EXPERIMENT 10 - Prelab

Digital to Analog Conversion (DAC)

Introduction

In this lab you will build an op-amp circuit to convert digital numbers to analog voltages. This circuit is called a digital-to-analog converter, or DAC. This circuit will be used again in Experiment 11 as the core of an analog to digital converter (ADC).

Experiment Objectives:

- Learn the principles of digital to analog and analog-to-digital converters (DAC's and ADC's),
- Learn to build and use a digital to analog converter (DAC),
- Continue to build experience with the laboratory equipment and components, including the Bit Bucket digital breadboarding system, Analog Trainer, op-amps, and digital logic IC's,
- Develop professional communication skills.

Bring to Lab:

Your completed Pre-Lab. Turn this in when you get to lab.

Theory: Analog and Digital Electronic Representations of Numbers

Numbers can be represented electronically in digital form or analog form. For example, the decimal number "one hundred" can be represented in the various digital forms shown in Table 1.

Table 1. Digital representations of the decimal number one hundred.

Base or Format	Digital Representation
Decimal (base 10)	100
Binary (base 2)	110 0100
Hex (base 16)	64
Roman numerals	C

Of all the possible representations shown in Table 1, the only one of interest in this experiment is the binary format, since we can handle this with digital logic circuits, in which a 1 corresponds to a high voltage, and a 0 corresponds to a low voltage (or vice-versa, if we choose).

An alternative way to represent numbers electronically is to use the size of a voltage or current, scaled as appropriate. For example, the number one hundred could be represented by a 100 mV voltage or a 100 mA current. This is called *analog* representation.

Discrete versus Continuous

Digital representation produces *discrete* values. The word "discrete" means there are only certain allowed values that can be represented. For example, Table 2 shows the discrete values that can be represented by 2 binary bits and by 3 binary bits. The more bits, the higher the *resolution*. The word resolution is commonly used in two ways- in one usage it means the number of bits of encoding, but it is also used to mean the voltage difference between discrete steps. For example, for the 3-bit encoding in Table 2, we could say our system has "3-bit resolution," or we could say "the resolution is 0.125 Volts." The latter usage is also called the least-significant bit, or LSB. For example, for the 2-bit encoding, we could say "the LSB corresponds to 0.25 Volts."

Table 2. List of the discrete values of voltage that can be represented by 2 binary bits and by 3 binary bits. The full-scale output is 1.00 Volt in each case.

2-bit encoding. Resolution = 0.25		3-bit encoding. Resolution = 0.125	
Binary Code	Voltage	Binary Code	Voltage
00	0.00	000	0.000
		001	0.125
01	0.25	010	0.250
		011	0.375
10	0.50	100	0.500
		101	0.625
11	0.75	110	0.750
		111	0.875

Notice that the voltage in the table never reaches the full-scale value of 1.00; the maximum is always one LSB below full-scale. We can also see that the resolution (or LSB) is determined by the number of bits. Equation 1 gives the exact relationship:

$$R = LSB = V_{FS}\left(2^{-N}\right) \qquad (1)$$

where R is the resolution in volts, N is the number of bits, and V_{FS} is the full-scale voltage.

Analog representation is *continuous*, which simply means that all values are allowed. However, in practical circuits the resolution is not zero- it is the smallest change of voltage that can be reliably detected, which depends on the amount of electronic noise that is present and on the precision of the various components.

A comparison of analog and digital representation is given in Table 3. Early computers used analog representation, and performed all calculations without converting to digital. The computers were called analog computers, and the circuits they used for performing arithmetic operations were called operational amplifiers, or op-amps. These same op-amp circuits were refined over the years and are the ones we now use for many applications such as amplification, buffering, and filtering, and digital-to-analog conversion.

DAC's and ADC's

Digital-to-analog converters (DAC’s) are circuits that have an N-bit digital value as input, and generate the corresponding analog voltage (or current) as output. They are most often used to convert computer-generated data into real-world signals such as sound and images.

