Study of Digital to Analog Converter (DAC) and Analog to Digital Converter (ADC) Circuits

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In the experiment, we studied the working of an ADC and DAC amplifier and constructed them using ICs and resistors. We found that the Analog output shows a small deviation from the expected values for the DAC circuit. We constructed both 3-bit and 4-bit DACs and compared their difference in outputs. In the second part, using a comparator, we converted analog output to 2-bit digital output. In the third part, we extended the circuit to obtain decimal output from the digital output, using `IC 7447` (binary to BCD decoder) and BCD display.

I. THEORY

A device that translates a continuous physical quantity (typically voltage) to a digital number that indicates the quantity's amplitude is known as an analog-to-digital converter (ADC). A DAC, on the other hand, accepts a binary number and generates an analog voltage or current signal. They are frequently employed in digital systems in conjunction to offer a comprehensive interface with analog devices and output devices for control systems.

A. Digital to Analog Converter

A Digital to Analog Converter (DAC) has several binary inputs and one output. In general, a DAC's number of binary inputs will be a power of two. DACs are classified into two types: weighted resistor DACs and $R/2R$ ladder DACs. The addition of digital inputs (0 or 1, where 1 equates to 5 volts) in a weighted resistor produces analogue output, which can be added with varied weights depending on their position in the binary number. However, because of the large number of bits, this form of circuit needs a large number of precise resistors. Using an $R-2R$ ladder network in the inverting adder circuit, the $R-2R$ Ladder DAC overcomes this disadvantage and delivers an analogue output that is almost identical to the digital (binary) input.

The performance of DAC is characterized by the following:

- **Resolution:** The resolution of a DAC is determined by the number of bits (N). The resolution is the lowest output increment that the DAC can produce. The resolution of an 8-bit DAC is 8 bits, or one part in 2^8. This yields a percentage of 0.39%.

- **Linearity/ Linear Errors:** The maximum permitted variation from an ideal straight line drawn between the zero-scale and full-scale outputs is defined as linearity. It is frequently expressed as a percentage or as a fraction of an LSB. For an 8-bit DAC, $(\frac{1}{2})$ LSB linearity equates to 0.195%.

- **Monotonicity:** If each digital code increase generates an output equal to or greater than the preceding code, the DAC is monotonic. A DAC is often anticipated to be monotonic to increments as tiny as an LSB, but its monotonicity is determined by the smallest increment for which the DAC stays monotonic.

- **Settling time:** The settling time is calculated as the time it takes from the instant a digital input code changes to the time the analogue output achieves its matching new value within a given error band. Typically, the output is anticipated to settle within a $\frac{1}{2}$ LSB error range. Typically, the worst-case settling time is evaluated between the zero-scale and full-scale codes.

- **Accuracy:** The maximum divergence between the actual converter output and the ideal converter output is defined as absolute accuracy. The greatest variation after removing gain and offset errors is referred to as relative accuracy.

B. Analog to Digital Converter

There are many different ways to take an analog voltage signal and convert it into an equivalent digital signal. While many analog-to-digital converter chips are available, it is possible to build a simple ADC using discrete components.

One simple and easy way is by using parallel encoding, also known as flash, simultaneous, or multiple comparator converters, in which comparators are used to detect different voltage levels and output their switching state to an encoder.

II. EXPERIMENTAL SETUP

Apparatus

1. Resistors: 330 Ω, 1 kΩ, 2 kΩ, R, and 2R (as per the $R/2R$ ladder requirements)
2. 74147 priority encoder IC
3. `7447` binary-to-BCD decoder IC
4. LM339 comparator IC
5. Digital multimeter
6. DC power supply
7. Breadboard and connecting wires
8. LEDs
9. Common anode BCD display

