ELECTRONIC DEVICES & CIRCUITS
Module 6

DACs

S3 CSE KTU

prepared by

Anjana Devi

DIGITAL TO ANALOG CONVERTER

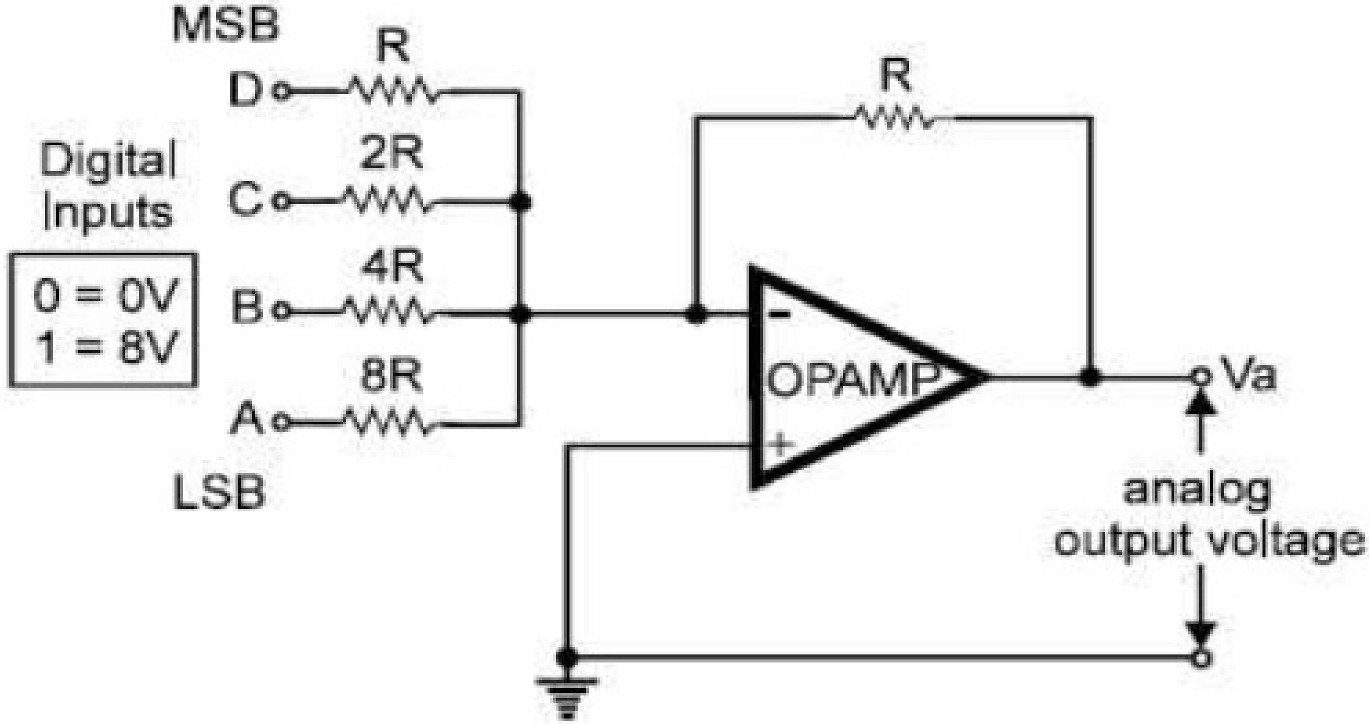
- A DAC (Digital-to-Analog Converter) is used to convert a digital signal to the analog format.
- For example, music stored in a DVD in digital format must be converted to an analog voltage for playing out on a speaker.
- Real signals (e.g., a voltage measured with a thermocouple or a speech signal recorded with a microphone) are analog quantities, varying continuously with time.
- An ADC (Analog-to-Digital Converter) is used to convert an analog signal to the digital format.
- Digital format offers several advantages: digital signal processing, storage, use of computers, robust transmission, etc.

DAC - INTRODUCTION

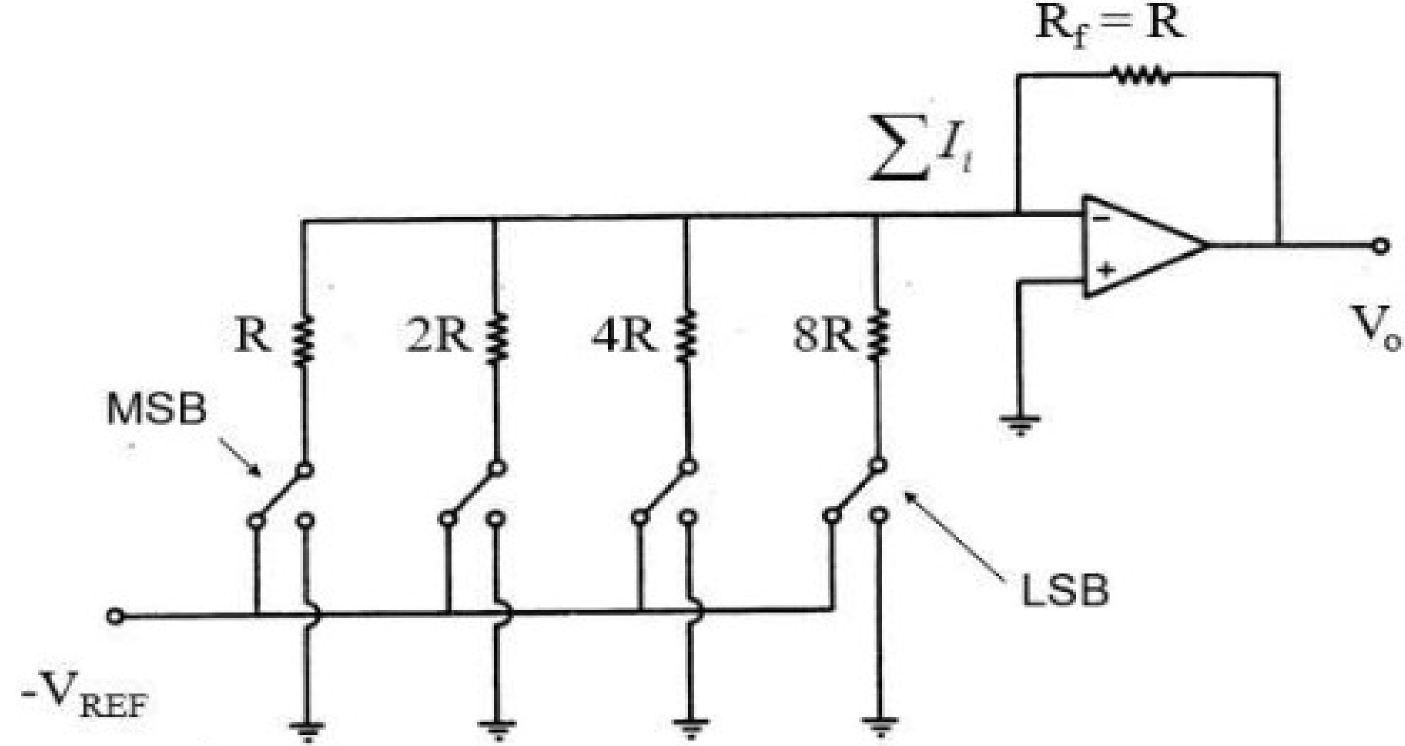
- The process of converting digital signal into equivalent analog signal is called D/A conversion.
- The electronics circuit, which does this process, is called D/A converter.
- The circuit has ‘n’ number of digital data inputs with only one output.
- Basically, there are two types of D/A converter circuits:

