Digital-to-Analog and Analog-to-Digital Conversion

<table>
<thead>
<tr>
<th>Laboratory Goal:</th>
<th>Build D-to-A and A-to-D circuits and demonstrate their operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning Objectives:</td>
<td>A/D and D/A conversion principles, applications of op-amp circuits, mixed signal applications</td>
</tr>
<tr>
<td>Suggested Tools:</td>
<td>Oscilloscope, op-amp summing amplifier, op-amp comparator, digital counter</td>
</tr>
</tbody>
</table>

The prelab is due at the beginning of the lab. For level 2, complete level 1 first because you will use the level 1 circuit in level 2.

**Level 1: Digital-to-Analog Converter:**

Design and construct a 4-bit binary-weighted digital-to-analog (D/A) converter. Demonstrate a properly functioning D/A converter to your TAs. It isn’t required, but if you really want to impress them, use a microcontroller instead of switches for the binary inputs. The microcontroller will replace the $V_{REF}$ and the four switches with four digital outputs. If you use a microcontroller, the $V_{REF}$ sent to the D/A converter will be the supply voltage of the controller. **Hint:** If you use the MSP430, the sample code from [github.com/ekzosuls](http://github.com/ekzosuls) will provide with the proper counting scheme, so you won’t have to get into writing code.

One of the simplest methods of converting from the digital to the analog domain is by using an Op-Amp summer circuit with appropriately weighted input resistors (Figure 1).

![Image of a 4-bit D/A converter circuit](image)

**Figure 1:** OP AMP summer four-bit D/A converter circuit. $V_{CC^+}$ and $V_{CC^-}$ should be larger in magnitude than $V_{REF}$. Switch Bit 0 is the least significant bit (LSB). Switch Bit3 is the most significant bit (MSB). Pin 6 of the OP AMP is the output of the D/A converter. The +/− VCC power supplies only powers the OP AMP. The $V_{REF}$ only provides signal to the input of the summer.

The D/A converter functions by using different gains for each input of the summer. If the same voltage is applied to each of the summer inputs, then each input will add a different component to the total output voltage. By selecting appropriate values for each of the summer input resistors, the gains or weights of each input can be set. In Figure 1, the values for the input resistors are set to give increasing binary weight to each input. The Bit 0 input is connected to...
the $8R$ (or 8 times $R$ value) resistor which sets a gain of $1/8$ for that input. This is the smallest gain and therefore has the least significant impact on the output. The Bit 3 input has an input resistor of $R$, therefore its gain is 1, this input has the most significant effect on the output and is called the most significant bit (MSB). All four switches are connected to a voltage source called $V_{\text{REF}}$. The value of $V_{\text{REF}}$ determines the magnitude of the output voltage from the D/A converter. Recall that the summer is an inverting circuit. Therefore the sign of the output polarity will be opposite that of $V_{\text{REF}}$. Also note that if $V_{\text{REF}}$ is too large in magnitude, it is possible to saturate the output of the converter. This is most likely to happen if all the inputs are in the on state and the resistor values set the gain too high.

Usually the input to the D/A converter is provided by digital outputs (figure 2), not mechanical switches or wires plugged into a breadboard. A digital output can be thought of as a positive or negative going step function. The step transitions from zero to $V_{\text{CC}}$ of the digital logic.

![D/A converter diagram](image)

Figure 2: D/A converter with a microcontroller ($\mu$C) providing the inputs. On many microcontroller eval boards such as the MSP430, the $\mu$C $V_{\text{CC}}$ power is provided over USB and you do not have to connect a power supply to the microcontroller. In this case it is important to know what the Voltage is so you can properly set the resistor values.

**Prelab**

You pulled all the stuffing out of your younger sibling’s teddy bear and are installing a microcontroller, D/A converter, amplifier, and speaker inside it so you can program it to speak to her.

You decided to make a four bit D/A converter so it will sound retro robotic. (As opposed to a high-bit converter that would sound more natural) You have a power supply module that can provide $+15\text{ V}$ and $-15\text{ V}$. You know that the output pin of the 741 op amps you are using can only accurately get within approximately 3 Volts of the power supplies before they start to saturate. The microcontroller you are interfacing to your D/A converter has output pins that transition from 0 V to 5 V.

Design a D/A converter similar to the one in Figure 2 that will provide good dynamic range but not saturate the output of the D/A converter.

Dynamic range can be defined as the ratio of the largest to the smallest signal that you can generate at the output of the converter. Since we know the maximum amplitude that the OP amp can output is three Volts in magnitude less than the supply Voltages, we want to set the
maximum output Voltage of the converter to slightly less than ±12 Volts. For this circuit the minimum signal size is specified by the number of bits.

**Level 2 Binary-Weighted Analog-to-Digital Converter**

Design and demonstrate a 4-bit A-to-D converter.

One common method for designing an A/D converter is to combine a D/A converter with a comparator and a counter that applies binary input digits to the D/A. The arrangement is shown below. The counter begins at binary 0000...0, then counts upward toward its highest value 1111...1. The upward counting increases the D-/A output upward from zero. When the latter reaches the analog input $v_A$, the comparator “flips” state and freezes the counter. The counter output then constitutes the binary word representing $v_A$.

