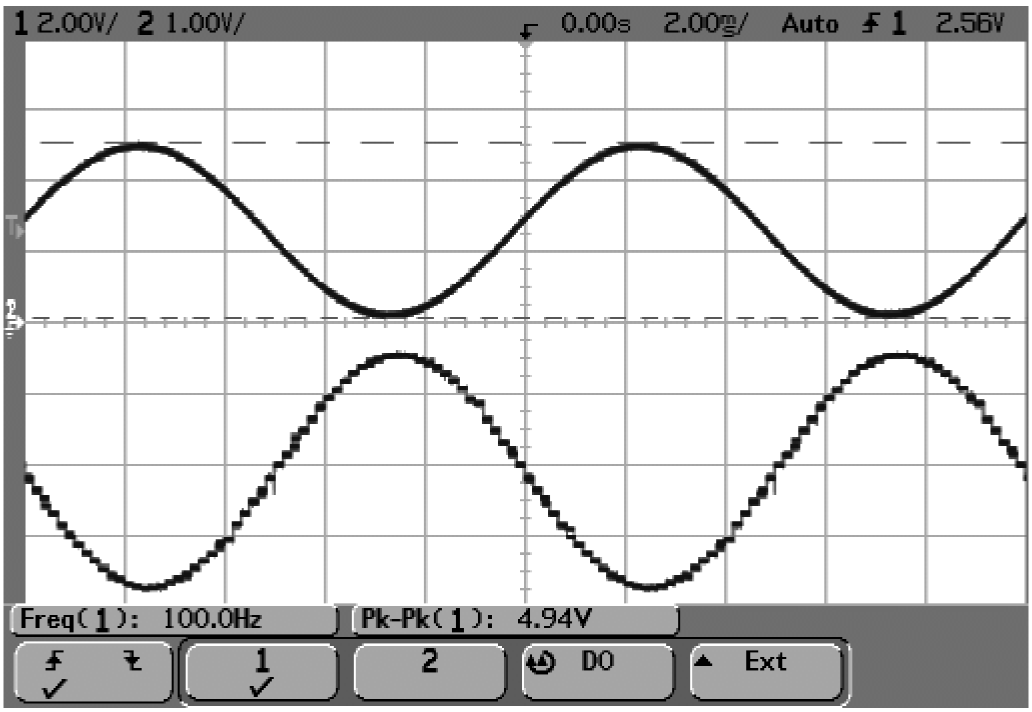
3. Turn on power. Using two 10X probes, connect Channel 1 to the input to the ADC, and Channel 2 to the output of the DAC. The display should look similar to the one below. Notice that Vin and Vout are 180° out of phase.



The input sinewave (top trace) is at 20 Hz., and is the input signal to the ADC.

The bottom trace is the output from the DAC. While it's hard to see, it is made up of 255 steps of voltage.

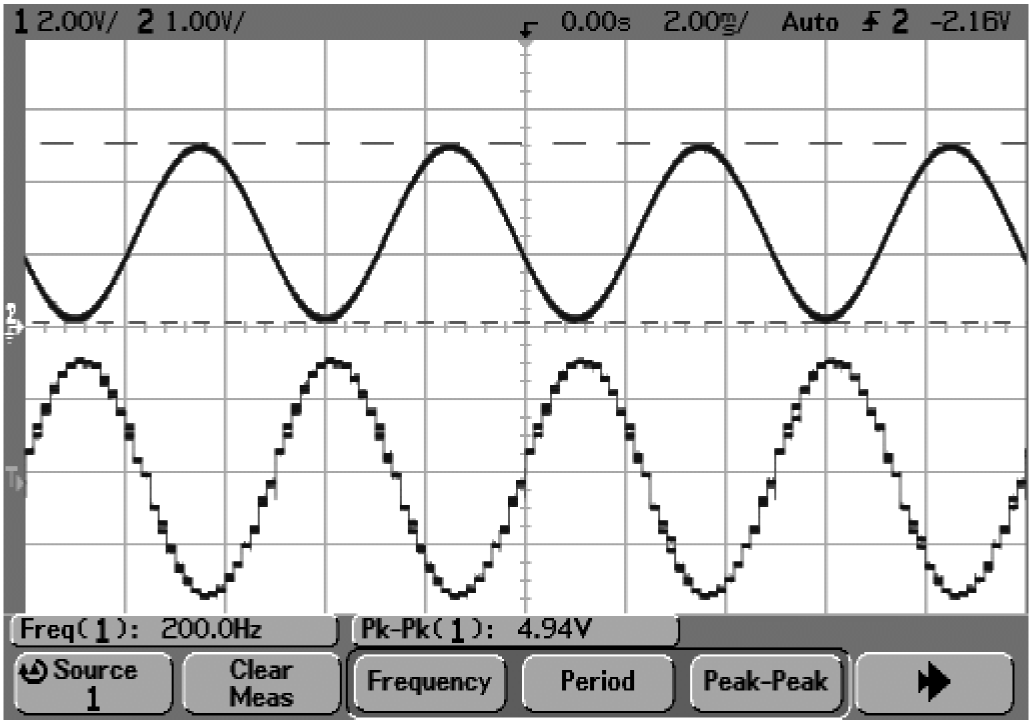
4. Now increase the frequency of the function generator to 100 Hz. The output (shown below) now doesn't look like a clean sine wave; clearly it is a step approximation to a sine wave.