A. 4 bit R/2R ladder DAC using 741 op-amp

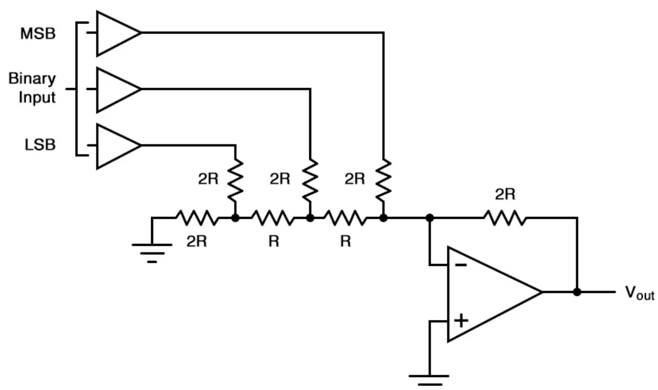


FIG. 1: Circuit diagram for 3-bit digital to analog conversion

The DAC circuit consists of a 3-bit R/2R ladder DAC using 741 op amp by choosing components appropriately and testing the circuit. The figure is depicted above. The output voltage of the DAC circuit is given by:

$$V_{out} = \frac{-R_F}{R}\left(\frac{d_1}{2^1} + \frac{d_2}{2^2} + \frac{d_3}{2^3}\right) \tag{1}$$

where d_1 is M.S.B and d_3 is L.S.B. In the above circuit, feedback resistance $R_f = 2R$. The output impedance of the $R - 2R$ network is always R for any number of bits in the network. This Another advantage of the circuit is that it simplifies the design of circuits that use DAC, such as filtering, amplification, etc. For a 4-bit DAC, the equation becomes

$$V_{out} = \frac{-R_F}{R}\left(\frac{d_1}{2^1} + \frac{d_2}{2^2} + \frac{d_3}{2^3}\frac{d_4}{2^4}\right) \tag{2}$$

B. ADC circuit to convert a 2-bit digital input to analog output

Figure 3 depicts the conversion's circuit diagram. This circuit employs an `LM339` comparator and `74147` priority encoders. The `LM339` comparator chip compares the analogue input from the DC power source with a reference voltage before passing it to the `74147` priority encoder circuit. The binary output from the `74147` chip may then be translated to BCD (Binary coded decimal) format and shown as a decimal digit on a common cathode 7-segment BCD display using the `7447` device. Use three of the four available comparators in `LM339`.

Digital binary output can be produced through D_0, D_1, D_2 and D_3. It should be noted that the `LM339` is a quad comparator integrated circuit. Because it has an open collector, it requires pull-up resistors at the comparator's output, as illustrated in Figure 3. Pull-up resistors of $3k\Omega$ are recommended. When utilising the `LM339` chip, always connect a $1k\Omega$ resistor in series with the LEDs. The supply voltage to the `LM339` can be as high as $15V$. Adjust the reference voltage as needed. Before connecting the ADC circuit, learn how the `LM339` works by connecting one of the comparators and testing the output. `74147` is a priority encoder with a range of 10 to 4. This IC's input and output are both low. The unused pins should be pulled up to $5V$.

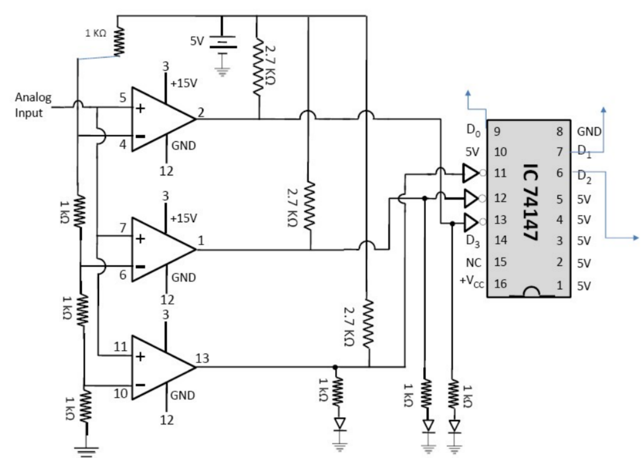


FIG. 2: Circuit diagram for 2-bit binary Analog to Digital conversion

Conversion of the binary display to decimal display

After converting analog voltage to binary number, it can be converted to binary coded decimal and displayed on a BCD display. `7447` is an input active high IC and output active low IC. The output of the `7447` must be connected to BCD display via a 330Ω resistor.