You can use a microcontroller as a counter to count up the D/A converter. Feed the comparator output into the microcontroller. The microcontroller program checks the comparator state each increment of the counter. Once the comparator goes low then the count stops. LEDs can be connected to the outputs of the binary counter to indicate the final value read in binary. Be sure to limit the LED current to less than 3mA to prevent loading of the microcontroller counter pins. This is important because if the LEDs load the pins then the output of the microcontroller will not reach VCC and it will produce large error in the DA converter output Voltage.
**Background**

Let’s face it – the world we humans encounter is an analog playground, but nowadays, nearly all signal processing related to that world is performed digitally. Prior to the digital age, physical variables were measured in analog and were subsequently processed in analog too. Today, physical variables are still measured in analog form, and the resulting signals are immediately converted to digital form for processing, transmission, or storage on computers and digital devices. Compare, for example, the two diagrams shown below which illustrate how music was recorded in 1990 versus how it is recorded today. In each figure, analog signals are carried by red lines; digital signals by blue lines.

**Recording and Listening to Music in 1990:**

![Diagram of music recording in 1990]

**Recording and Listening to Music in 2013:**

![Diagram of music recording in 2013]

Most other sensing and signal processing jobs that used to be fully analog are now completely digital: the thermometer, speedometer, odometer, music, television, video, and movie projection.

Interfacing between nature’s analog world and human-made digital systems requires a special class of circuits. Two important members of the interface family are the analog-to-digital (A/D)
converter, and the digital-to-analog (D/A) converter. The diagrams shown below illustrate these conversion concepts in block form. In this laboratory assignment, you will build and otherwise become acquainted with each type of circuit.

### Representing Analog Voltages in Digital Form

Let’s assume that the physical variable serving as the object of our attention has been converted to a voltage by a sensor or transducer. (For example, a microphone converts sound waves into a varying voltage signal.) When an analog voltage $v_A$ is converted to its equivalent digital representation, it’s all done with respect to some user-defined reference voltage $V_{REF}$. The ratio $v_A/V_{REF}$ determines the binary number value that will represent $v_A$. For this to happen, the voltage range between 0 and $V_{REF}$ (or $-V_{REF}$ to $V_{REF}$ in some systems) is divided into discrete voltage levels, where the latter are separated by the same small increment, called the converter’s **voltage resolution**. The analog voltage $v_A$ is assigned to the discrete voltage level lying closest to it in value. The concept is illustrated to the right for the very simplified case of a reference voltage of 5-V divided into 12 levels.

As noted above, the voltage increment separating the discrete levels is called the converter’s **voltage resolution** (equal 0.416 V in the above example). The resolution determines the granularity, or fineness, with which $v_A$ can be discerned by the converter.

In the above example demonstrates 12 discretization levels. In a more practical converter, the number will be at least 256 (for an 8-bit converter) and may be as high as 65,536 (for a state-of-the-art 16-bit converter.)
For a more realistic example, let’s look at an 8-bit converter with a reference voltage $V_{REF} = 10$ V. Eight bits of ones and zeros (1 and 0) yields 256 possible numbers from [0000 0000] to [1111 1111], i.e., from 0 to the base-10 number 255. The ratio $v_A/V_{REF}$ determines which of the 255 levels, and hence which binary value, will be chosen to represent $v_A$. For example, if $v_A = V_{REF}/2$, the binary value of 128 is chosen (about half of 255). Similarly, if $v_A = V_{REF}/4$, a binary value of 64 is chosen (about one quarter of 255). If $v_A = V_{REF}$, then the assigned value would be 256, but that would require a ninth carry bit [1 0000 0000]. From this example, we see that an A/D converter can represent inputs almost up to $V_{REF}$, i.e., just one discretization level below.

The formulas pertinent to A/D and D/A conversion describes the relationship between analog voltages and their binary representations:

$$n = (2^N - 1) \frac{v_A}{V_{REF}}$$

and

$$v_A = \frac{n}{2^N - 1}V_{REF}$$

Here $N$ is the maximum binary value possible (256 in the above example), and $n$ is the decimal (base-10) equivalent of the binary representation of $v_A$. Here $V_{REF}$ is, again, a reference voltage.

**Analog-to-Digital Bin Converter**

A bin converter is one in which the output consists of a simple linear row of digits, rather than a base-2 number. Its bits are set to 1 in linear sequence as $v_A$ is increased. Bin converters are used, for example, in LED-based bar graphs. In the latter, the illuminated length of a row of lights indicates the relative magnitude of $v_A$. The bin converter determines the level to which the input should be assigned, as in Figure 1 above.

An op-amp connected as an open-loop voltage comparator is useful in designing a bin converter. In a comparator, the feedback path is absent. Recall that an op-amp will saturate with $v_{OUT} = V_{POS}$ when $v_+ > v$. Similarly, $v_{OUT} = V_{NEG}$ if $v_+ < v$. In the circuit shown to the right, the input $v_A$ is compared to $V_{REF}$. The op-amp output will be $V_{POS}$ when $v_A > V_{REF}$. Conversely, the output will be $V_{NEG}$ if $v_A < V_{REF}$. 

**FIGURE 2**

**FIGURE 3**