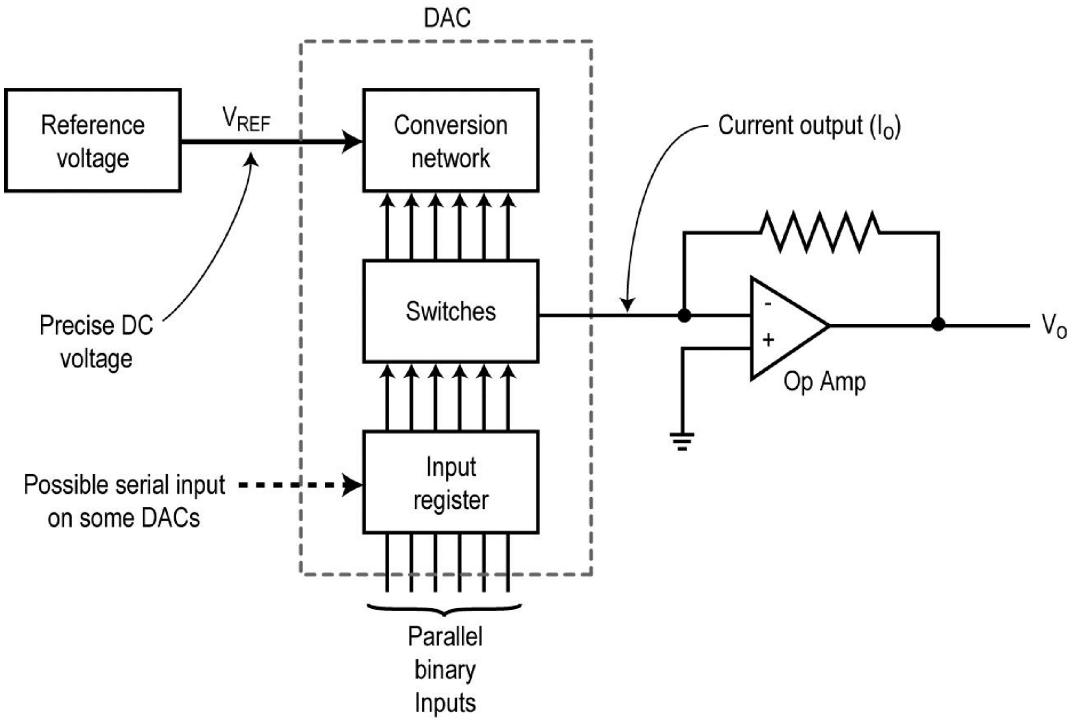
Digital-to-Analog Converters

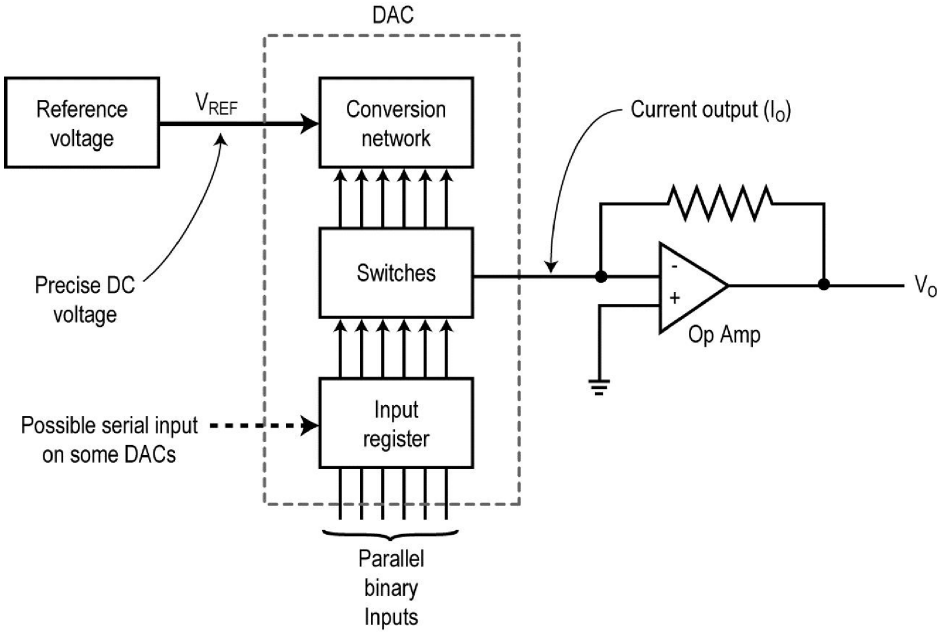
Architecture, Operation, and Specifications

DAC Architecture



A discussion of this graphic is presented in the pages that follow. You can print this graphic for study purposes before going on.

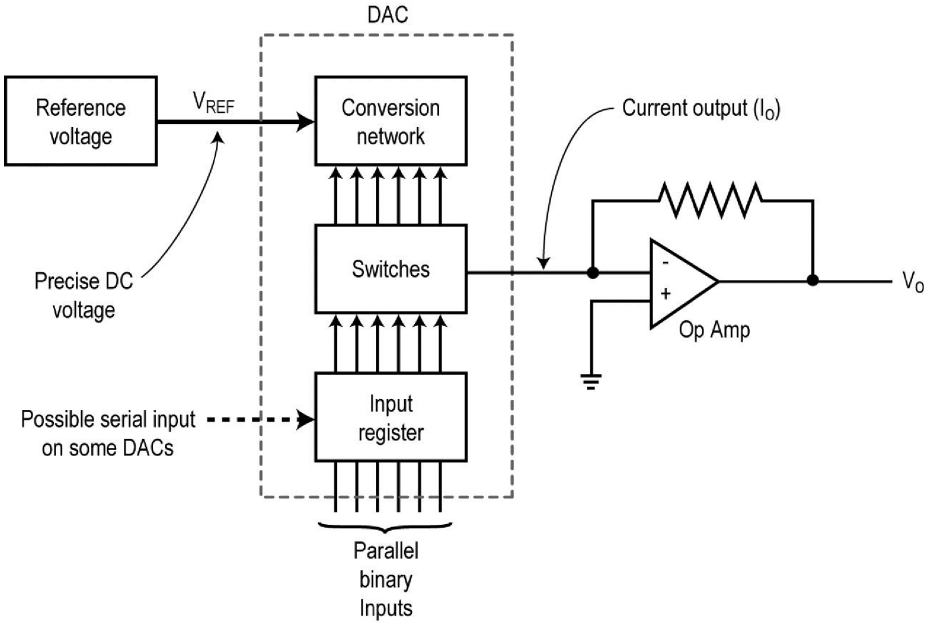
DAC Architecture



The DAC input can be either a precise DC reference voltage or a current. This input is divided up into increments represented by one of the binary input codes.

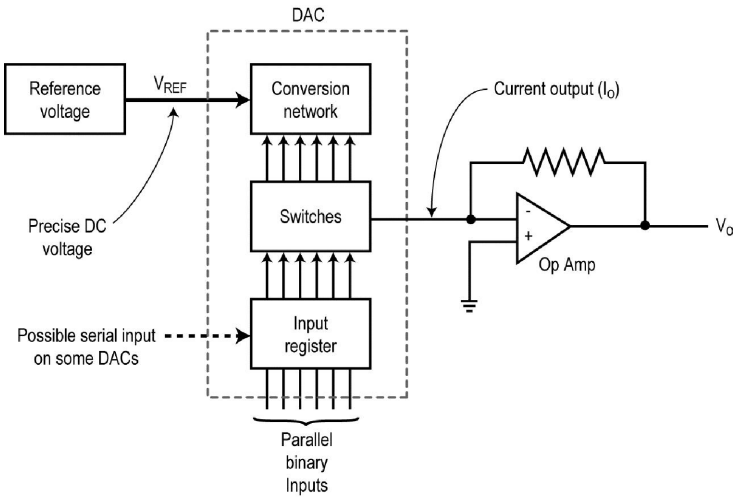
The reference voltage is typically supplied by a separate integrated circuit (IC) made up of a temperature compensated Zener diode and an op amp buffer. Common reference voltages are in the 1 to 10 volt range.

DAC Architecture



The reference voltage feeds the conversion network. The conversion network is a circuit that performs the division of the reference into increments. One common circuit is a resistor network. Other networks include a capacitor array or multiple current sources.