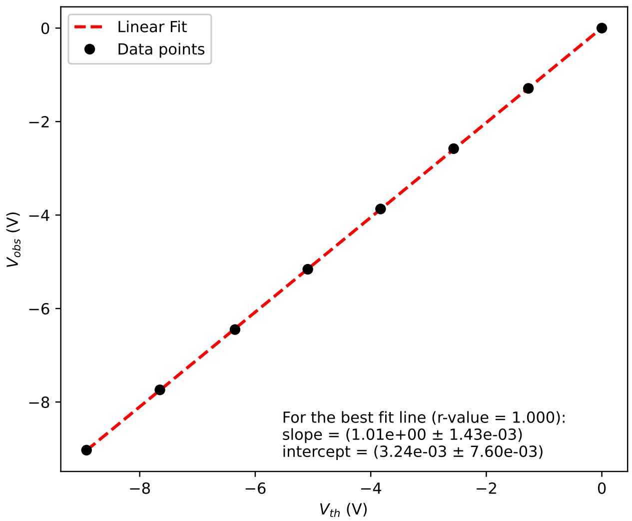


FIG. 3: $V_{\rm obs}$ vs. $V_{\rm th}$ for a 3-bit DAC

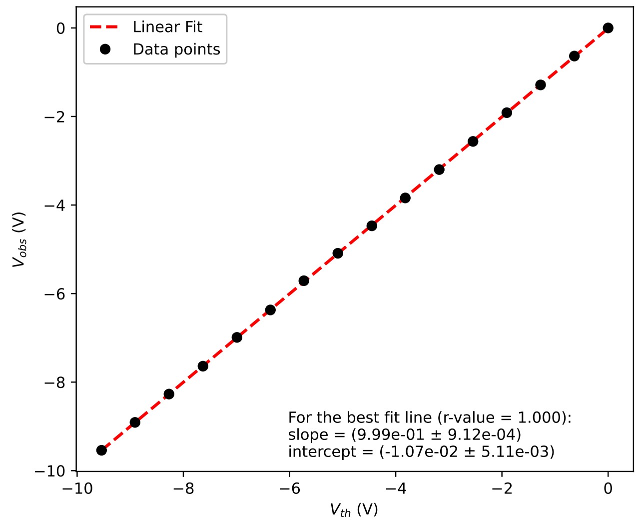


FIG. 4: $V_{\rm obs}$ vs. $V_{\rm th}$ for a 4-bit DAC

III. OBSERVATION AND CALCULATIONS

A. Digital to Analog Conversion

1. *3-bit input*

We constructed 3 bit R/2R ladder DAC circuit using `IC741` op-amps, with a constant power supply of 5V corresponding to 1 bit and 0V corresponding to 0 bit. Fig. 5 shows the circuit in action. In Table I, we can see that observed voltage values are very close to the theoretical values calculated using Eq. 1. This is reflected in Fig. 3, which shows a linear relationship between $V_{\rm obs}$ and $V_{\rm th}$ with a slope nearly 1 ($\approx 1.01 \pm 0.001$). All voltages obtained are negative since we use the op-amp in inverting configuration.

bit-0 (MSB)	bit-1	bit-2 (LSB)	$V_{\rm obs}$ (V)	$V_{\rm th}$ (V)
0	0	0	0	0
0	0	1	-1.271	-1.29
0	1	0	-2.565	-2.58
0	1	1	-3.83	-3.87
1	0	0	-5.09	-5.16
1	0	1	-6.35	-6.45
1	1	0	-7.65	-7.74
1	1	1	-8.92	-9.03

TABLE I: Output of 3 bit DAC using $R = 1$ kΩ resistors

2. *4-bit input*

Similarly, we constructed a 4-bit DAC (by adding an additional $R - 2R$ ladder in Fig. 1). In Table II, we can see that observed voltage values are very close to the theoretical values calculated using Eq. 2. Fig. 4 again shows a linear relationship between $V_{\rm obs}$ and $V_{\rm th}$ with a slope nearly 1 ($\approx 0.99 \pm 0.0009$).

bit-0 (MSB)	bit-1	bit-2	bit-3 (LSB)	$V_{\rm obs}$ (V)	$V_{\rm th}$ (V)
0	0	0	0	0	0
0	0	0	1	-0.635	-0.636
0	0	1	0	-1.287	-1.272
0	0	1	1	-1.914	-1.908
0	1	0	0	-2.563	-2.545
0	1	0	1	-3.199	-3.181
0	1	1	0	-3.84	-3.82
0	1	1	1	-4.47	-4.45
1	0	0	0	-5.09	5.09
1	0	0	1	-5.71	-5.73
1	0	1	0	-6.37	-6.36
1	0	1	1	-6.99	-6.99
1	1	0	0	-7.64	-7.63
1	1	0	1	-8.27	-8.27
1	1	1	0	-8.91	-8.91
1	1	1	1	-9.54	-9.54

TABLE II: Output of 4 bit DAC using $R = 1$ kΩ resistors

For both the circuits we can see a very small deviation in the observed values from the theoretical values. This could be because we have assumed $R = 1$ kΩ in all our calculations. The actual value of R can vary since the resistors we used were a combination of 1% and 20% tolerance resistors.