Analog–to-digital converters (ADC’s) perform the opposite function- they convert an analog input voltage to a digital format. ADC’s are most often used to convert real-world signals into binary form for processing or storage by a computer system.

In this experiment we will build and test a 4-bit DAC. In Experiment 11 we will build and test a 4-bit ADC.

Table 3. Comparison of Analog and Digital Representations.

Analog	Digital
Characteristics • Uses the actual value of a voltage or current to represent numbers. • Continuous representation	**Characteristics** • Uses digital form (usually binary) to represent numbers. • Discrete representation
Advantages • Any value can be represented. • No conversion is required if signals are already in analog form. • Analog calculation circuits can sometimes model real-world systems faster than digital circuits	**Advantages** • Resolution can be made as high as desired by increasing the number of bits. • Resistant to noise - can be copied and transferred without losing information. • Modern computers and microprocessors are designed to process digital information. • Digitally-encoded values can be stored indefinitely (e.g., on CD, magnetics, etc.)
Disadvantages • Analog signals are easily corrupted by noise; there is always loss of precision when copying or transferring values. • High-precision circuits for processing analog signals are expensive to design and build. • It is difficult to store analog voltages for long periods of time.	**Disadvantages** • Only "allowed" values can be represented. • Real-world signals (such as sensor readings, microphones, etc.) must be converted to digital format before being processed, which takes time. • Digital calculations can be slower than analog.

THEORY: The R-2R Ladder DAC

The DAC we will build in this experiment is based on an op-amp circuit called the R-2R ladder. This is an extremely clever circuit invented during the 1950's. It was considered unique enough to earn a patent, which is quite unusual for a circuit design. A 4-bit R-2R circuit is shown in Fig. 1. The resistance R can be any value, but it is usually chosen to be large to reduce the current required from the V_{FS} source.

In this circuit, the binary digital input is provided by the switches S_1 through S_4. Each input terminal is connected to either V_{FS} (logic 1) or to ground (logic 0). The most significant bit (MSB) is input B_4 provided by switch S_4. When all the input bits are 0, V_{OUT} = 0. By direct circuit analysis, one can calculate the change in output voltage contributed by each input. The results for our 4-bit circuit are shown in Table 4.

Table 4. Change in output voltage when each input is switched from logic 0 (ground) to logic 1 (V_{FS}).

Bit	**Output voltage change,** ΔV_{OUT}
B_4 (MSB)	$-\frac{1}{2}V_{FS}$
B_3	$-\frac{1}{4}V_{FS}$
B_2	$-\frac{1}{8}V_{FS}$
B_1	$-\frac{1}{16}V_{FS}$

The output voltage change is negative, because the op-amp is used in the inverting configuration. Using the principle of superposition, we can derive the analog output for any combination of input bits. The result is expressed in Equation 2:

$$V_{OUT} = -\left(Binary\ Value\right)\left(2^{-N}\right)V_{FS} \tag{2}$$

where *Binary Value* is the number represented by $B_4B_3B_2B_1$, and N is the number of bits.

Example 1.

A 4-bit R-2R DAC has V_{FS} = 5.0 V, and the input is 1011. Calculate the output voltage.
Answer: Using Eq. 2 with *Binary Value* = $1011_2 = 11_{10}$, N=4, and V_{FS} = 5.0 V yields