DAC Architecture

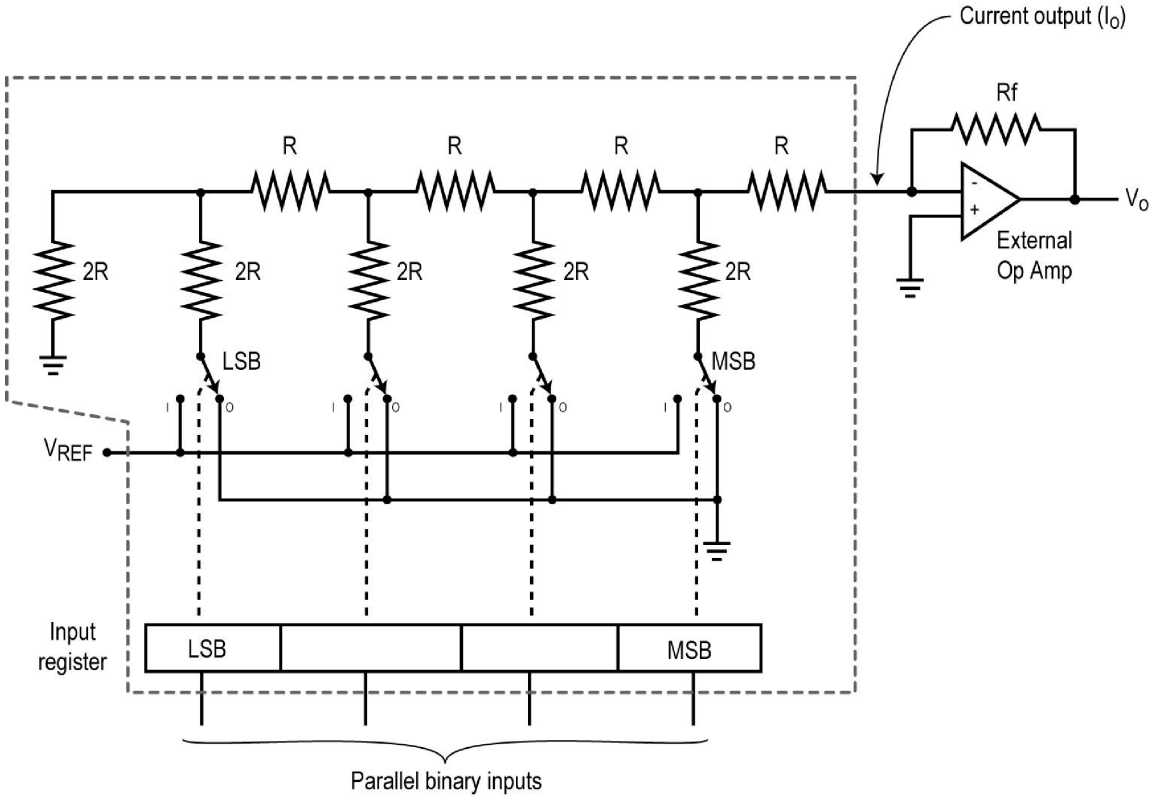


A set of fast bipolar or MOSFET switches turn the segments of voltage or current in the conversion network off or on according to the binary input.

The input register holds the binary input. It may have a parallel input or it may be a shift register if the input is serial binary.

The output is usually a current converted to voltage by the op amp.

R-2R DAC



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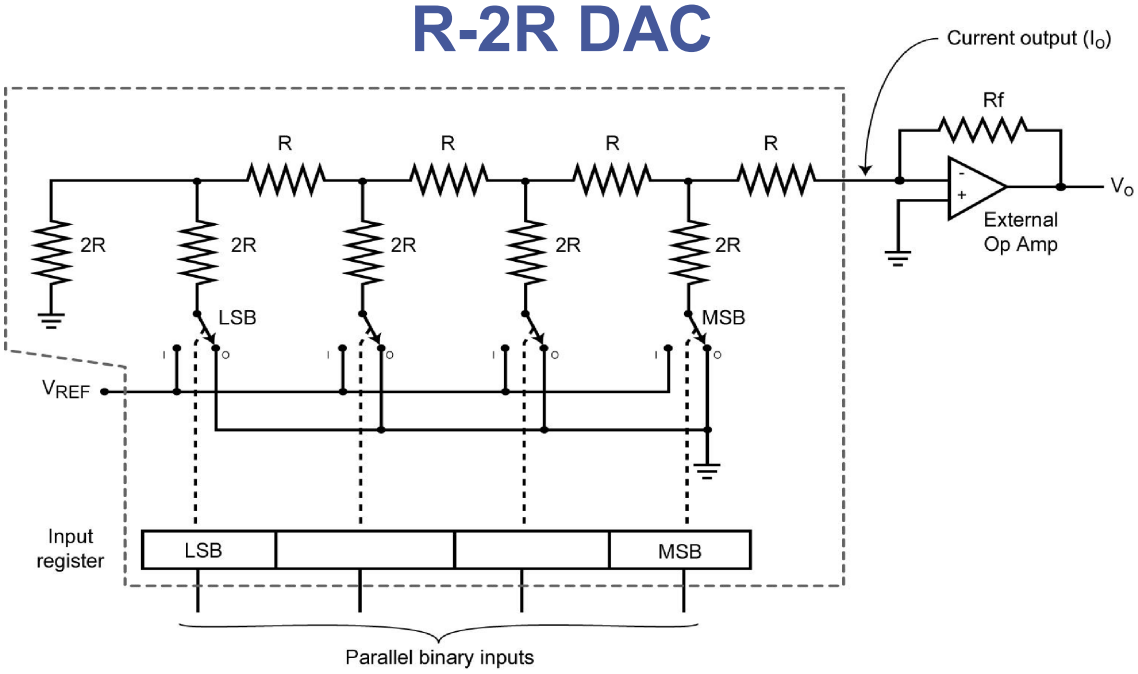
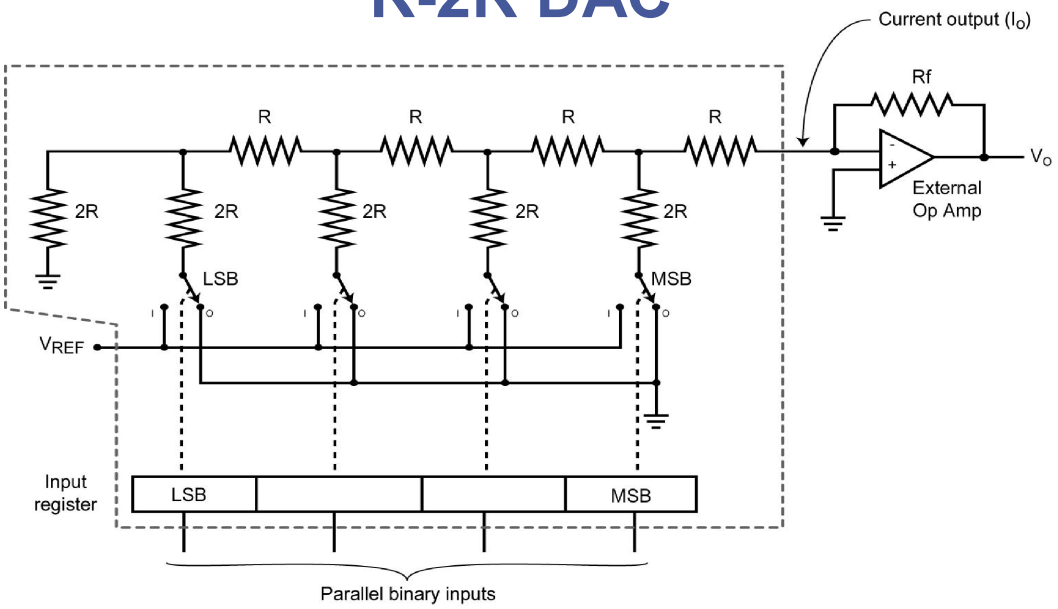
R-2R DAC



The most common circuit used to convert the reference into current increments is the R-2R network. It uses only two resistor values R and 2 x R.

The resistor networks were originally discrete resistors. Later thin film integrated resistors were used. Today, the resistor networks are made on a monolithic chip and are laser trimmed to have the desired precise values.

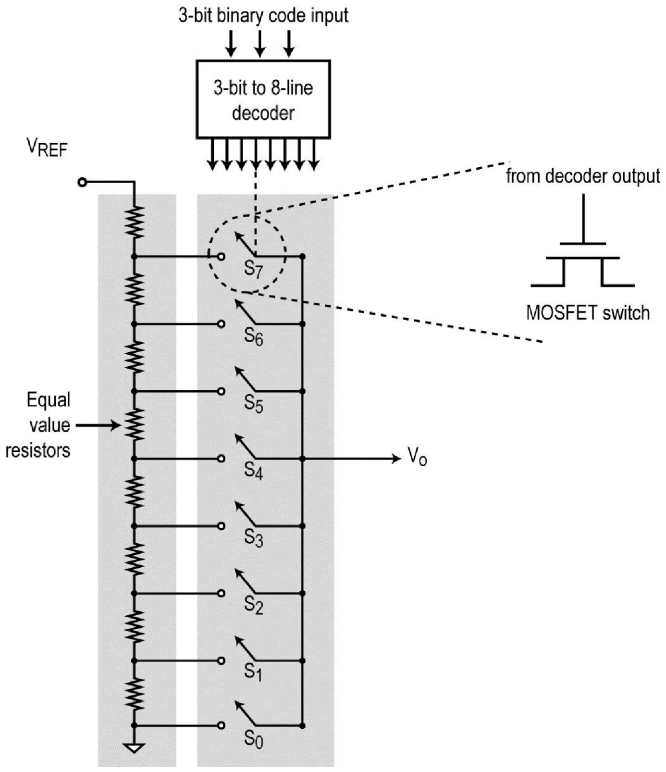
R-2R DAC



The SPDT mechanical switches are implemented with bipolar transistors or MOSFETs in modern DACs. The switches are controlled by the binary value in the input register. The resistors are switched in or out. The output current is proportional to the reference voltage and the binary input value.

The detailed analysis and operation of this circuit is not described here as it appears in most common texts.