The input sinewave (top trace) is at 100 Hz., and is the input signal to the ADC.

The bottom trace is the output from the DAC. It is easier to see, at this frequency, that the output waveform is made up of steps of voltage (and far fewer than 255 steps - Why?).

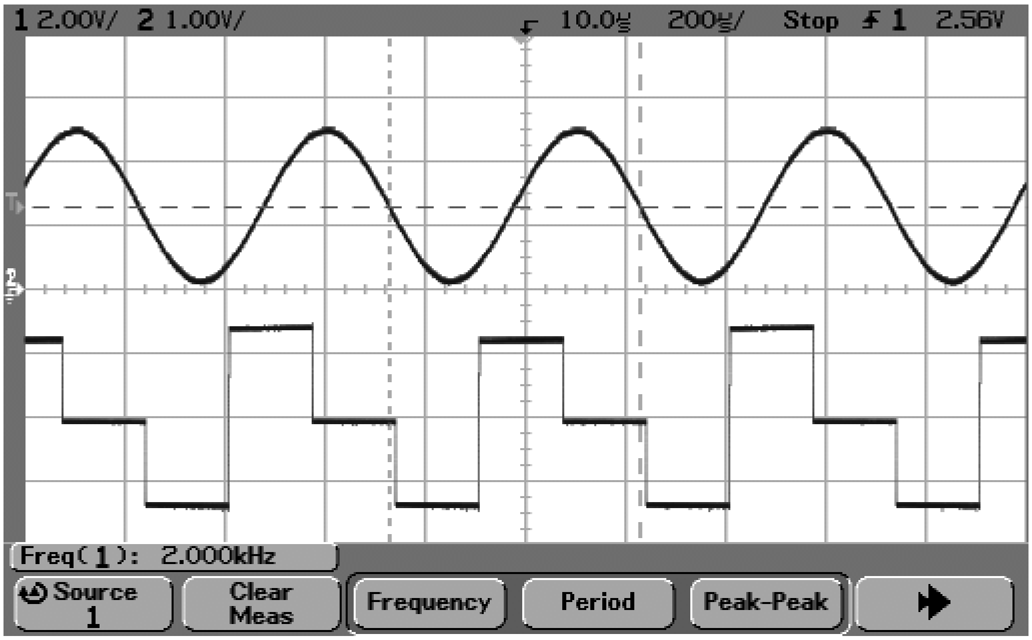
5. Now increase the frequency of the function generator to 200 Hz. The output (shown below) now doesn't look like a clean sine wave; clearly it is a step approximation to a sine wave.



The input sinewave (top trace) is at 200 Hz., and is the input signal to the ADC.

The bottom trace is the output from the DAC. It is easier to see, at this frequency, that the output waveform is made up of steps of voltage, some of them quite large. Recall that the resolution of our DAC is 16.1 mV; some of the steps above are over 200 mV!

6. Now increase the frequency of the function generator to 2,000 Hz. The output (shown below) now doesn't look like a clean sine wave; clearly it is a 2-step 3-level approximation to a sine wave.