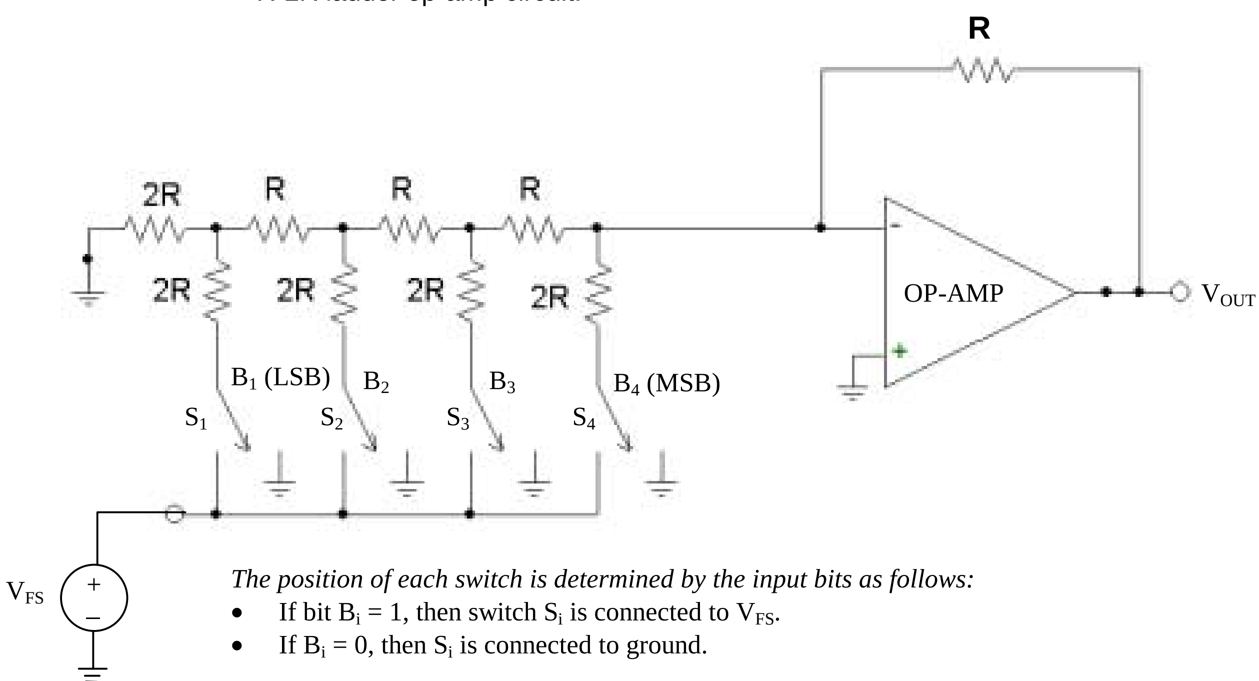
$$V_{OUT} = -(11)\left(2^{-4}\right)5.0 = -11\left(6.25\times10^{-2}\right)5.0 = -3.44\ \text{V}$$

Example 2.

A 10-bit R-2R DAC has V_{FS} = 10 V. What is the resolution?
Answer: We can use Eq. 2 with the binary value set equal to 1. Then

$$V_{OUT} = -(1)\left(2^{-10}\right)10 = -1\left(9.77\times10^{-4}\right)10 = -9.77\ \text{mV}$$

Figure 1. Four-bit digital-to-analog converter (DAC) using an R-2R ladder op-amp circuit.



The position of each switch is determined by the input bits as follows:

- If bit B_i = 1, then switch S_i is connected to V_{FS}.
- If B_i = 0, then S_i is connected to ground.

Your Name____

Prelab Questions (10 points)

Answer these questions before coming to lab and turn them in when you arrive. You may do your work on separate paper (for example you might want to do your work on a computer), but please attach your work to this sheet for submission.

1. Use Eq. 2 to calculate the values of ΔV_{OUT} in Table 4.

2. Calculate the output voltage of a 4-bit R-2R DAC if the input is 1010_2 and V_{FS} = 2.0 V.

3. High-end CD players use 20-bit DAC's with V_{FS} = 1.00 V. Calculate the smallest voltage change in the analog signal.

4. Sketch the layout of a 4-bit R-2R DAC using the 4558C op-amp. Show the pin connections to the chip, and all component values. Use R = 100 kΩ and V_{FS} = 5.0 V, and assume the op-amp power supplies are V_{CC} = +15 V and V_{EE} = -15 V. A pin-out diagram for the op-amp chip is shown in Fig. 2 on the next page.

Figure 2. Pin-out for the LM1458 dual operational amplifier. This is the same as the 4558C we use in our lab.