String DAC



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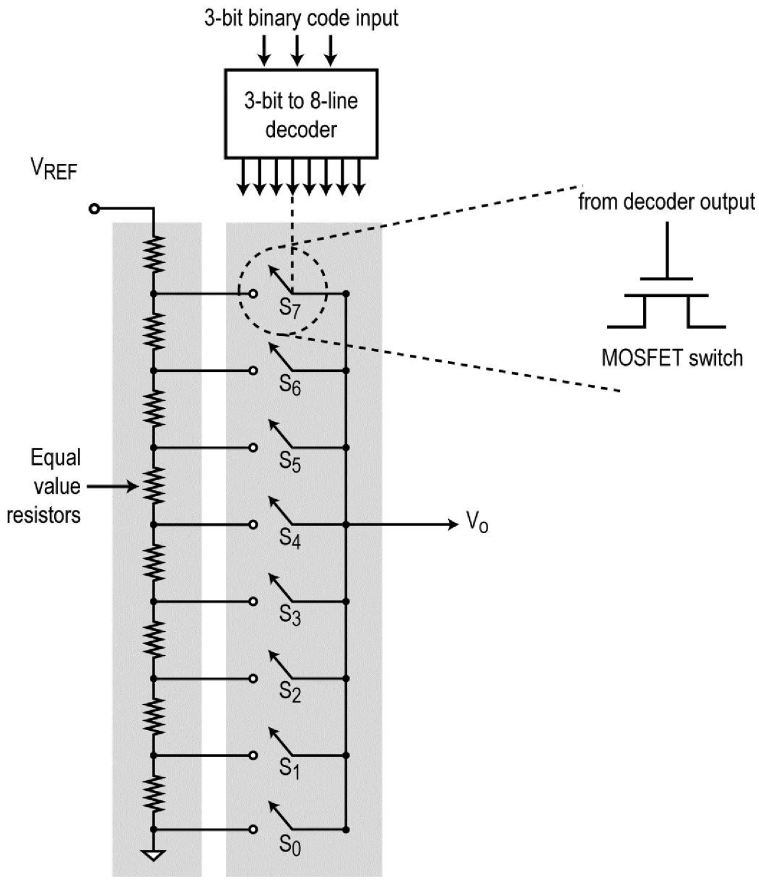
String DAC

Another common DAC is the string DAC. It uses a string of equal value resistors that form a voltage divider.

The number of taps on the voltage divider determines the resolution of the DAC. This 3-bit DAC has $2^N = 2^3 = 8$ resistors and taps.



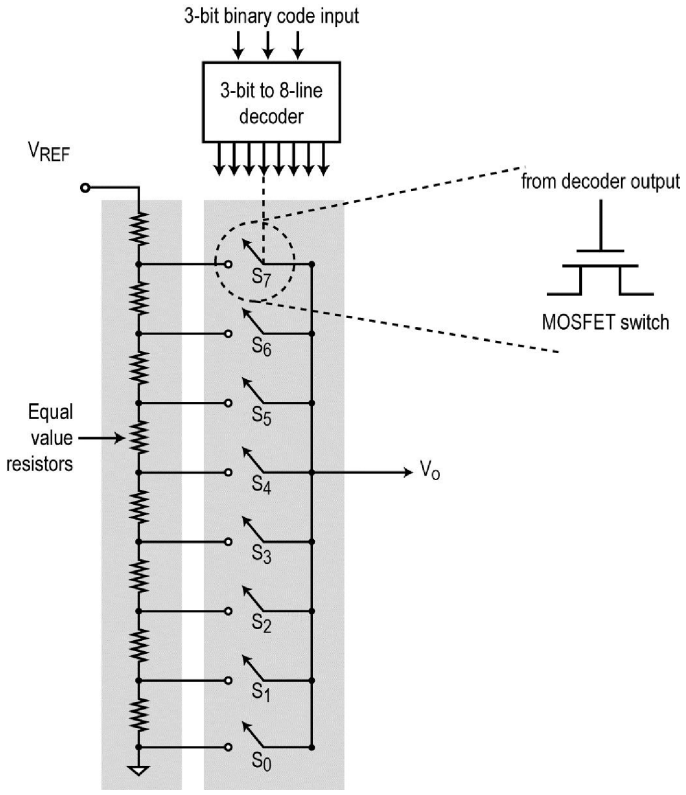
String DAC

If the reference voltage V_{REF} is 10 volts, the resolution is 10/8 = 1.25 volts. With 000 input, switch S0 is closed and the output is zero. If the input is 111, switch S7 is closed, the output is 8.75 volts.

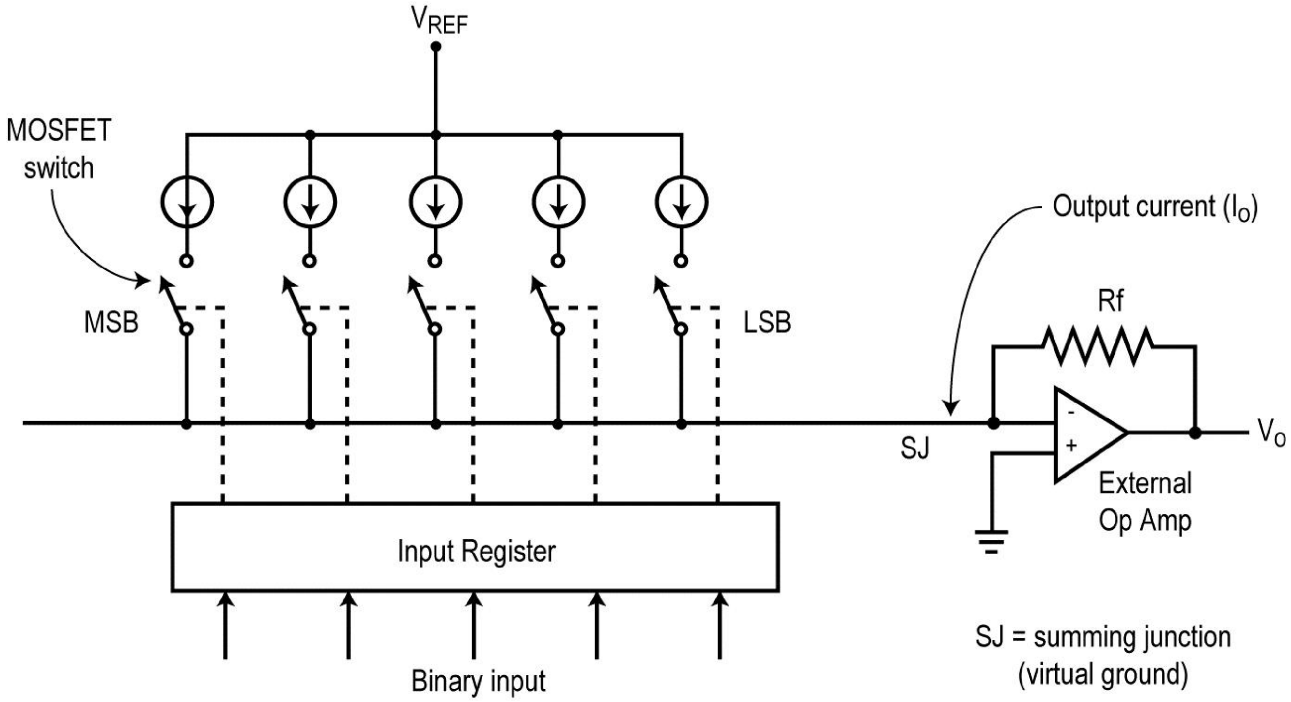
Each switch is a fast enhancement mode MOSFET.

Only one of the MOSFETs is selected as determined by the binary input code. The binary code input is decoded and used to activate the desired switch.

The output is a voltage V_o that is usually buffered by an op amp.



Current Source DAC



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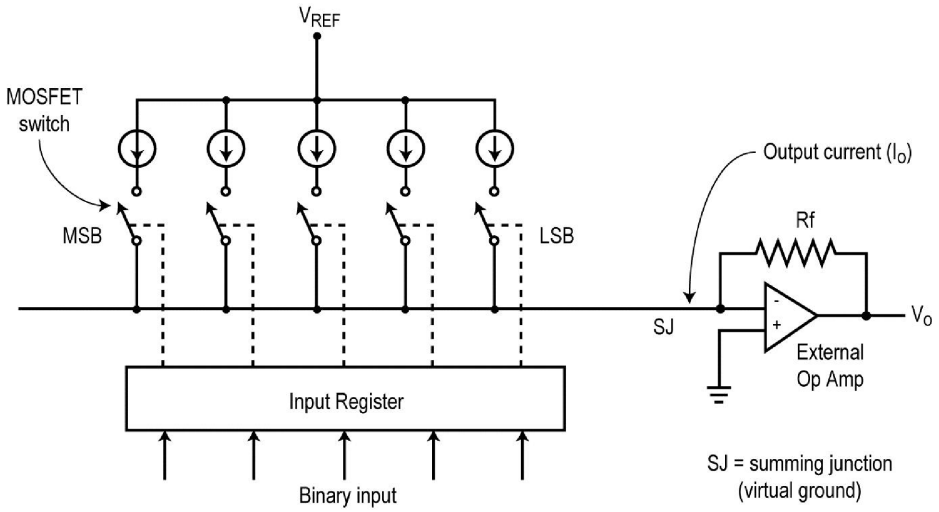
Current Source DAC

