Introduction
This lab deals with simple resistive circuits to perform Digital-to-Analog (D/A) conversion. We also introduce the use of a basic Analog-to-Digital (A/D) converter.

The D/A Converter
Preliminary Definitions

Analog signal: May assume a continuous range of values for both time and amplitude. Most “real world” signals are analog. Examples include: Audio emanating from a loudspeaker and photographs taken with a film exposure camera.

Digital signal: Is characterized by discrete, uniform time steps and is quantized to discrete values in amplitude. Typically, an analog signal is sampled and quantized to create a digital signal. Examples include: Information stored on a Compact Disc and computer images.

Binary representations: Digital information is encoded into binary symbols before it can be processed and stored in computers and other digital electronic devices. These symbols consist of a series of 0’s and 1’s (bits) representing binary low and high (or off and on) respectively. Binary numbers are used in computers and other electronic devices because electronic “switches” (commonly transistors) can be easily used to produce the binary on/off states. Common base 10 or decimal numbers, such as voltage magnitudes for instance, are represented by one of the 10 digits (0-9) separated by placeholders in powers of 10. These numbers can also be represented in binary, using only 2 digits (0-1), by using placeholders in powers of two.

Example: 1932 decimal and binary representations

Decimal (base 10) = 1932 >>
(1x10^3)+(9x10^2)+(3x10^1)+(2x10^0) =1932

Binary (base 2) = 11110001100 >>
(1x2^10)+(1x2^9)+(1x2^8)+(0x2^7)+(0x2^6)+(0x2^5)+(1x2^4)+(1x2^3)+(0x2^2)+(0x2^1)+(0x2^0) =1932

In binary, the digit to the left is called the most significant bit (MSB) because it represents the largest placeholder. The digit to the right is called the least significant bit (LSB) because it represents the smallest placeholder. It can be seen that more bits are needed in the binary representation, as the values grow larger.

Digital-to-analog (D/A) converters: A device used in many control and signal-processing applications for converting digital information (binary) used in electronic devices into usable “real world” analog information. For example, CD players use D/A converters to convert digital audio information that is read from the CD into an analog audio signal. Typically, the inputs to the D/A converter are digital logic signals, 0V and 5V for binary “low” and “high” respectively.
3-bit D/A Conversion Example

**Sampler** – Samples the continuous-time analog signal at uniform time instants $T$, creating a discrete-time signal with continuous amplitude.

**Quantizer/Mapper** – Assigns the samples of the discrete-time signal a binary value based on the desired number of levels, creating a digital signal that is both discrete in time and amplitude.

**Digital signal Processing (DSP) or Memory** – Manipulates or stores the digital signal. The signal is not altered by this block in the example.

**D/A Converter** – Converts the digital signal back into an analog signal that is both continuous in time and amplitude. The resulting signal in the example is an approximation of the original analog input signal $f(t)$.
**Part 1: 4-bit Ladder Resistive Summing Network**

In this exercise, a digital (binary) output will be converted to an equivalent analog voltage using a 4-bit R–R/2 D/A converter shown in Figure 1. For a 4-bit digital input, the analog output should have $2^4$ or 16 possible values since there are 16 combinations of digital input voltages. Each of the 16 combinations is shown in Table 1. Therefore, the analog output will not be smooth, but instead will be discretized into 16 steps. The discretization can be reduced by increasing the number of binary input bits, since the number of discrete steps goes as $2^n$, where $n$ is the number of bits.

Basic circuit theory (nodal analysis) can be used to analyze the circuit. However, the Superposition Theorem simplifies the circuit analysis. To use superposition, an input signal (+5 V) is applied to only one input at a time with all of the other inputs at 0 V (ground). The output voltage resulting from each input combination is determined and is labeled $V_{out,A}$, $V_{out,B}$, $V_{out,C}$, and $V_{out,D}$. To find the total output voltage, the output voltage due to each of the input combinations are added. For example, for this 4-bit R–R/2 D/A converter, the total output voltage $V_{out,total}$ is given by:

$$V_{out,total} = V_{out,A} + V_{out,B} + V_{out,C} + V_{out,D}.$$  

This procedure can also be used to determine a general expression for $V_{out,total}$ in terms of the input voltages $V_A$, $V_B$, $V_C$, and $V_D$. In this case, the total output voltage $V_{out,total}$ is given by:

$$V_{out,total} = (V_A + 2V_B + 4V_C + 8V_D) / 2^4$$

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Binary DCBA</th>
<th>Measured Analog Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0000</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0001</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0010</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0011</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0100</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0101</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0110</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0111</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1001</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1010</td>
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</tr>
<tr>
<td>11</td>
<td>1011</td>
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<td>12</td>
<td>1100</td>
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<tr>
<td>13</td>
<td>1101</td>
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</tr>
<tr>
<td>14</td>
<td>1110</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1111</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Analog equivalent of four-bit, digital number.
**Part 1: Procedure**

1. Build the 4-bit R–R/2 D/A converter shown in Figure 3. Let $R = 30 \, \text{k}\Omega$ — *choose resistors with the same tolerances for consistency*. Place the LSB towards the top of the breadboard for expansion capability.