The input sinewave (top trace) is at 2,000 Hz., and is the input signal to the ADC.

The bottom trace is the output from the DAC. At this frequency the output waveform is made up of **TWO** steps of voltage, and three levels. The width of each step is the conversion time of the ADC0804 analog-to-digital converter (about 166 µs).

Procedure Three - Looking at the Bits of an ADC/ DAC System with A Sinusoidal Input:

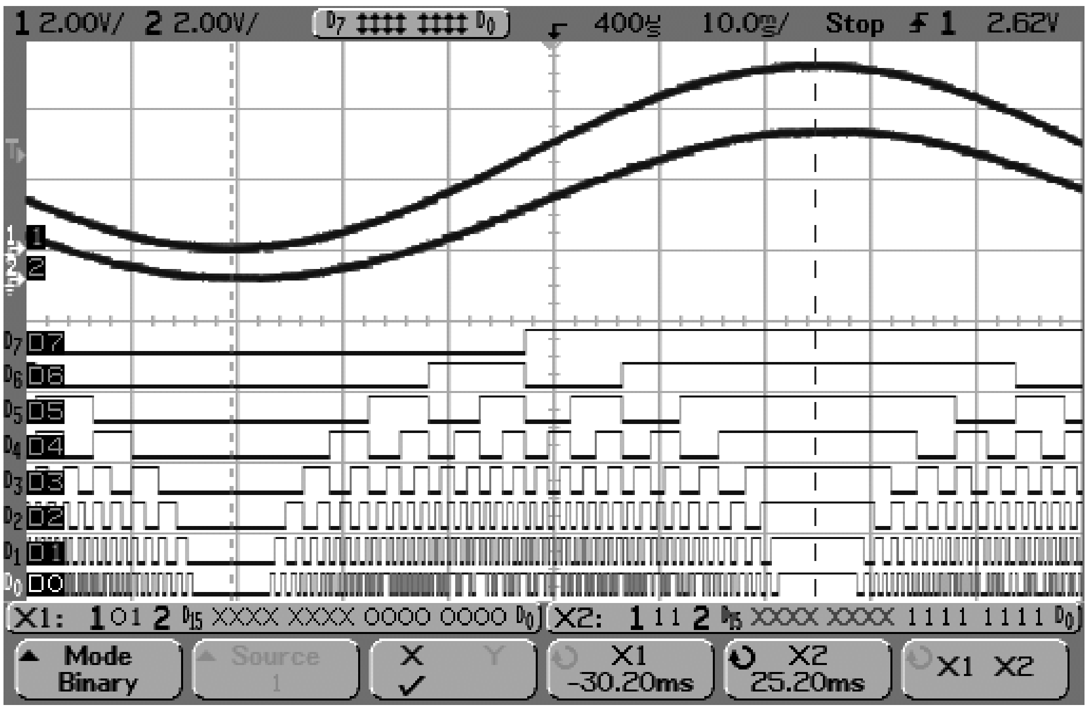
1. Set the frequency of the function generator to 9 Hz, and then disconnect the function generator from the ADC circuit. Turn off the power supply. Connect one half of the 16-bit digital input harness, using the 8 bits labeled D0 – D7, to the digital outputs of the ADC. Make sure D0 (the LSB) is connected to pin 18 (the LSB output of the ADC). Use short pieces of bare wire in the breadboard slots, and be sure that the digital harness connectors don't touch each other or cause short circuits on the data bus.