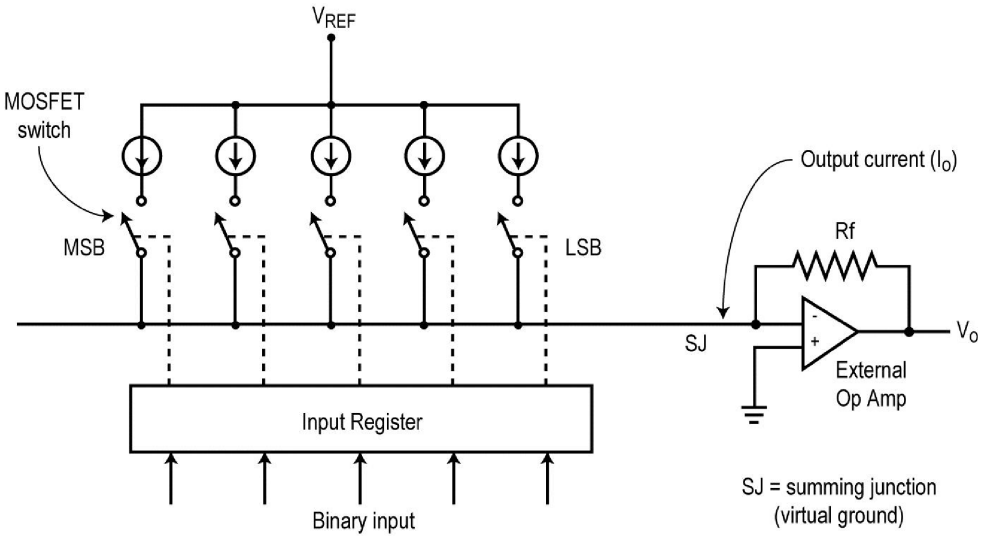


Another simple DAC uses current sources. The current sources are operated by the reference voltage.

The current sources are formed in a variety of ways using MOSFETs and in some cases resistors.

The current (I) values are binary weighted (I, I/2, I/4, I/8, I/16, etc.)

Current Source DAC



The switches are either MOSFETs or bipolar transistors.

The input binary number is stored in a register and used to turn the switches off or on.

The resulting output current is summed at the input to the summing junction (virtual ground) at the input of an op amp.

DAC Specifications

Modern DACs are available in integrated circuit (IC) form where all or most of the circuitry is made on a single silicon chip.

The reference voltage source and the output op amp may be separate in some devices or may be included on the chip in others.

Many DACs are now incorporated into other larger chips. Since they are systems on a chip (SoC), they may be completely inaccessible.

Digital to analog converter specifications are described in the pages that follow.

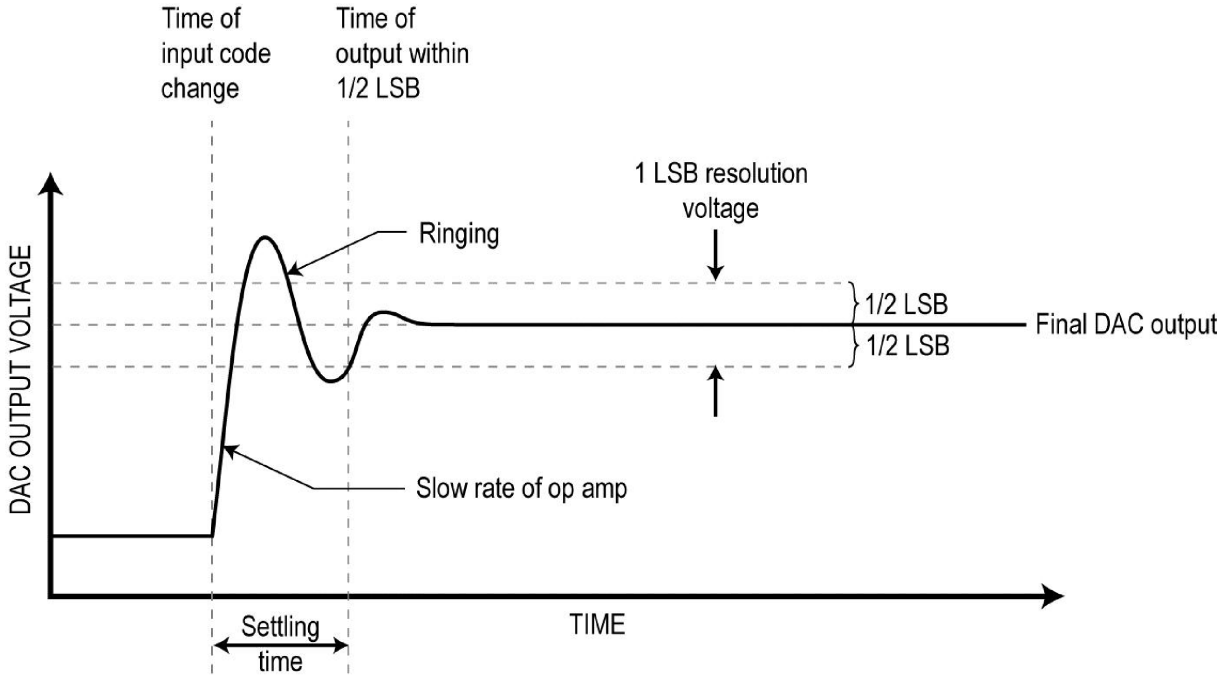
DAC Specifications

- Number of DACs per chip: Some DAC ICs contain more than one DAC. ICs with 2, 4, and 8 DACs are available. Most have serial inputs.
- DC power supply: Usually +5 volts. Other voltages may be 2.5 or 3.3 volts, or ±5 volts. Current drain or power dissipation may also be specified.
- Resolution or number of bits (N): DACs are available with input bit sizes of 6, 8,10, 12, 14, 16, 18, 20, and 24 bits.
- Input format: Parallel or serial digital.
- Input voltage levels: May be older TTL or CMOS levels or newer lower voltage levels in the 1.1 to 3.3 volt range. Fast DACs may accept current source logic (CML) levels or use low voltage differential signaling (LVDS).

DAC Specifications

- Serial interface: Either SPI or I^2C which are common on embedded controller microcomputers.
- Reference voltage: Usually in the 1 to 10 volt range. May be external or internal.
- Current output level: Maximum full scale current. It is a function of the reference voltage and the resolution.
- Type of input code: The input code is usually binary and the output is unipolar. Unipolar output has only one output voltage polarity either positive or negative. Some DACs accept various other binary codes to represent positive and negative numbers. Some accommodate 2's complement binary and produce bipolar analog outputs. Other DACs may use the BCD input code.

Settling Time



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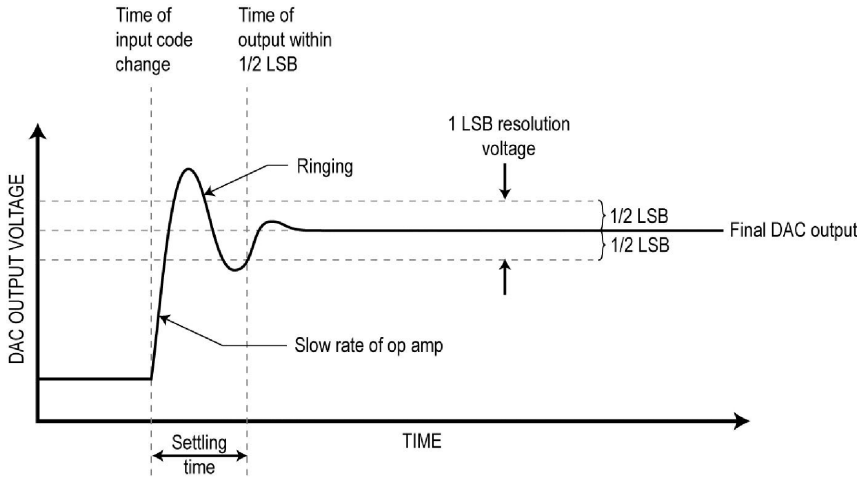
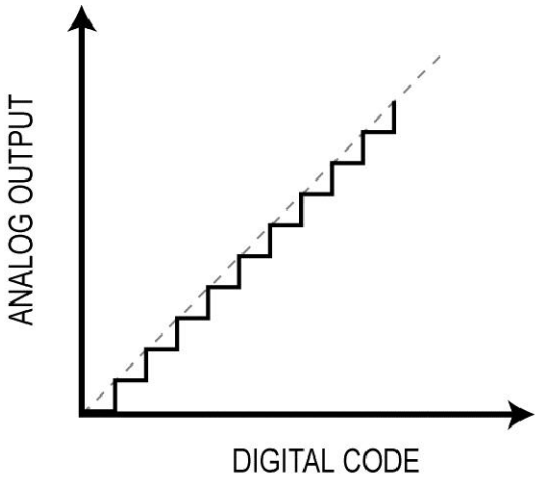
DAC Specifications

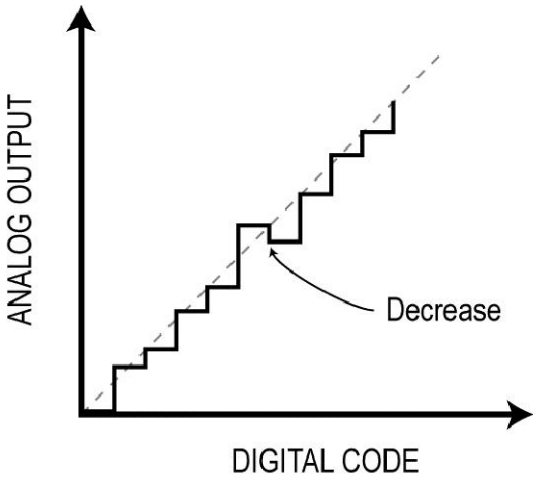


- Settling time: The time it takes for the output to settle to within ± LSB worth of resolution of the desired output. When an input code changes, the bipolar or MOSFET switches turn off and/or on. This produces transients as stray and distributed capacitance and inductance charge or discharge and produce output ringing or other variations. Op amp slew rate is usually included in this time as well. Depending upon the device, settling time may be several microseconds to a few nanoseconds.