1. Weighted resistors D/A converter circuit and
2. Binary ladder or R–2R ladder D/A converter circuit.

WEIGHTED RESISTORS D/A CONVERTER



BINARY WEIGHTED RESISTOR



- **Here an opamp is used as summing amplifier.**
- **There are four resistors R, 2R, 4R and 8R at the input terminals of the opamp with R as feedback resistor.**
- **The network of resistors at the input terminal of opamp is called as variable resistor network.**
- **The four inputs of the circuit are D, C, B & A.**
- **Input D is at MSB and A is at LSB.**
- **Here we shall connect 8V DC voltage (say) as logic–1 level.**
- **So we shall assume that 0 = 0V and 1 = 8V.**
- **Now the working of the circuit is as follows.**
- **Since the circuit is summing amplifier, its output is given by the following equation –**

$$V_o = -R.\left(\frac{D}{R} + \frac{C}{2R} + \frac{B}{4R} + \frac{A}{8R}\right)$$

- **When digital input of the circuit DCBA = 0011, then putting these value in previous equation, we get**

$$V_O = -R.\left(\frac{0}{R} + \frac{0}{2R} + \frac{8V}{4R} + \frac{8V}{8R}\right) = -R.\left(\frac{8V}{4R} + \frac{8V}{8R}\right) = -3V$$

- **In this way, when digital input changes from 0000 to 1111, output voltage (Vo) changes proportionally.**
- **This is given in the conversion chart.**

Digital inputs				Analog output
D	C	B	A	Voltage (V_a)
0	0	0	0	0V
0	0	0	1	–1V
0	0	1	0	–2V
0	0	1	1	–3V
0	1	0	0	–4V
0	1	0	1	–5V
0	1	1	0	–6V
0	1	1	1	–7V
1	0	0	0	–8V
1	0	0	1	–9V
1	0	1	0	–10V
1	0	1	1	–11V
1	1	0	0	–12V
1	1	0	1	–13V
1	1	1	0	–14V
1	1	1	1	–15V

BINARY WEIGHTED RESISTOR

Result:

$$\sum I = V_{REF}\left(\frac{B_3}{R} + \frac{B_2}{2R} + \frac{B_1}{4R} + \frac{B_0}{8R}\right)$$

$$V_{OUT} = I \cdot R_f = V_{REF}\left(B_3 + \frac{B_2}{2} + \frac{B_1}{4} + \frac{B_0}{8}\right)$$

Vref is -ve for getting +ve voltage

- B_i = Value of Bit i

For 3 bit DAC $V_{OUT} = V_{REF}\left(B_2 + \frac{B_1}{2} + \frac{B_0}{4}\right)$

A 5-bit D/A converter produces $V_{OUT} = 0.2$ V for a digital input of 0001. Find the value of Vout for an input of 11111.

Solution

Obviously, 0.2 V is the weight of the LSB. Thus, the weights of the other bits must be 0.4 V, 0.8 V, 1.6 V, and 3.2 V respectively. For a digital input of 11111, then, the value of V_{OUT} will be 3.2 V + 1.6 V+ 0.8V + 0.4V + 0.2 V = 6.2 V.

Resolution

Resolution of a D/A converter is defined as the smallest change that can occur inthe analog output as a result of a change in the digital input.

Resolution is the change is analog o/p voltage/current corresponding to change in LSB

Eg: For Vref = 5V, o/p corresponding to LSB of a 4 bit DAC = Vref/8 = 5V/8 = 0.625V

Resolution = 0.625V

For Vref = 10V, o/p corresponding to LSB = 10V/8 = 1.25V
Resolution = 1.25V

5 bit DAC, Vref = 10V, change in o/p corresponding to LSB = 10V/16 = 0.625V

$$\% \, resolution = \frac{1}{total\ number\ of\ steps} \times 100\%$$

For an N-bit binary input code the total number of steps is 2^N-1.