2. Changing the binary inputs, complete Table 1 measuring the open-circuit output voltage relative to ground of the D/A converter.  
*Note: 0V indicates that the input must be grounded.*

3. Insert a 30 k\(\Omega\) load resistor. Measure the output voltage of the D/A converter using the DMM for at least 3 of the input combinations from step 2. Repeat the measurements using a 1 k\(\Omega\) resistor.  
Comment on the similarities and differences between the output voltage with no load and with each one of the loads.
Part 2: Using time varying input to the D/A Converter

In this exercise, an analog-to-digital converter integrated circuit (ADC0804LCN) is used to generate digital data from the waveform generator. This data is used as the input to the R–R/2 D/A converter. Here, rather than considering only one input combination at a time, the digital input waveforms vary as function of time leading to time varying analog output waveforms. The computer outputs 8-bits, therefore, for this part of the lab the four most significant bits should be used as inputs to the D/A converter.

Part 2: Procedure

1. Disconnect the input voltages and the load resistor from your 4-bit D/A converter.
2. Insert the ADC0804LCN A/D converter chip into the breadboard, straddling the gap meant for dual-in-line (DIP) integrated circuit chips.
3. Referring to Figure 4, ground the appropriate pins as shown, creating a wire switch for pins 3 & 5. Using the DC power supply, connect +5V to pin 20. Connect the four most significant bits from the ADC0804LCN A/D converter to the input of the R–R/2 D/A converter.
4. Configure the digital waveform generator for a 5Vp-p 20Hz sinusoid with a DC offset of 2.5V. Connect the OUTPUT terminal of the waveform generator to pin 6 of the A/D converter– this is the waveform that will be converted to an 8-bit digital signal. Make sure that there the waveform does not have negative voltages.
5. Configure another waveform generator (analog) for a pulse output of 500 kHz. Connect the TTL output to pin 4 of the A/D converter – this produces the 0-5V square-wave clock signal.

Figure 4. ADC0804LCN A/D converter connection diagram
6. Using the wire switch, simultaneously disconnect pins 3 & 5 of the A/D converter from ground - this activates the A/D conversion. Note.- The conversion starts when the A/D converter notices a change of voltage in pins 3 and 5. For this reason, it is necessary to have the pins grounded first and then disconnected.

7. Using the oscilloscope, simultaneously monitor the sinusoidal output of the waveform generator and the output of the D/A converter. Make a sketch of these waveforms including Vp-p measurements. Determine the number of discrete voltage steps that are displayed between the minimum and the maximum voltage.

Part 3: 8-bit Ladder Resistive Summing Network

In this exercise, four bits are added to the D/A converter to determine the effect of the number of digital output bits on the analog output waveform.

Part 3: Procedure

1. Disconnect the load resistor from the 4-bit R–R/2 D/A converter.

2. Add the resistors required to make an 8-bit D/A converter and connect the eight MSBs of the A/D converter chip output to the input of the R–R/2 D/A converter chip.

3. Activate the A/D conversion as in Part 2.

4. Using the oscilloscope, simultaneously monitor the sinusoidal waveform generator output and open-circuit output voltage of the D/A converter. Make a sketch of these waveforms including Vp-p measurements. Determine the number of discrete voltage steps that are displayed between the minimum and the maximum voltage.
Discussion Questions

Discuss and thoroughly explain each of numbered the concepts below, listed by exercise. When applicable, consider the following items when formulating your responses:

- A comparison of theoretical and experimental results.
- An identification and description of the likely sources of error.
- A description of the purpose and function of each circuit and possible applications.
- A comparison of similar circuits in the lab and the respective functions.
- A discussion of relevant observations, results, and deductions.

Part 1

1. Comment on the pattern of voltages determined in the pre-lab exercise from Table 1.
2. Discuss the purpose of binary representations and the respective effects of the MSB and LSB on the output of the D/A converter.

Part 2

3. Describe the time-varying input to the resistive ladder network, considering the form of the output. What does each input bit’s signal look like and how do they differ?
4. Explain the loading effect and why it is a concern, commenting on the time-varying results from both load resistor combinations.
5. State significance of a load resistor and what it represents in the real world. Give an example of a device that can be modeled using a load resistor other than the one given in the appendix.

Part 3

6. Discuss the effect on the output of adding more bits to a D/A converter.
7. Compare the theoretical values of Vmin and Vmax for the 4-bit and 8-bit converters and explain how and why they differ.