2. Turn on the D0 - D7 inputs of the MSO, using the hardkey on the front panel.

3. Invert Channel 2 (simply for convenience, so that it appears in phase with Channel 1).

4. Turn on the power supply, then reconnect the function generator to the ADC input.

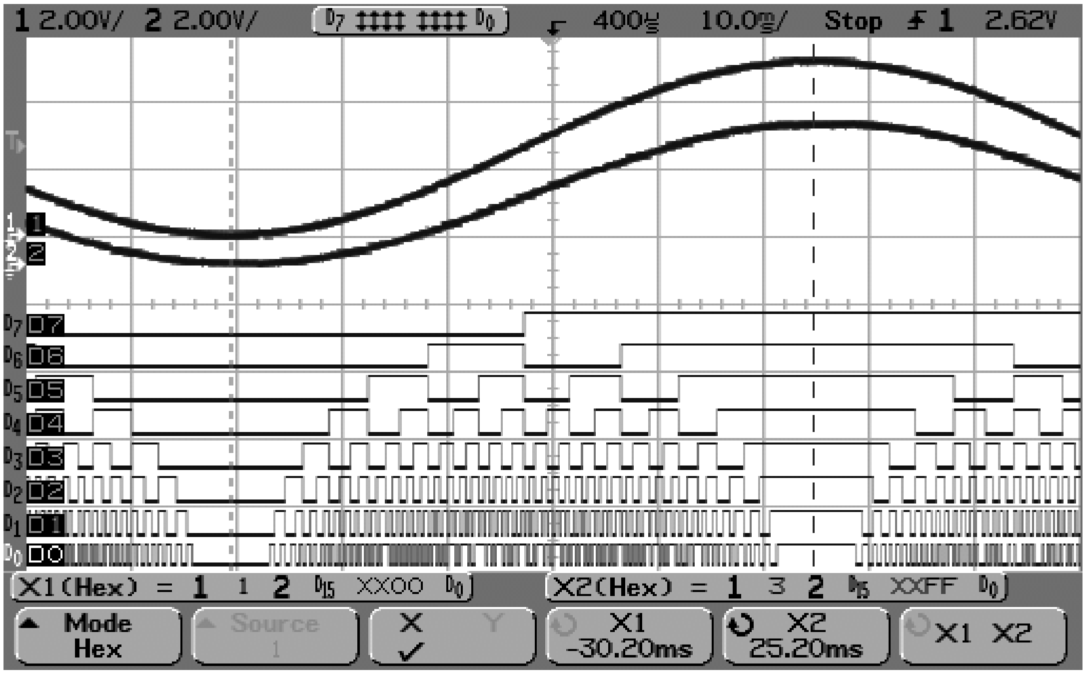
5. Your display should look like the those on the next page. Note that cursors are turned on, and either **Binary** mode or **Hex** mode (hexadecimal) can be used. The 8-bit digital output can be seen to go from 0000 0000 to 1111 1111 (in binary), or 00 to FF (in hexadecimal).



Input sinewave at 9 Hz. Digital display shows D0 - D7. **Cursor mode is *BINARY.***
Even though only 8 bits (D0 - D7) have signal, D8 – D15 are shown as X (don't care).

At the minimum of the sinewave, digital value is XXXX XXXX 0000 0000_2 = $XX00_H$

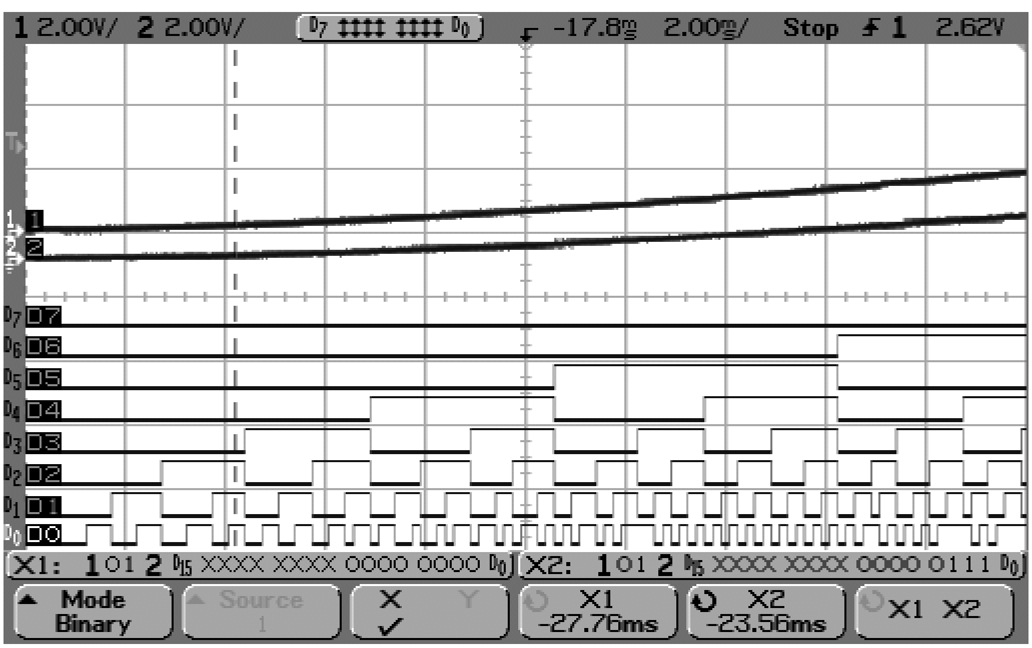
At the maximum of the sinewave, digital value is XXXX XXXX 1111 1111_2 = $XXFF_H$