Monotonicity



Monotone output of 3-bit DAC



Non-monotone output of 3-bit DAC

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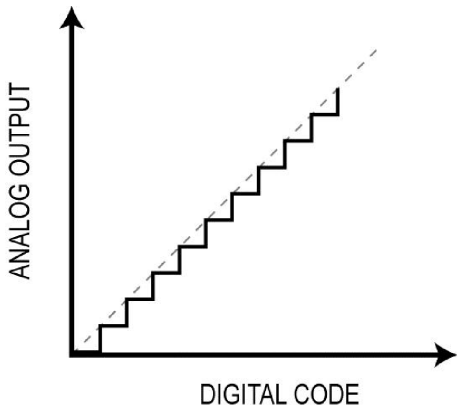
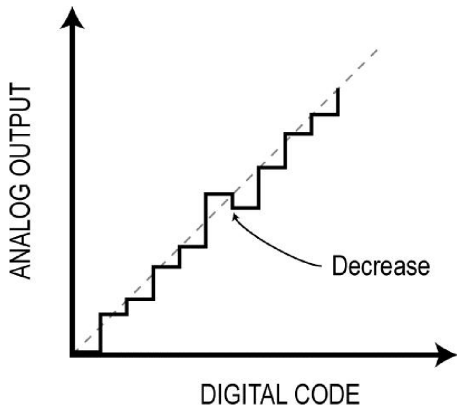
DAC Specifications



Monotone output of 3-bit DAC



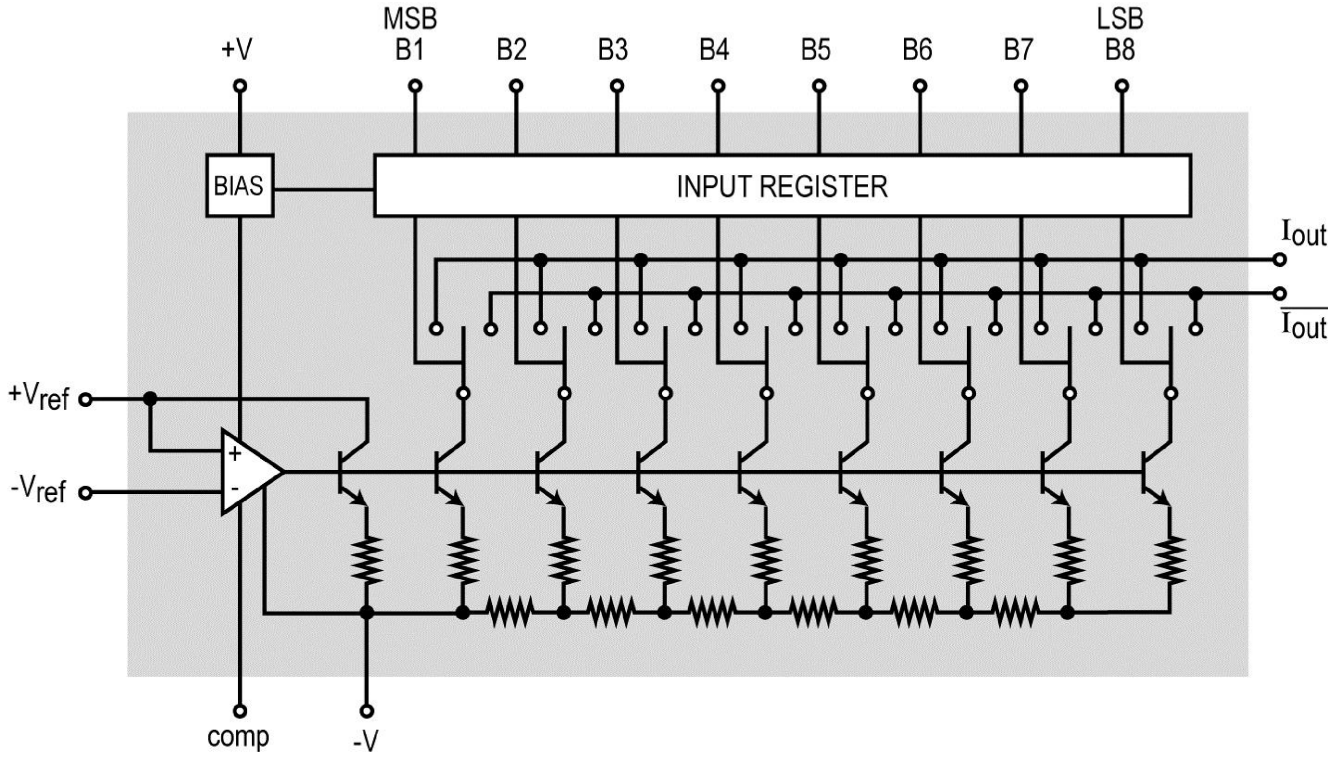
Non-monotone output of 3-bit DAC

- Monotonicity: A monotonic DAC is one that produces an incremental output increase for each and every binary input code increment. This is a function of the precision and accuracy of the resistor or current source network. A non-monotonic DAC has an output decrease for an incremental code increase.

DAC Specifications

- Differential non-linearity (DNL): The difference between the actual step voltage or current increment and one LSB of resolution. If the DNL is less than 1 LSB, the DAC will be monotonic. A DNL of more than 1 LSB can produce non-monotonic behavior.
- Conversion time: The time from an input code change to when the final output is available. It is usually the same as settling time.

Typical R-2R Bipolar DAC



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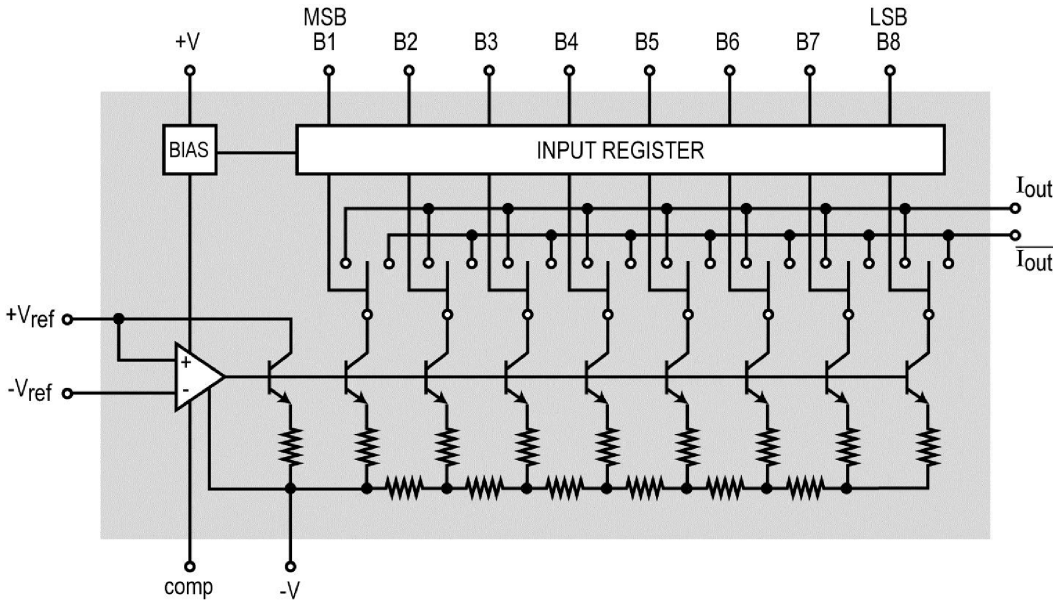
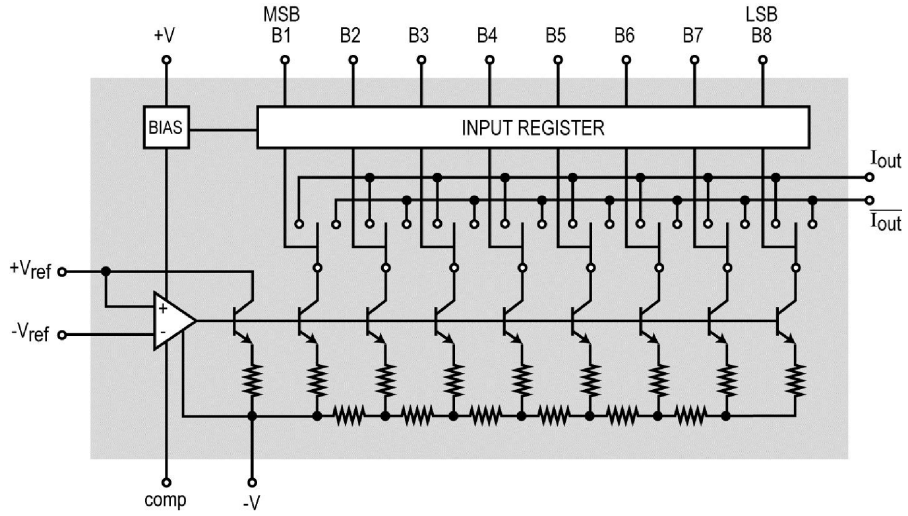
Typical R-2R Bipolar DAC



An older R-2R DAC with bipolar transistors is shown here. It is National Semiconductor's model DAC0800. Several versions are available with different temperature ranges.