B. Analog to Digital Converter

We used three out of four comparators available in `LM339` and verified it's working for a 5V constant power supply. Now, using `LM339` comparator and `74147` priority encoder, we constructed the 2-bit digital to the analog circuit using the circuit in Figure 2. Finally to convert binary to human decimal outputs, we used `IC 7447` (binary to BCD decoder) chip which then connected to a common anode BCD display via a 330 kΩ resistors.

From Table III, we can verify it's working. It successfully converts analog signal into 2-bit digital output. Fig. 6 shows all of the combination of input and output values achived based on Table III.

Transition Voltage (V)	Comparator Output			IC 74147 Output		BCD Output (V)
	D_2	D_1	D_0	Q_1	Q_0	
0	0	0	0	0	0	0
1.3	0	0	1	0	1	1
2.5	0	1	1	1	0	2
3.8	1	1	1	1	1	3

TABLE III: Output of ADC circuit to convert 2-bit digital input to analog output

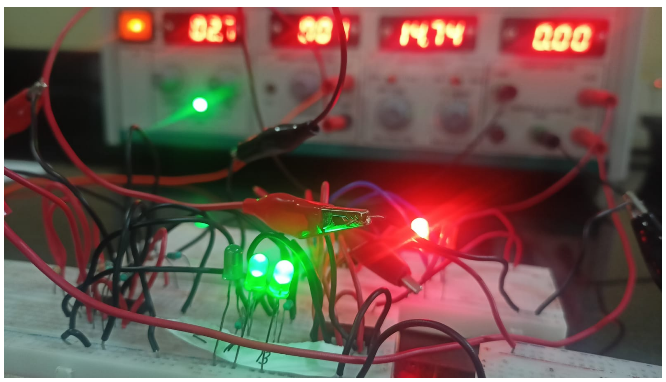
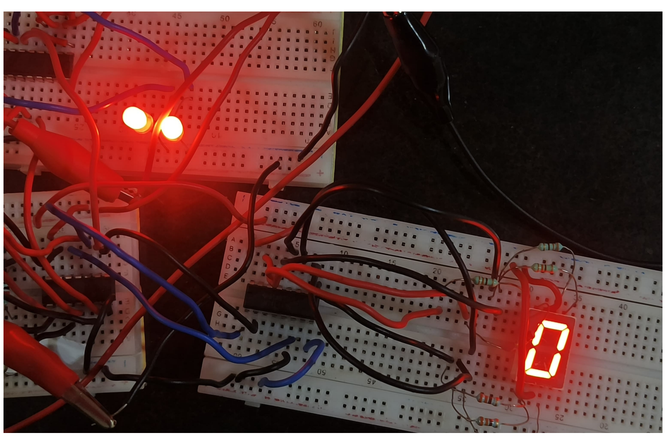
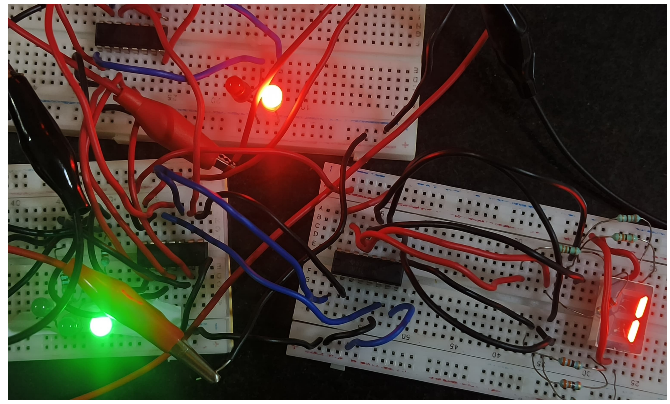


