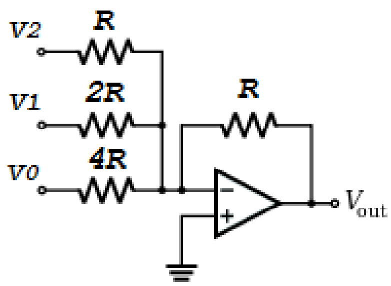
Digital to Analog Converter

A digital-to-analog converter (DAC, D/A, D2A or D-to-A) is a circuit that converts digital data (usually binary) into an analog signal (current or voltage). One important specification of a DAC is its resolution. It can be defined by the numbers of bits or its step size.

Digital to Analog Converter using the Summing Amplifier

The following diagram shows a 3 bit digital to analog converter implemented using a summing opamp amplifer.



From the summing (inverting-amplifier#summing) amplifier circuit (see equation 6), the output voltage is

$$V_{out} = -R(\frac{V_2}{R} + \frac{V_1}{2R} + \frac{V_0}{4R}) \tag{1}$$

Simplifying, we obtain

$$V_{out} = -\frac{1}{4}(4V_2 + 2V_1 + V_0) \tag{2}$$

Output Table

V2	V1	V0	Digital Value	Vout
0	0	0	0	0
0	0	1	1	-0.25
0	1	0	2	-0.5
0	1	1	3	-0.75
1	0	0	4	-1.0
1	0	1	5	-1.25
1	1	0	6	-1.5
1	1	1	7	-1.75

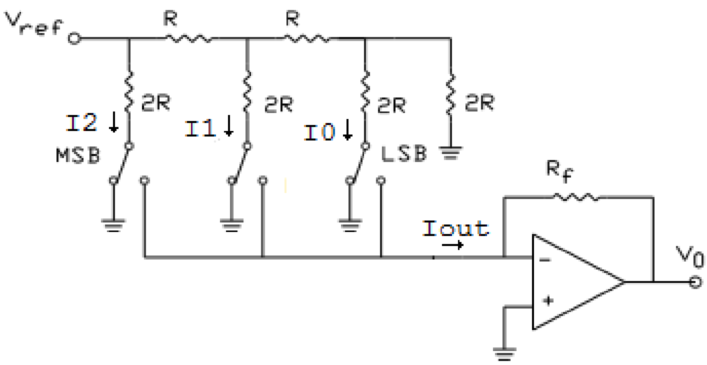
From the table, we can conclude the following

- The inputs can be thought of as a binary number, one that can run from 0 to 7.
- V2 is the MSB (most significant bit) and V0 is the LSB (least signifcant bit).

- The output is a voltage that is proportional to the binary number input.
- The resolution of this DAC is 3 (the number of bits) or -0.25V (the step size).
- To have more bits, add an additional resistor for each additional bit. Note the relationship between adjacent resistor values.

R-2R Binary Ladder Digital to Analog Converter

The R-2R Digital to Analog Converter uses only two resistance values R and 2R regardless of the number of bits of the converter compared to the summing amplifier implementation where each bit resistor has a different value. The circuit shown is a 3 bit DAC.



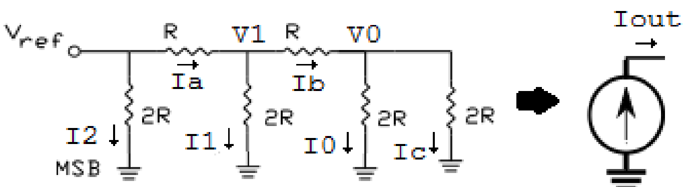
Depending on the state of bit B2, B1 or B0, the respective current I2, I1 or I0 is switched either to ground or to V- of the op amp. Thus

$$I_{out} = B_2 I_2 + B_1 I_1 + B_0 I_0 \tag{3}$$

To analyse this circuit, first we observe that since the output is connected to V- through R_f, the opamp is in a negative feedback (opamp#neg-feedback) configuration. Thus

$$V_- = V_+ = 0 \tag{4}$$

Therefore the individual current values I2, I1, I0 are unaffected by the switch setting and the resistor network circuit can be redrawn to the following



Due to the nature of the resistance network and values, we can obtain the current values by inspection.

From ohms law,

$$I_0 = I_c \tag{5}$$

From KCL at node V0,

$$\begin{aligned} I_b &= I_0 + I_c \\ &= 2I_0 \end{aligned} \tag{6}$$

From KVL,

$$V_1 = I_b R + I_0 2R \tag{7}$$

Substituting equation 6 into equation 7

$$V_1 = 4I_0 R \tag{8}$$

Again applying ohms law to I1 and using equation 8, we obtain

$$V_1 = I_1 2R = 4I_0 R \tag{9}$$

or

$$I_1 = 2I_0 \tag{10}$$

From KCL at node V1, and using equation 6 and 10

$$\begin{aligned} I_a &= I_b + I_1 \\ &= 2I_1 \end{aligned} \tag{11}$$

From KVL,

$$V_{ref} = I_a R + I_1 2R = 4I_1 R \tag{12}$$

We leave the reader to figure out how we obtain

$$I_2 = 2I_1 = 4I_0 = \frac{V_{ref}}{2R} \tag{13}$$

Thus the R-2R network can be seen to be like a current source whose output depends on switch setting B2, B1, B0 that controls I2, I1, I0 respectively

$$I_{out} = \frac{V_{ref}}{8R}(4B_2 + 2B_1 + B_0) \tag{14}$$

Including the opamp which behaves like I-V converter (current-voltage-converter), we obtain the voltage ouput (note the direction of the current source)

$$V_{out} = -\frac{V_{ref}R_f}{8R}(4B_2 + 2B_1 + B_0) \tag{15}$$

Letting Vref = 1 and Rf = 2R, we obtain the following output table

Output Table

B2	B1	B0	Digital Value	Vout
0	0	0	0	0
0	0	1	1	-0.25
0	1	0	2	-0.5
0	1	1	3	-0.75
1	0	0	4	-1.0
1	0	1	5	-1.25

1	1	0	6	-1.5
1	1	1	7	-1.75