Input sinewave at 9 Hz. Digital display shows 8 bits: D0 - D7. **Cursor mode is *Hex.***

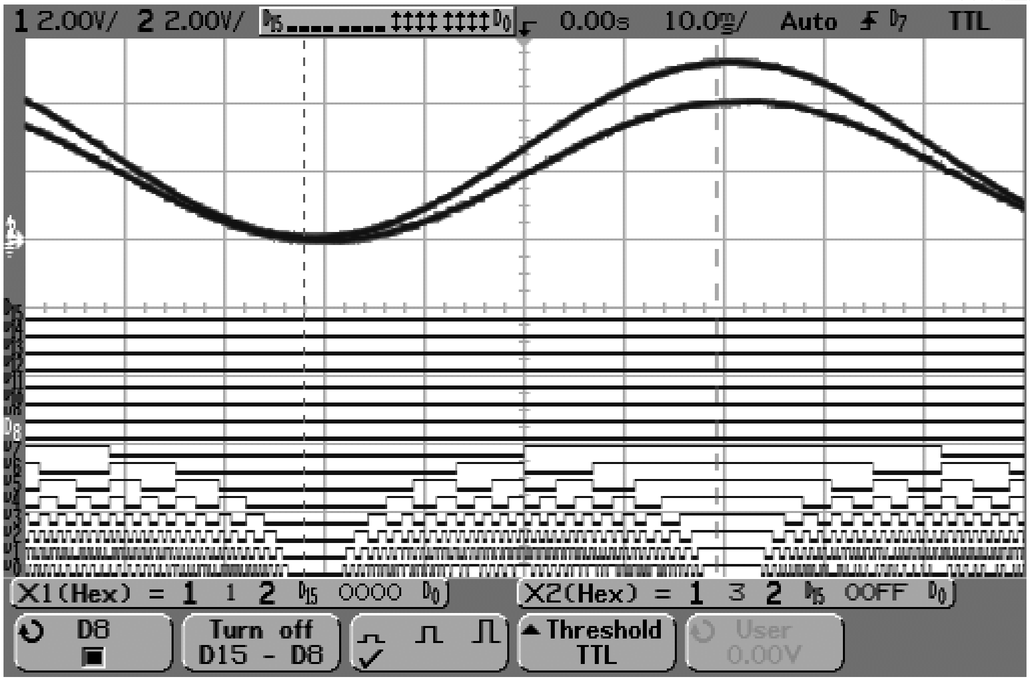
At the minimum of the sinewave, digital value is $0000\ 0000_2$ = $XX00_H$ (the X meaning D8-D15 are not used, X = don't care)