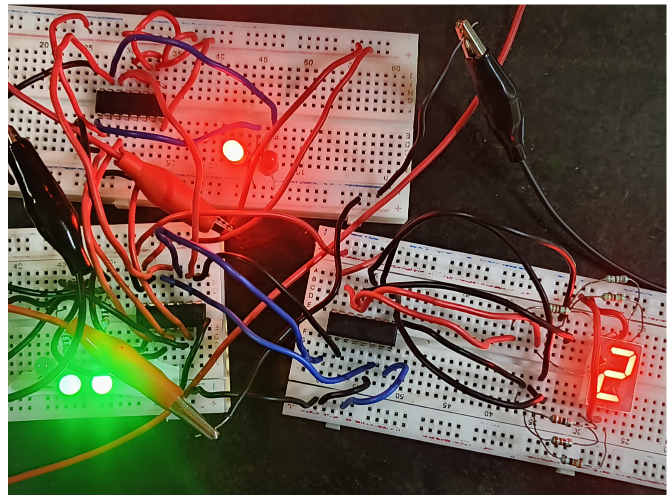
FIG. 5: 3-bit DAC circuit constructed on a breadboard. The input (shown using the LEDs) is 011 corresponding to -3.83 V on the multimeter (not pictured here).



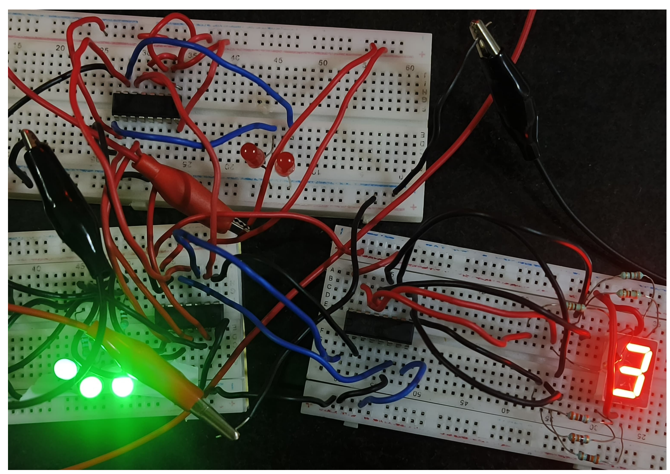
(a) Analog output 0



(b) Analog output 1



(c) Analog output 2



(d) Analog output 3

FIG. 6: ADC circuit constructed on a breadboard, along with the BCD analog output. The 2 LEDs on the top represent the (inverted) IC 74147 output and the 3 LEDs below show represent the comparator output.

IV. DISCUSSION & CONCLUSION

In the experiment, we investigated the operation of an ADC and DAC amplifier and built them with simple electronic components. We discovered the linearity error in the slope of the DAC plot between the theoretical and experimental values using our understanding of the numerous parameters governing the performance of a converter and discovered that it agreed more for larger number of bits at the digital input, but the difference iwas negligible. We noticed that while the DAC converter is operational, it displays a tiny deviation from the required voltage, which may be ignored. However, with larger bit converters, the variation is seen to decrease. These variations could be due to the assumption of $R = 1$ kΩ in our calculations, which may not be the case at all times. The resistors we used in the experiment had a tolerance rate upto 20%.

We have also seen how the precision of the setup increases with the increase in number of bits as seen in the difference in successive voltage values in 3-bit and 4-bit DAC, which were on average 1.27 V and 0.64 V respectively.

We also learnt how to convert digital output to decimal using a BCD display. Hence, these experiments highlight the importance of accurate component selection and proper circuit design in ensuring reliable and efficient signal conversion.

V. PRECAUTIONS AND SOURCES OF ERROR

1. To avoid loose connections and short circuits, the connections should be correctly constructed.
2. Resistors and integrated circuits must be tested for characteristics and functionality before being used in a circuit.
3. To avoid fusing, connect the LEDs to the resistor.
4. To avoid burning an op-amp, the biassing voltage should not exceed the specified value.

[1] SPS, *Digital to Analog Converter (DAC) and Analog to Digital Converter (ADC)*, NISER (2023).

[2] P. Horowitz and W. Hill, *The art of electronics* (Cambridge University Press, 2015).