$$\% \, resolution = \frac{1}{2^N - 1} \times 100\%$$

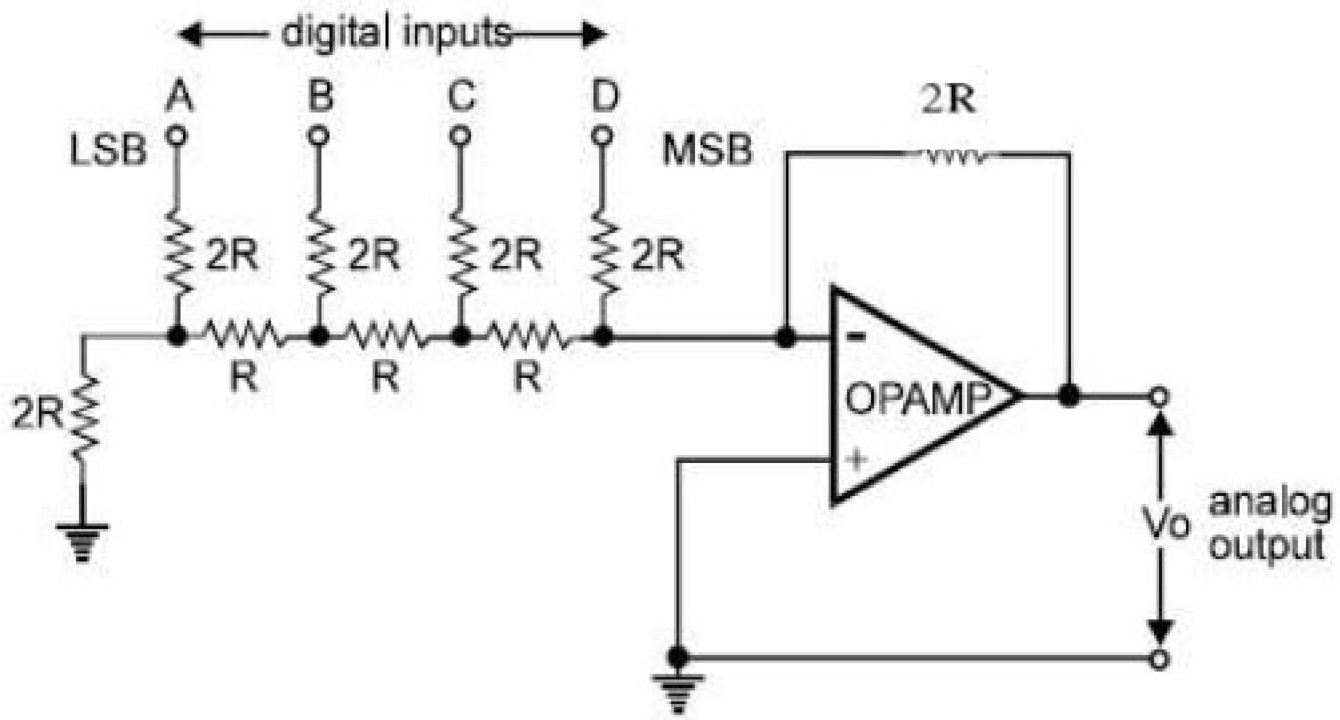
For a 10 bit DAC

$$\% \, resolution = \frac{1}{2^{10} - 1} \times 100\%$$

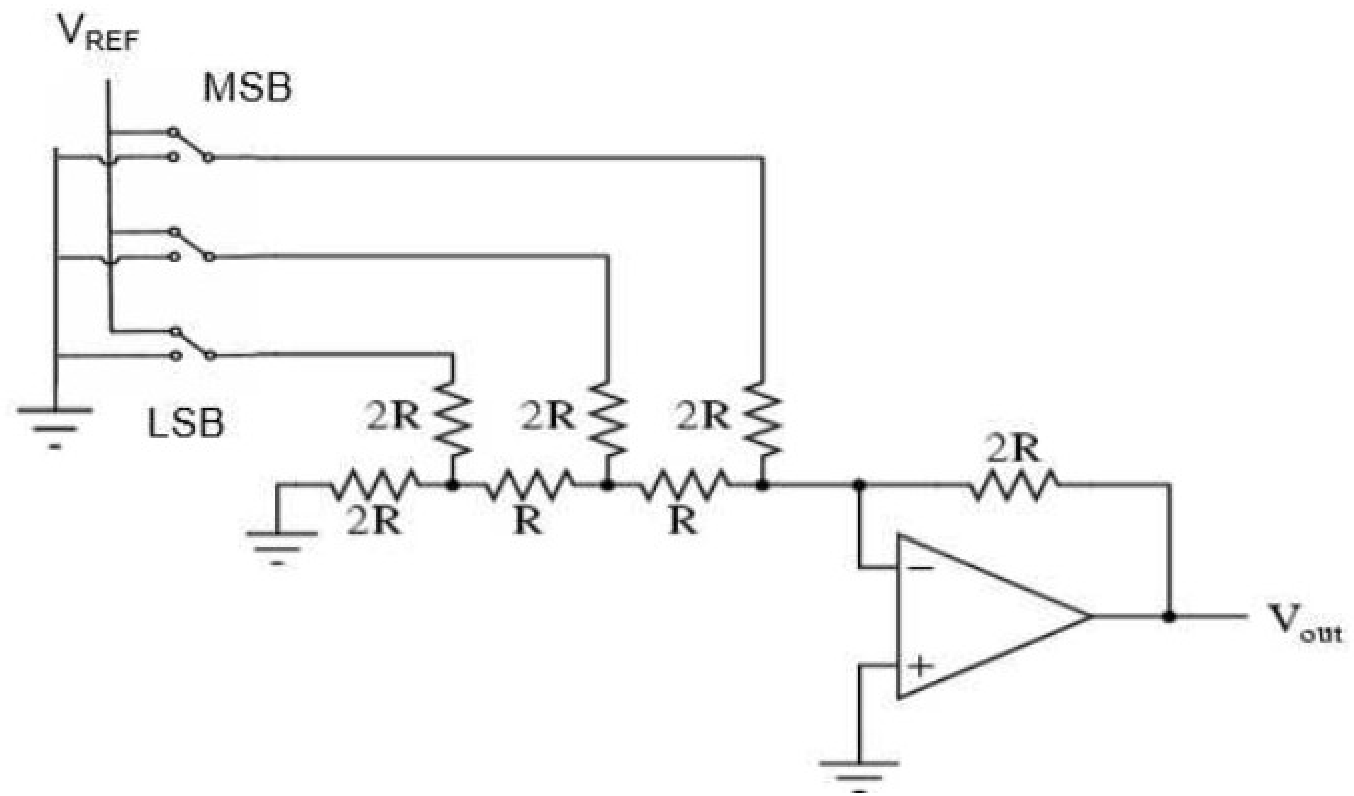
$$= \frac{1}{1023} \times 100\%$$

$$\approx 0.1\%$$

R-2R LADDER

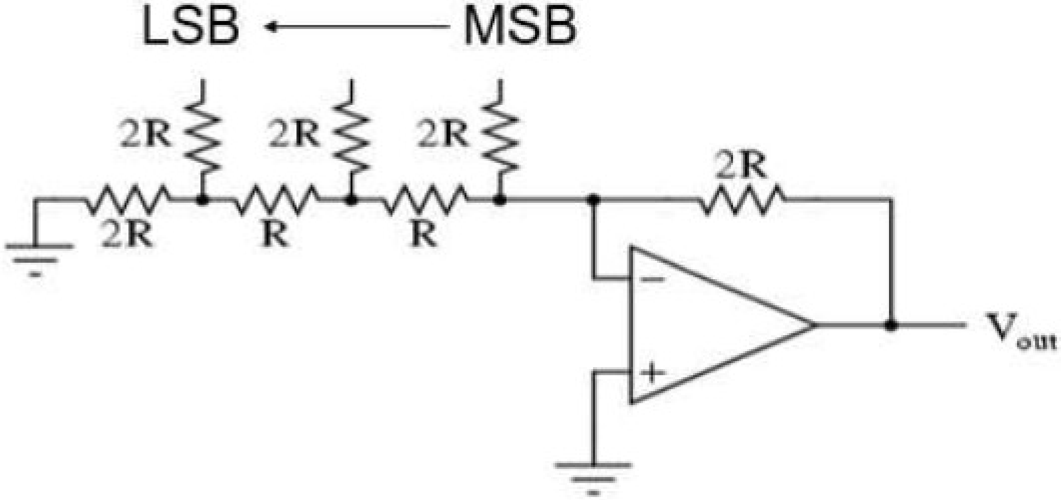

digital inputs
A
B
C
D
LSB
MSB
2R
2R
2R
2R
2R
R
R
R
2R
OPAMP
Vo
analog
output

R-2R LADDER



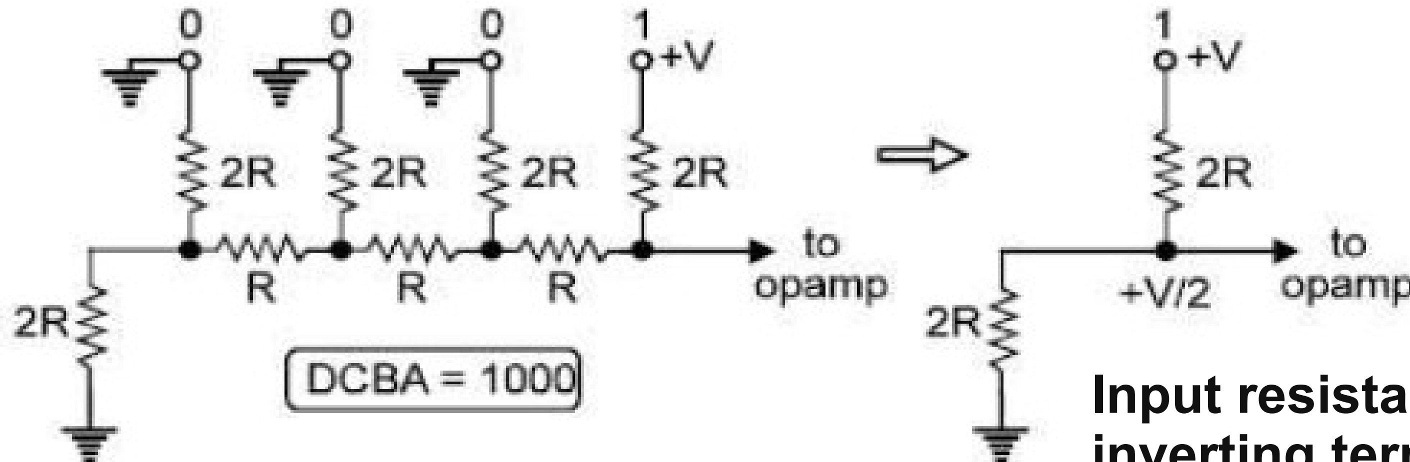
R-2R LADDER

- **The less significant the bit, the more resistors the signal must pass through, before reaching the op-amp**
- **The current is divided by a factor of 2 at each node**



- It has only two values of resistors the R and 2R.
- These values repeat throughout in the circuit.
- The opamp is used at output for scaling the output voltage.