At the maximum of the sinewave, digital value is $1111\ 1111_2$ = $XXFF_H$



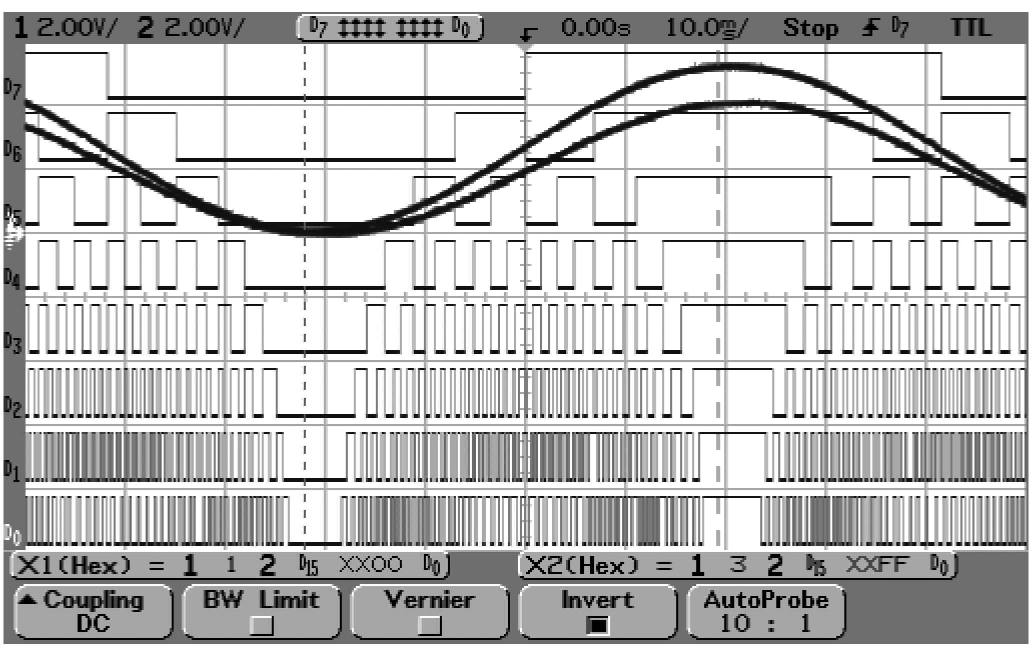
Input sinewave at 12 Hz. Digital display shows D0 - D7.

Time base is changed to show 8-bit digital output from ADC changing upward, with cursors showing $0000\ 0000_2$ (X1 cursor) to $0000\ 0111_2$ (X2 cursor).



Input sinewave at 12 Hz. Digital display shows D0 - D7 and D8-D15 at minimum height. The bottom half of the display shows all 16 digital inputs; even though only 8 bits (D0 - D7) have signal, D8-D15 are turned on and are low (logic 0).

At the minimum of the sinewave, digital value is $0000\ 0000\ 0000\ 0000_2 = 0000_H$
At the maximum of the sinewave, digital value is $0000\ 0000\ 1111\ 1111_2 = 00FF_H$



Input sinewave at 12 Hz. Digital display shows D0 - D7 at maximum height, filling the entire display and overlapping the analog display of Channel 1 and Channel 2.
At the minimum of the sinewave, digital value is $0000\ 0000_2 = XX00_H$ (the X meaning D8-D15 are not used, X = don't care)
At the maximum of the sinewave, digital value is $1111\ 1111_2 = XXFF_H$

Supplemental Information and Ideas for Additional Experimentation

A) Filled in table from page 5. These are actual measured values from doing the experiment, and may be used as a reference when this experiment is performed by you. Your values will be different, but should not differ much from those below.

MSB LED	LED	LED	LED	LED	LED	LED	LSB LED	Vin (V) to the ADC	Vout (V) from the DAC
Off	Off	Off	Off	Off	Off	Off	Off	5.16	-4.17
Off	ON	ON	ON	ON	ON	ON	ON	2.57	-2.09
ON	Off	ON	ON	ON	ON	ON	ON	1.286	-1.048
ON	ON	Off	ON	ON	ON	ON	ON	0.644	-0.524
ON	ON	ON	Off	ON	ON	ON	ON	0.327	-0.262
ON	ON	ON	ON	Off	ON	ON	ON	0.158	-0.1309
ON	ON	ON	ON	ON	Off	ON	ON	0.084	-0.0655
ON	ON	ON	ON	ON	ON	Off	ON	0.0437	-0.0325
ON	ON	ON	ON	ON	ON	ON	Off	0.0221	-0.0165
ON	ON	ON	ON	ON	ON	ON	ON	0.000	0.000

B) To add a new dimension to this experiment, connect an audio amplifier with speaker to the output of the DAC. **Be sure to use a coupling capacitor (220µF), with the *negative* side connected to pin 4 (the output) of the DAC.** Listen to the audio as the input frequency is raised, and notice the appearance of the “alias” frequency as the input frequency approaches 50% of the conversion frequency.

C) Use the Channel Math feature to perform an FFT on analog Channel 1, and on Channel 2, to see the distortion created by the digitizing of the signal.

D) Use the Channel Math feature to perform an FFT on analog Channel 1, and on Channel 2, to see appearance of the alias frequency as the input frequency approaches 50% of the conversion frequency.