Typical R-2R Bipolar DAC



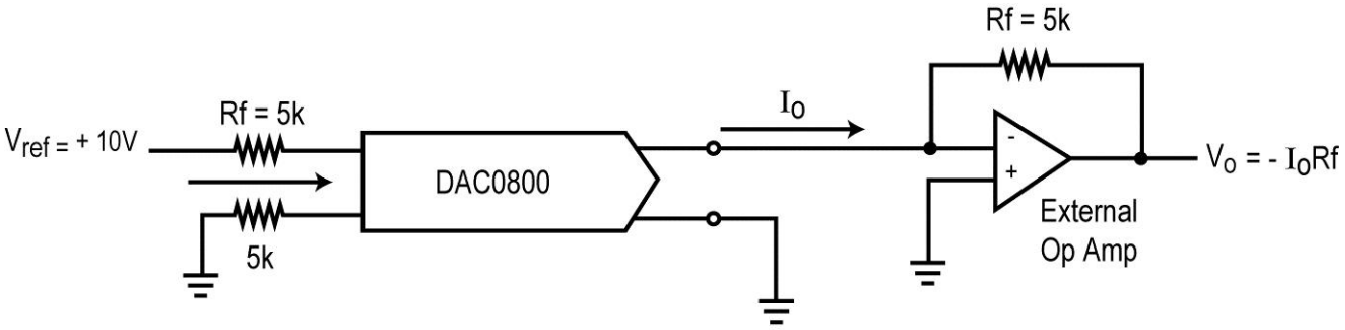
The DAC0800 accepts an 8-bit parallel TTL or CMOS input on lines B1 through B8 and generates a proportional output current I_{out}. An op amp is used to convert the current into an output voltage.

Supply voltage may be any value between ±4.5 to ±18 volts.

The reference V_{REF} is supplied by a DC source and a resistor to produce 2 mA.

The settling time or minimum conversion time is 100 nS.

R-2R DAC Circuits



$$I_{ref} = \frac{V_{ref}}{R_{ref}} = \frac{10\ V}{5\ k} = 2\ mA$$

I_{fs} = Full scale current

$$I_{fs} = \frac{255}{266}(I_{ref})$$

$$I_O = I_{fs}$$

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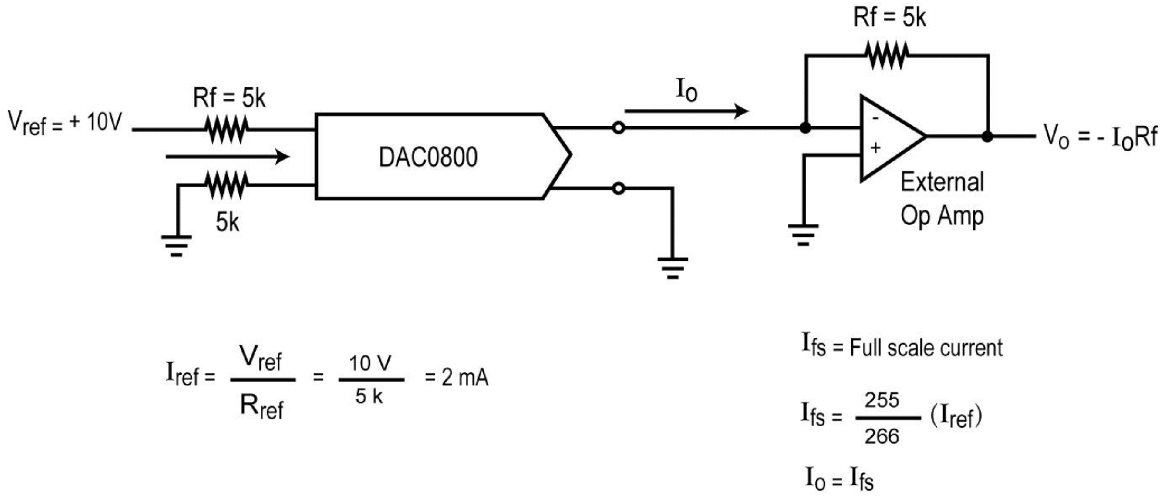
R-2R DAC Circuits



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I_{fs} = Full scale current

$$I_{fs} = \frac{255}{266}(I_{ref})$$

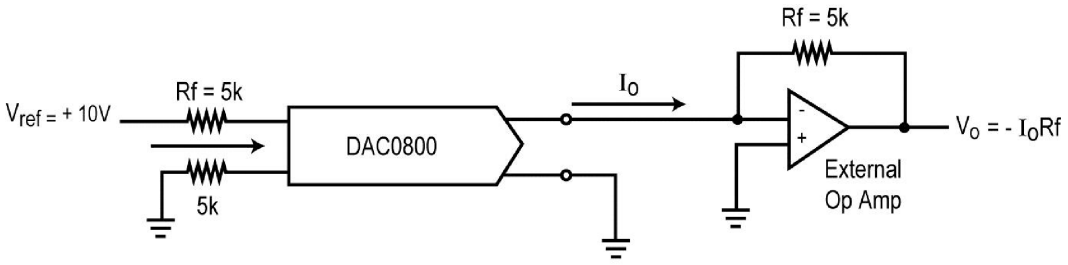
$$I_O = I_{fs}$$

The figure shown here shows the DAC0800 connected in a standard mode with an op amp.

The reference is supplied by a 10 volt DC source and a 5K ohm resistor providing a 2 mA reference current I_{REF}.

$I_o = I_{REF}(CODE/256)$ where CODE is the decimal value of the 8-bit binary input code.

R-2R DAC Circuits



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I_{fs} = Full scale current

$$I_{fs} = \frac{255}{266}(I_{ref})$$

$$I_o = I_{fs}$$

The op amp output is $V_o = I_o$ x Rf. The op amp feedback resistor allows you to scale the output to the desired level. Assume a value of 5K for Rf.

With an input of 11111111 or 255, the maximum full scale output I_{FS} is:

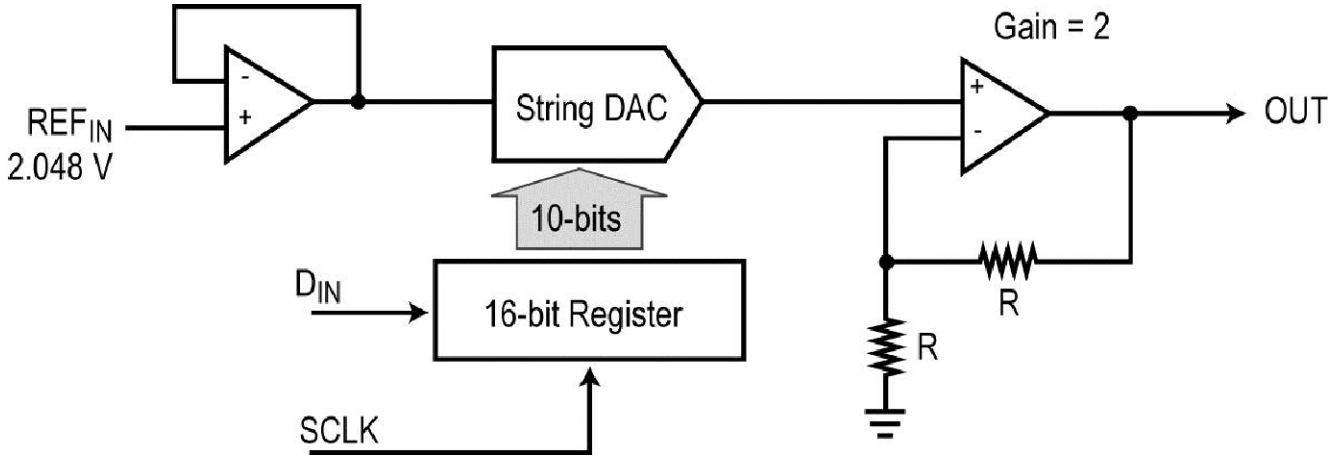
$I_{FS} = I_o = I_{REF}(255/256) = 2(0.996) = 1.992$ mA

Vo = (1.992)(5000) = 9.96 volts

With an input of 00000001 or decimal 1, the output is

2 mA(1/256)(5K) = .039 volts. The LSB resolution is 39 mV.