- For simplicity, we ignore the opamp in the above circuit (
- Now consider the circuit, without opamp.
- Suppose the digital input is DCBA = 1000.



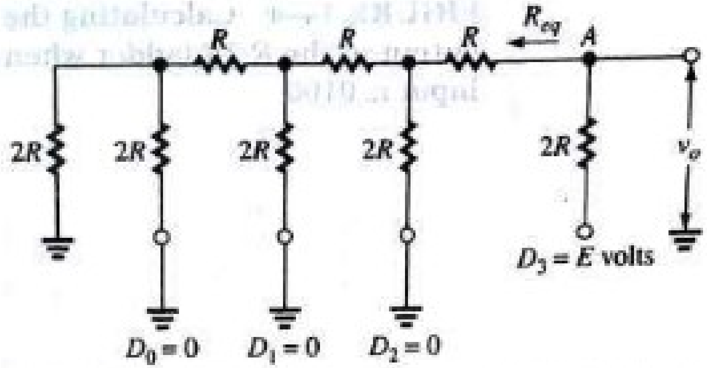
Input resistance on inverting terminal is reduced to 2R || 2R = R

- **Its output is given by –**

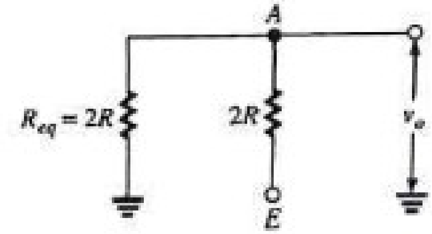
$$\text{output} = \left(\frac{2R}{2R+2R}\right)\times(+V) = \frac{V}{2}$$

- **Now suppose digital input of the same circuit is changed to DCBA = 0100.**
- **Then the output voltage will be V/4, when DCBA = 0010, output voltage will be V/8, for DCBA = 0001, output voltage will be V/16 and so on.**

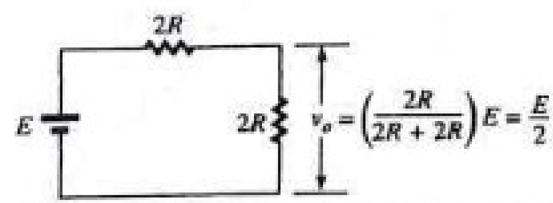
Analysis When MSB = 1



(a) When the input is 1000, D_0, D_1, and D_2 are grounded (0 V) and D_3 is E volts.

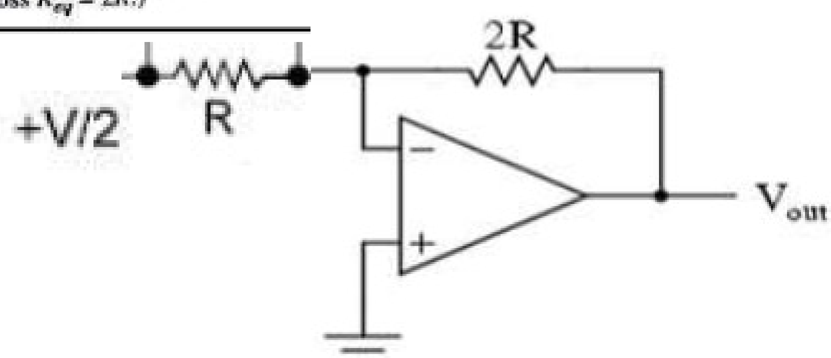


(b) The circuit equivalent to (a) when the network to the left of node A is replaced by its equivalent resistance, R_{eq}.

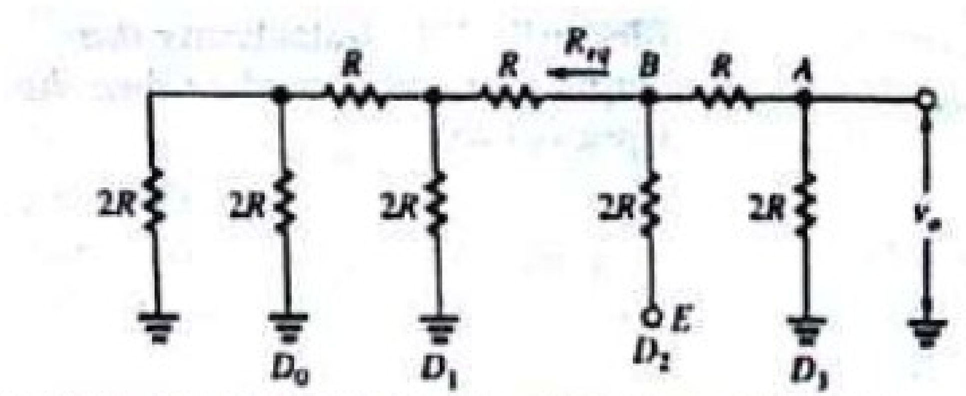


(c) Calculation of v_o using the voltage-divider rule. (Note that v_o in (b) is the voltage across $R_{eq} = 2R$.)

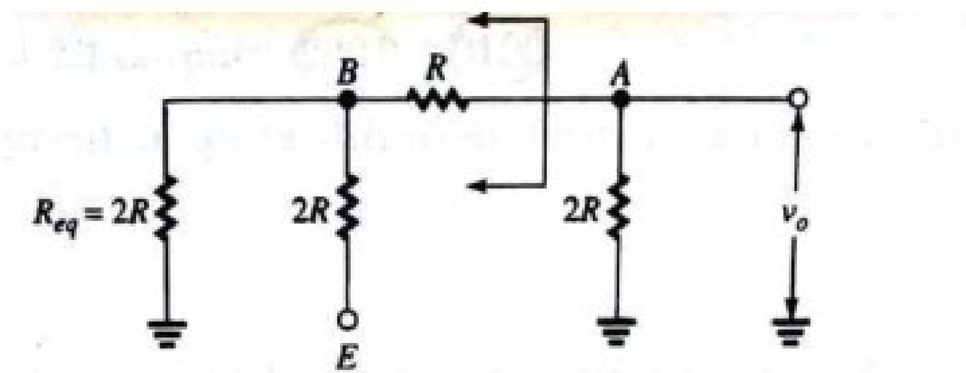
When MSB = 1, the R-2R ladder DAC will reduce to



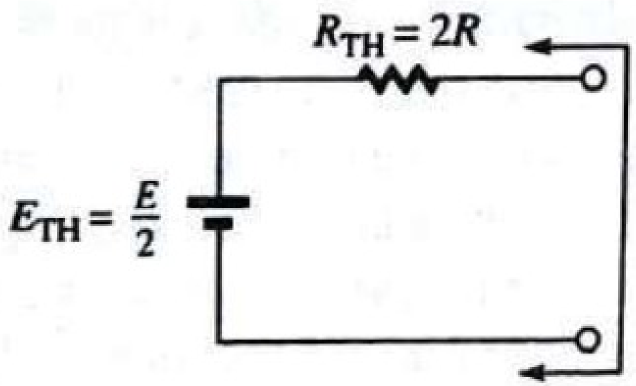
Analysis When the next highest bit = 1



(a) When the input is 0100, D_0, D_1, and D_3 are grounded and D_2 is E volts.



(b) The circuit equivalent to (a) when the network to the left of node B is replaced by its equivalent resistance ($2R$). The Thevenin equivalent circuit to the left of the bracketed arrows is shown in (c).

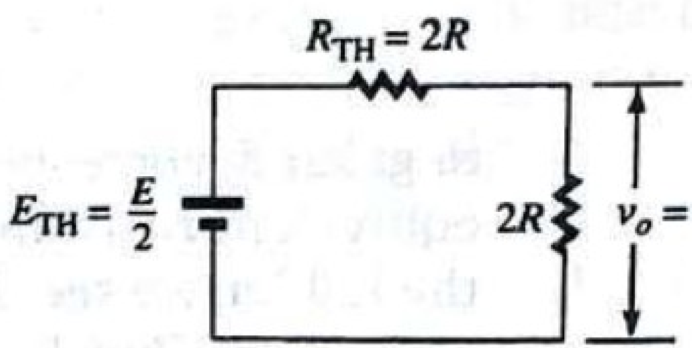


$$R_{TH} = R + 2R || 2R = 2R$$

$$E_{TH} = \left(\frac{2R}{2R + 2R}\right) E = \frac{E}{2}$$

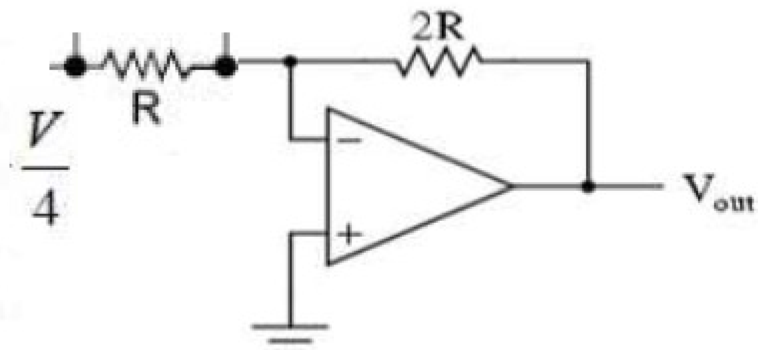
(c) The Thevenin equivalent circuit to the left of node *A*.