Typical String DAC



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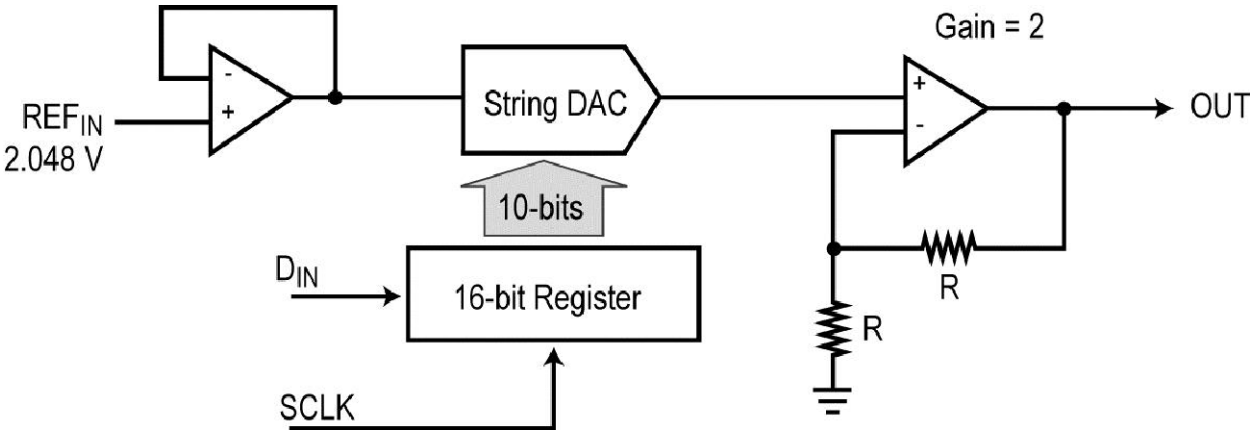
Typical String DAC



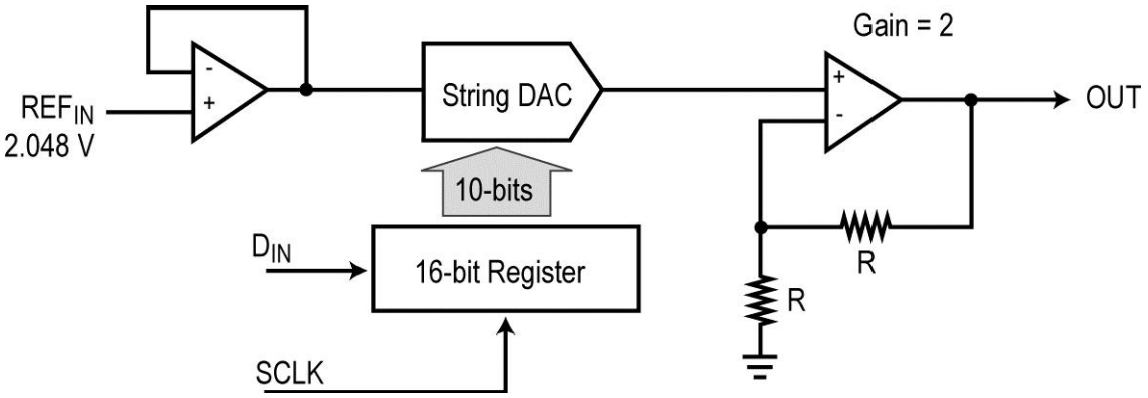
The Texas Instruments TLC5615C shown here is a 10-bit serial DAC.

The 1 LSB resolution is $1/2^{10} = 1/1024 = .0009765$ or .09765%.

The DAC operates from a single 5 volt supply with an external DC reference of 2.048 volts applied (REF_{IN}).

The output (OUT) is buffered by a non-inverting op amp on-chip with a gain of 2.

Typical String DAC



The binary input (D_{IN}) is serial and uses an SPI interface. Data is shifted in by the clock (SCLK) in 16-bit words. Six of the bits are not used. The 10 data bits are transferred to the DAC where they are decoded to operate the string switches.

Maximum serial data rate is 14 Mb/s, however, much lower rates are typical.

The settling time is 12.5 µS which limits the 16-bit data update rate to 80 kHz.

String DAC Calculations

The DAC output is $V_o = 2(REF_{IN})(CODE/1024)$.

CODE is the decimal value of the 10-bit binary input code.

Full scale output with 1111111111 input (1023) is

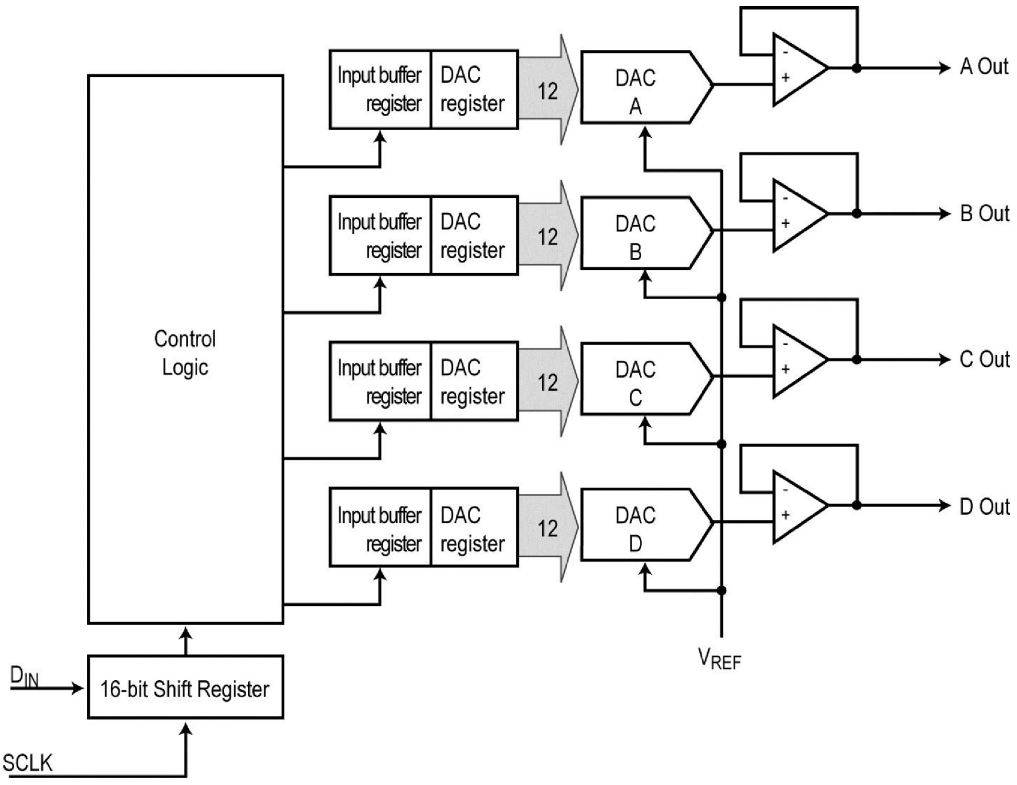
2(2.048)(1023/1024) = 4.092 volts

With an input of 0000000001 or 1, the output is

2(2.048)(1/1024) = .00039997 or about .0004 volts.

This is 1 LSB of resolution.

Quad DAC



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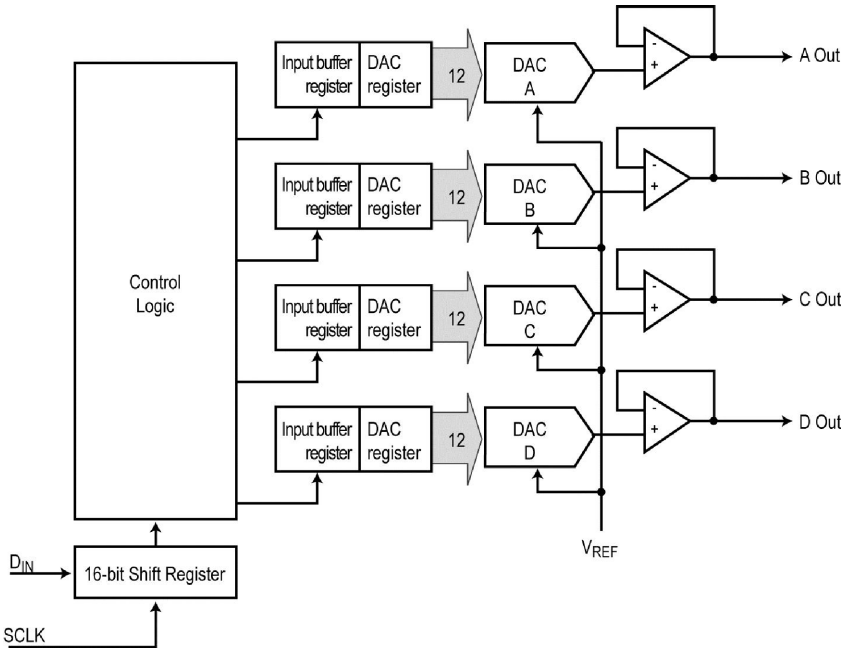
Quad DAC



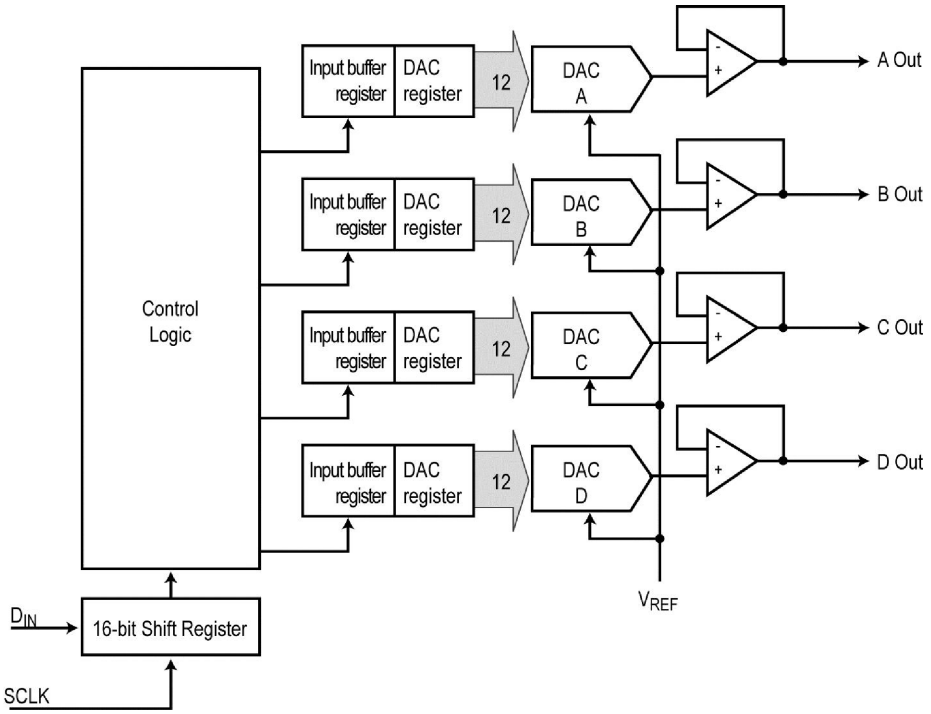
This is a simplified block diagram of the Maxim Integrated Products MAX5580 quad DAC. It contains four 12-bit DACs with a serial input.