When DCBA = 0100, the R-2R ladder DAC will reduce to



$$v_o = \left(\frac{2R}{2R + 2R}\right) \frac{E}{2} = \frac{E}{4}$$

(d) Calculation of v_o using the voltage-divider rule.



- The general formula for the above circuit of R–2R ladder, including the opamp also, will be –

Vo = -2R/R(Vref D/2 + Vref C/4 + Vref B/8 + Vref A/16)

$$V_{OUT} = V_{REF}\left(B_3 + \frac{B_2}{2} + \frac{B_1}{4} + \frac{B_0}{8}\right)$$

Same as weighted resistor if gain of op-amp summing amplifier is 2

Imp: Gain of OP-AMP in weighted resistor DAC = 1

For 3 bit DAC

$$V_{OUT} = V_{REF}\left(B_2 + \frac{B_1}{2} + \frac{B_0}{4}\right)$$

PROS & CONS

	Binary Weighted	R-2R
Pros	Easily understood	Only 2 resistor values Easier implementation Faster response time Easily scalable to any desired number of bits
Cons	Limited to ~ 8 bits Large # of resistors Susceptible to noise Expensive Greater Error	More confusing analysis

(ii)A 4-bit Weighted resistor DAC having R= 10 kΩ and V_R= 10 V. Find its resolution and output voltage for an input 1101. (4)

$$V_{OUT} = -V_{REF}\left(B_3 + \frac{B_2}{2} + \frac{B_1}{4} + \frac{B_0}{8}\right)$$

Resolution of 4 bit weighted resistor DAC with Vref = 10V is 10/8 = 1.25V

(ii)A 4-bit R-2R ladder type DAC having R= 10 kΩ and V_R= 10 V. Find its resolution and output voltage for an input 1101. (4)

$$V_{OUT} = -V_{REF}\left(B_3 + \frac{B_2}{2} + \frac{B_1}{4} + \frac{B_0}{8}\right)$$

Resolution of 4 bit R-2R ladder DAC with Vref = 10V is 10/8 = 1.25V

% Resolution of 4 bit DAC

(1/15)*100 = 6.67%.

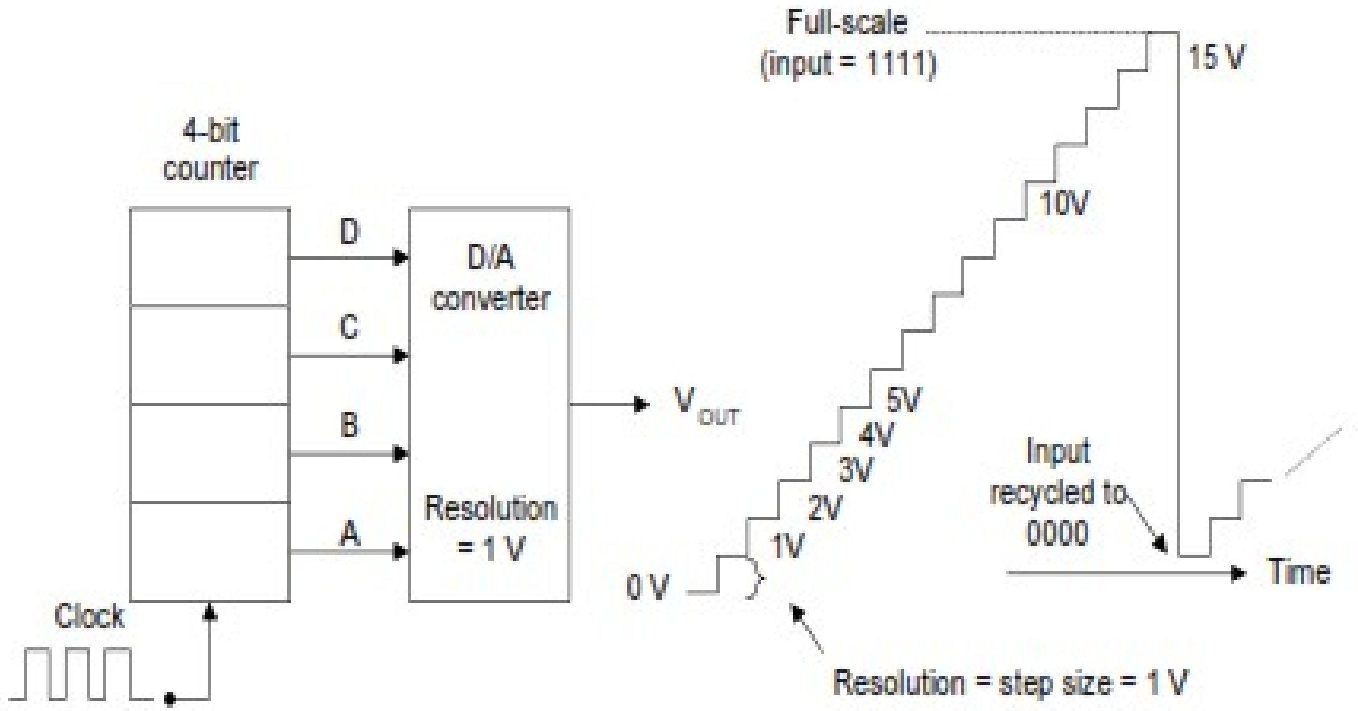


Fig. 7.3 : Output wave forms of a four bit DAC.

Other methods for finding analog o/p voltage or current

analog output = K × digital input

where K is the proportionality factor and it is constant value for a given DAC. The analog output can of course be a voltage or current. When it is a voltage, K will be in voltage units, and when the output is current, K will be in current units. K is the amount of voltage (or current) per step, a

ie, K = step size

Remember, the proportionality factor, K, will vary from one DAC to another.

The step size is 0.2 V, which is the proportionality factor K. The digital input is 10001 = 17_{10}. Thus we have :

V_{OUT} = (0.2 V) × 17
= 3.4V

A 5-bit DAC has a current output. For a digital input of 101000, an output current of 10mA is produced. What will IOUT be for a digital input of 11101?

Solution

The digital input 10100_2 is equal to decimal 20. Since I_{OUT} = 10 mA for this case, the proportionality factor as 0.5 mA. Thus, we can find for a digital input such as $11101_2 = 29_{10}$ as follows :

$$I_{OUT} = (0.5\text{mA}) \times 29$$
$$= 14.5 \text{ mA}$$

What is the largest value of output voltage from an 8-bit DAC that produces 1.0V for a digital input of 00110010?

Solution

$00110010_2 = 50_{10}$
$1.0\ V = K \times 50$

Therefore,
$K = 20\ mV$

The largest output will occur for an input of $11111111_2 = 255_{10}$.

$V_{OUT}(max) = 20mV \times 255$
$= 5.10\ V$

SPECIFICATIONS OF DAC (1)

1. **Resolution : The resolution of a DAC is a measure of the fineness of the increments between the output values.**
   - **For example a 4-bit DAC has a resolution of one part in $2^4 - 1$: (1/15)*100 = 6.67%.**
2. **Accuracy: Accuracy is derived from a comparison of the actual output of a DAC with the expected output.**
   - **It is expressed as a percentage of a full-scale or maximum output voltage.**
   - **If a converter has a full-scale output of 10v and the accuracy is +/-0.1%, then the maximum error for any output voltage is (10V)(0.001) = 10 mV**

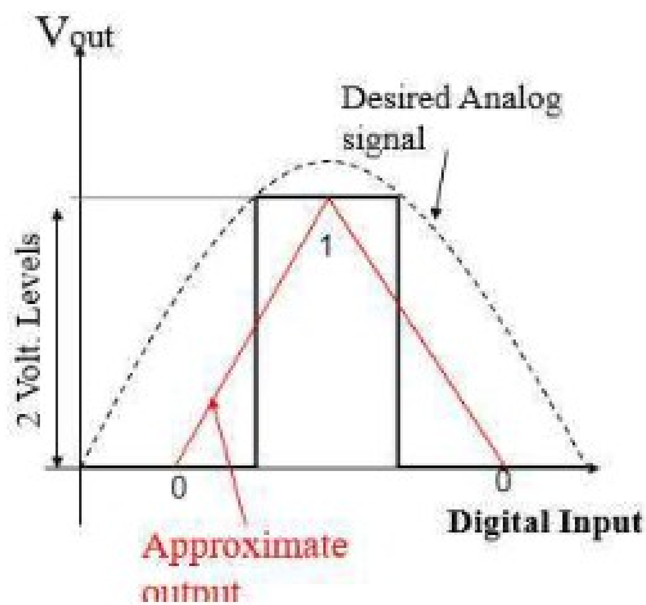
SPECIFICATIONS OF DAC (2)

3. **Linearity: A linear error is a deviation from the ideal straight-line output of a DAC.**
   - **A special case is an offset error, which is the amount of output voltage when the input bits are all 0's.**
4. **Monotonicity: A DAC is monotonic if it doesn't take any reverse steps when it is sequenced over its entire range of input bits.**
5. **Settling Time: Normally defined as the time it takes a DAC to settle within +/- ½ LSB of its final value when a change occurs in the input code.**

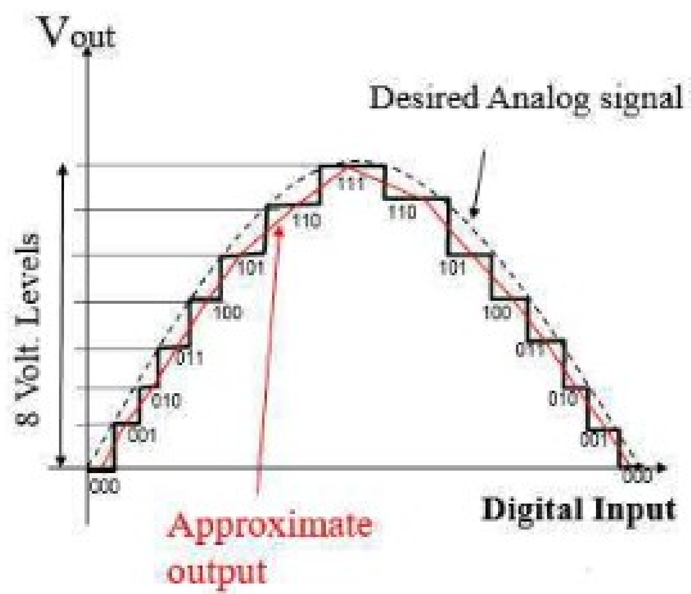
RESOLUTION

- **Resolution is the measure of how closely can we approximate the desired output signal (Higher Res. = finer detail = smaller Voltage divisions)**

Poor Resolution(1 bit)