The resolution is $1/2^{12} = 1/4096 = .00024$ or .024%.

The chip operates from separate digital and analog DC supplies in the 2.7 to 5.25 volt range with 5 volts being typical.

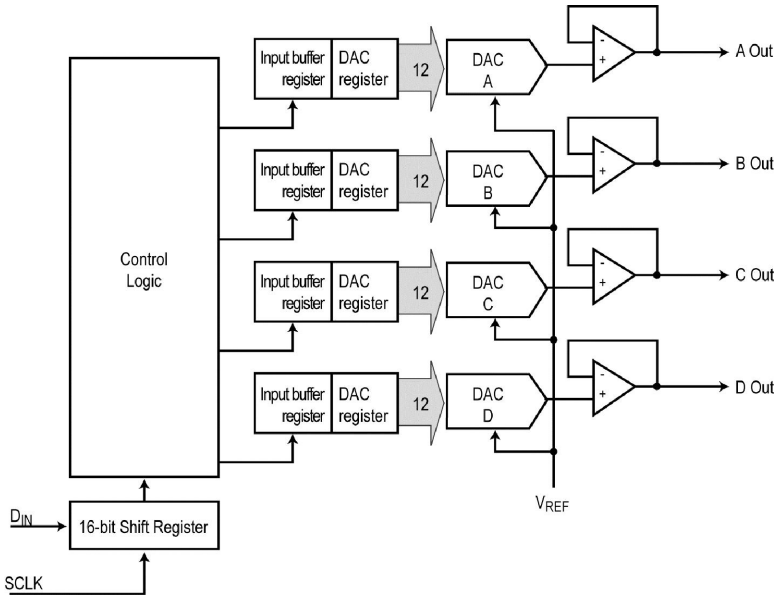
The reference input can be any voltage from 0.25 to 5.25 volts.

Quad DAC



Each DAC has a 12-bit data storage register and a 12-bit buffer input register. The input buffer registers are loaded serially from a 16-bit input shift register under the direction of the control logic. DIN is the serial input and SCLK is the clock.

Quad DAC



The serial interface is typically SPI with a maximum serial clock rate of 20 MHz, 12-bits of the 16-bits of input are the DAC data while the other 4-bits are control bits that select which DAC is to be updated.

Each DAC has its own op amp follower output. Settling time is 3 µS maximum.

Quad DAC Calculations

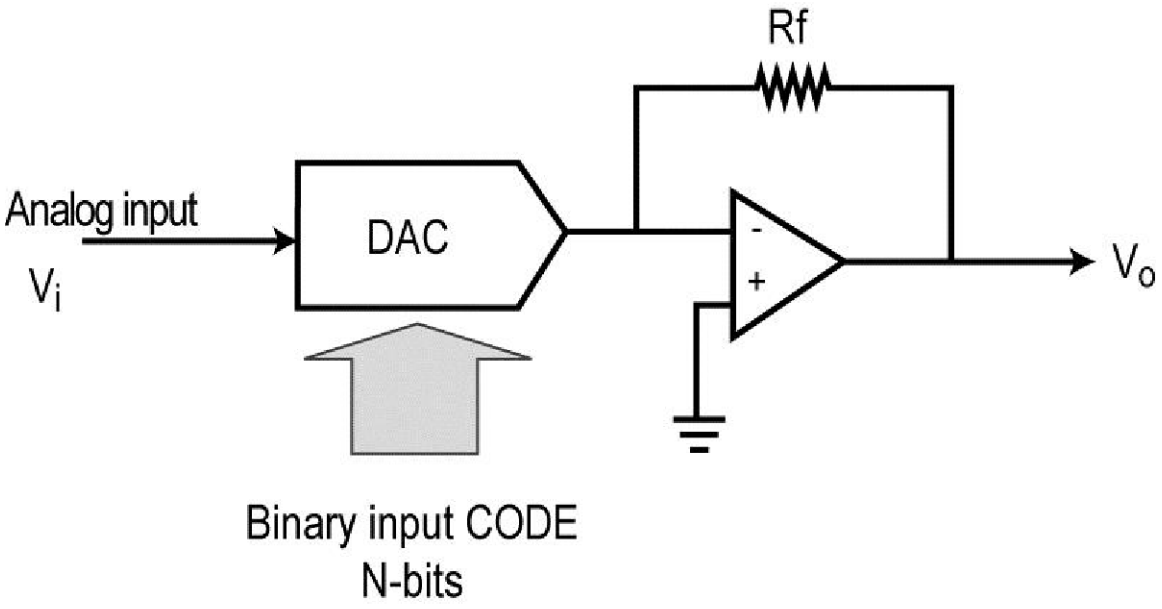
The output of each DAC is $V_o = V_{REF}(CODE/4096)$ where CODE is the decimal value of the 12-bit binary input.

Full scale output is achieved with an input of 111111111111.

The output with a 5 volt reference is 5(4095/4096) = 4.99879 volts.

With an input of 000000000001, the output is 5(1/4096) = .00122 volts or 1.22 mV which is the LSB resolution.

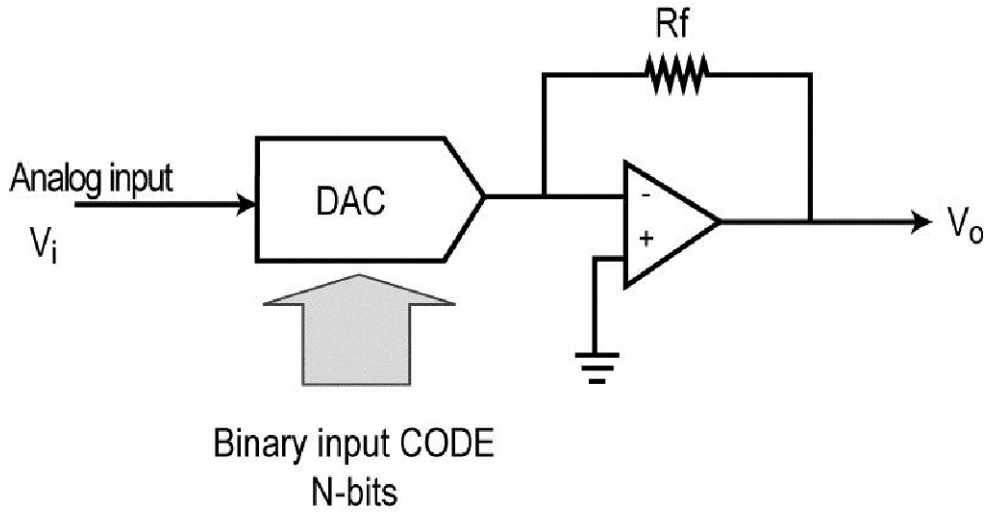
Multiplying DAC



$$V_o = V_i \left({}^{CODE}/_{2^N} \right)$$

A discussion of this graphic is presented in the pages that follow. You can print this graphic for study purposes before going on.

Multiplying DAC

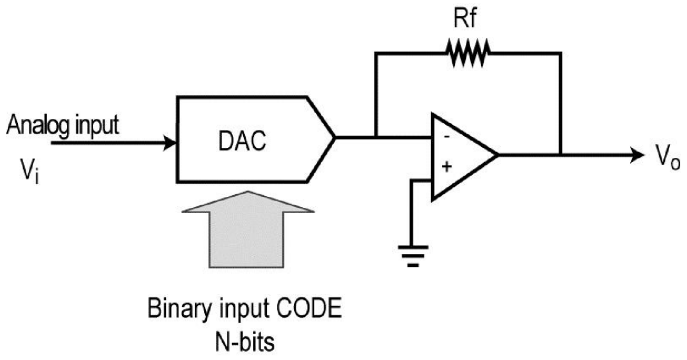


$$V_o = V_i \left({}^{CODE}/_{2^N} \right)$$

A multiplying DAC is one that produces an output proportional to the value of an analog input and a binary input. The analog input is the reference input while the binary input is the usual data input.

The output voltage equation is the product of the reference (input) voltage and the binary CODE value.

Multiplying DAC



$$V_o = V_i \left(\frac{CODE}{2^N} \right)$$

The DAC network, switches, and bias are usually structured so that the analog input may be positive or negative making AC operation possible. If the input changes, the output changes directly for a given binary input. For example, if the input is a sine wave, the output is also a sine wave whose amplitude is determined by the binary input value.

A typical application of a multiplying DAC is a digitally controlled gain circuit which allows the amplitude of an analog input signal to be varied by the binary input in increments of $1/2^N$ where N is the number of bits.

Amplitude modulation can also be achieved.

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Digital-to-Analog Converters

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