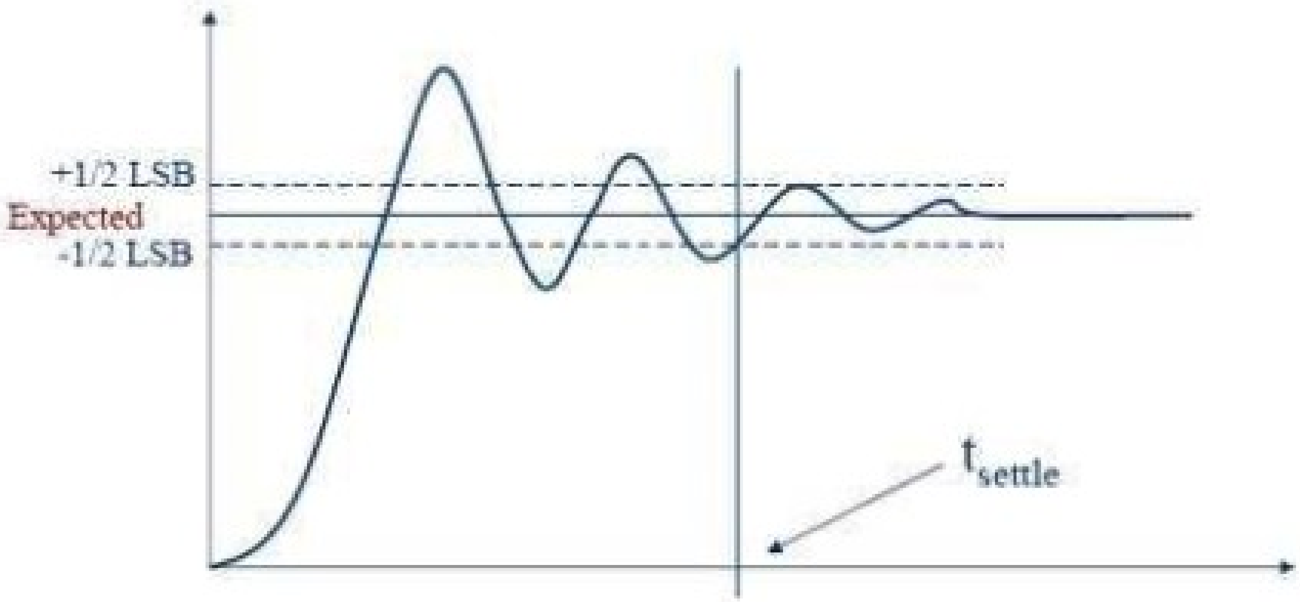


Better Resolution(3 bit)



SETTLING TIME

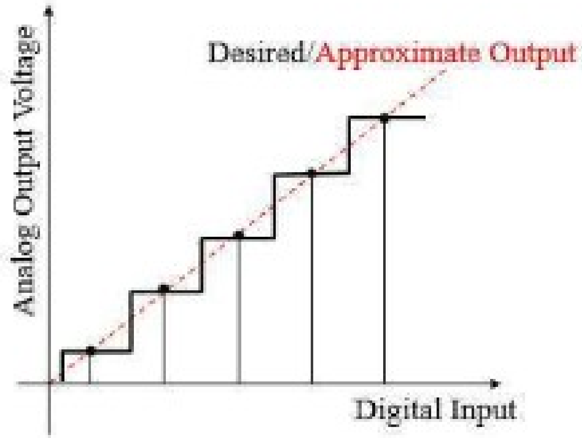
- **Settling Time:** The time required for the input signal voltage to settle to the expected output voltage(within +/- V_{LSB}).
- Any change in the input state will not be reflected in the output state immediately.
- It is also called conversion speed.



LINEARITY

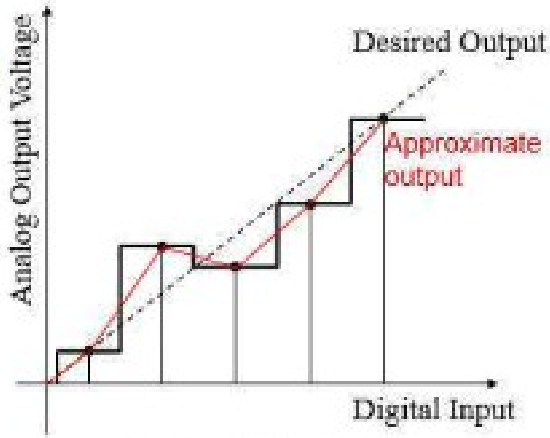
- **<u>Linearity:</u> is the difference between the desired analog output and the actual output over the full range of expected values.**
- **Ideally, a DAC should produce a linear relationship between a digital input and the analog output, this is not always the case.**

Linearity(Ideal Case)



Perfect Agreement

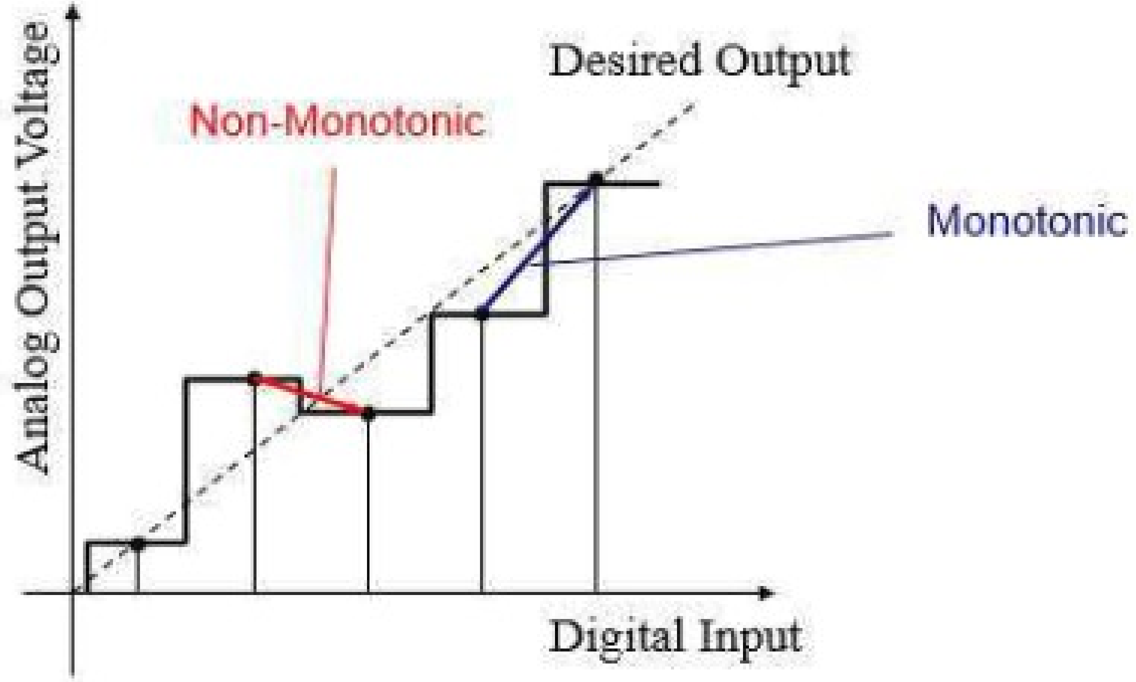
NON-Linearity(Real World)



Miss-alignment

MONOTONICITY

- **A DAC is Monotonic if its output increases or remains the same for an increment in the Digital Code.**
- **Conversely, a DAC is Non-Monotonic, if the Output decreases for an increment in the Digital Code.**



ACCURACY

- The Accuracy of a DAC is the difference between output practical analog output to the ideal expected output for a given digital input.
- For an example if a DAC of 10 V is said to have an accuracy of 0.01% there will be 10mv output deviation.
- Accuracy is measured in terms of the DAC offset error, gain error and Linearity issues.