ELECTRONIC MEASUREMENT & INSTRUMENTATION (BEC-29)

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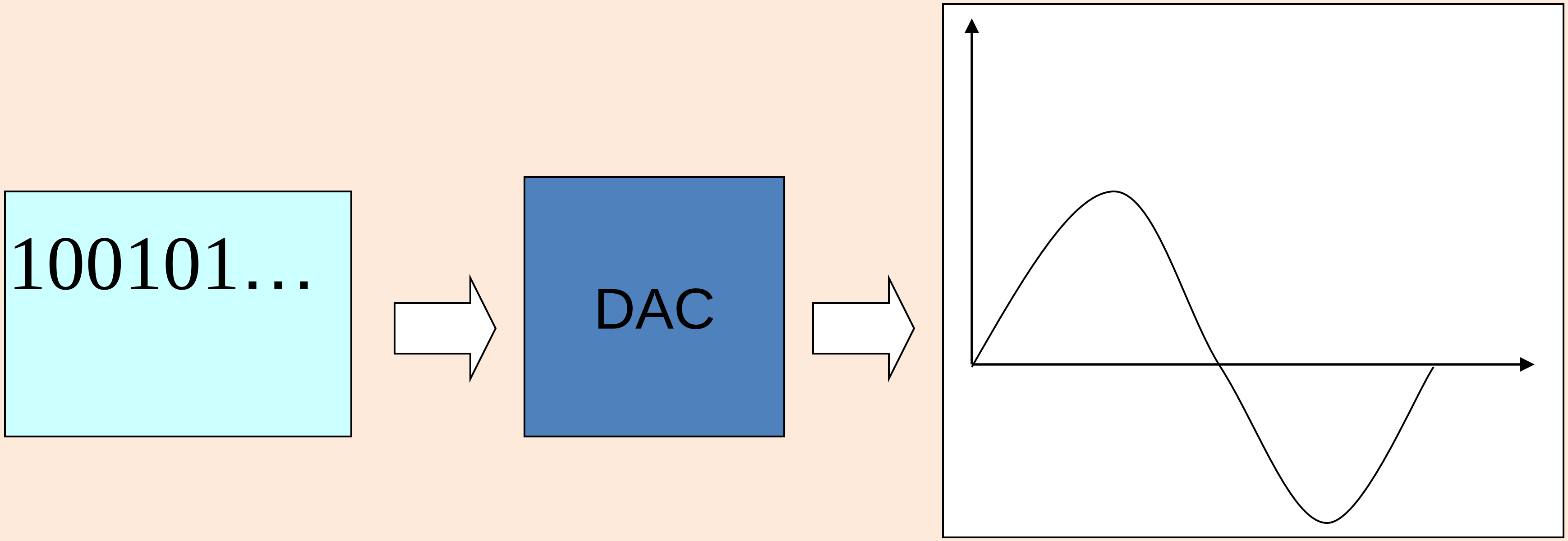
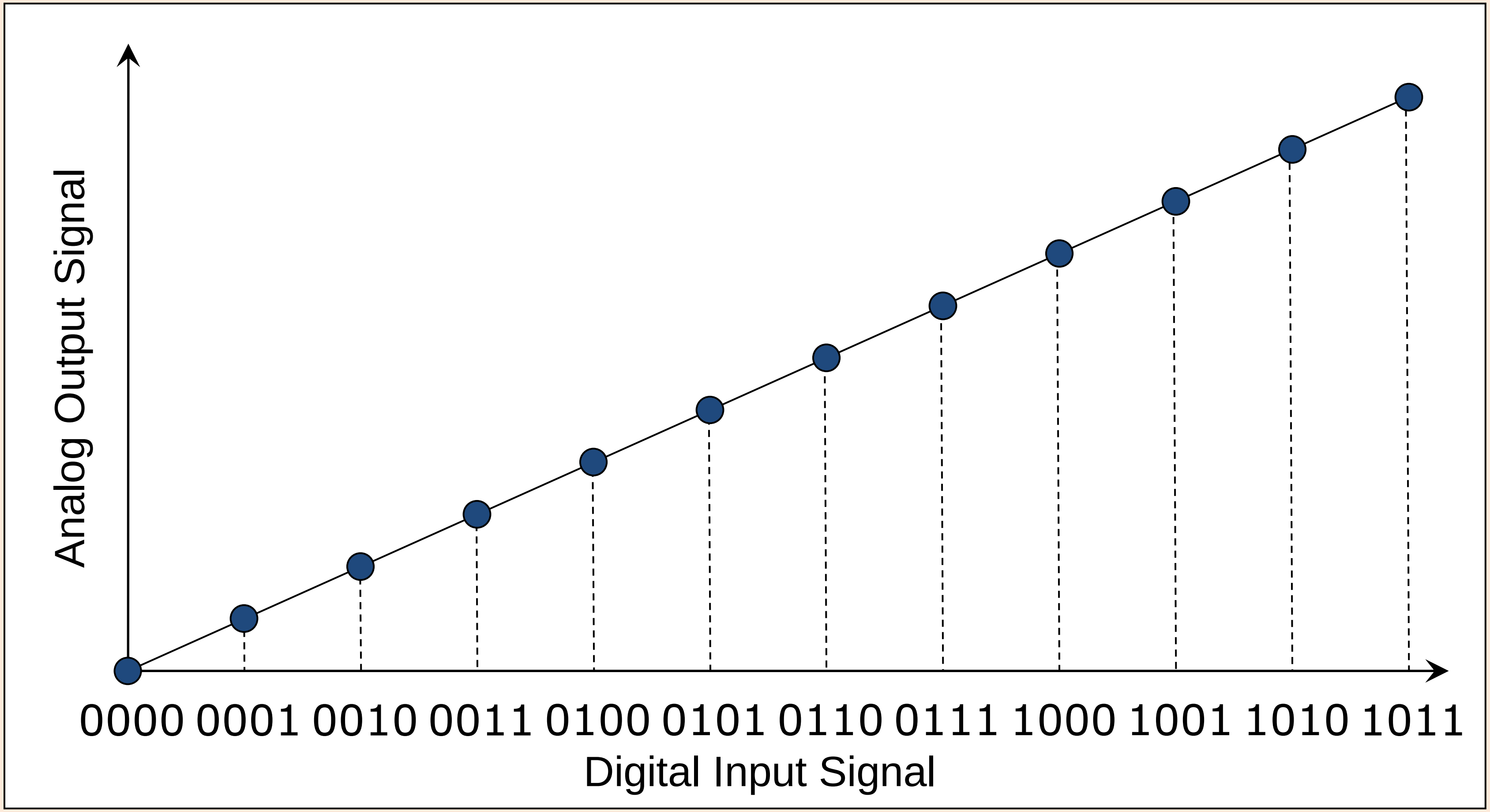
UNIT-III
Digital to Analog Converters (DAC)

What is a DAC?

- A digital to analog converter (DAC) converts a digital signal to an analog voltage or current output.



What is a DAC?



Analog Output Signal
0000 0001 0010 0011 0100 0101 0110 0111 1000 1001 1010 1011
Digital Input Signal

Types of DACs

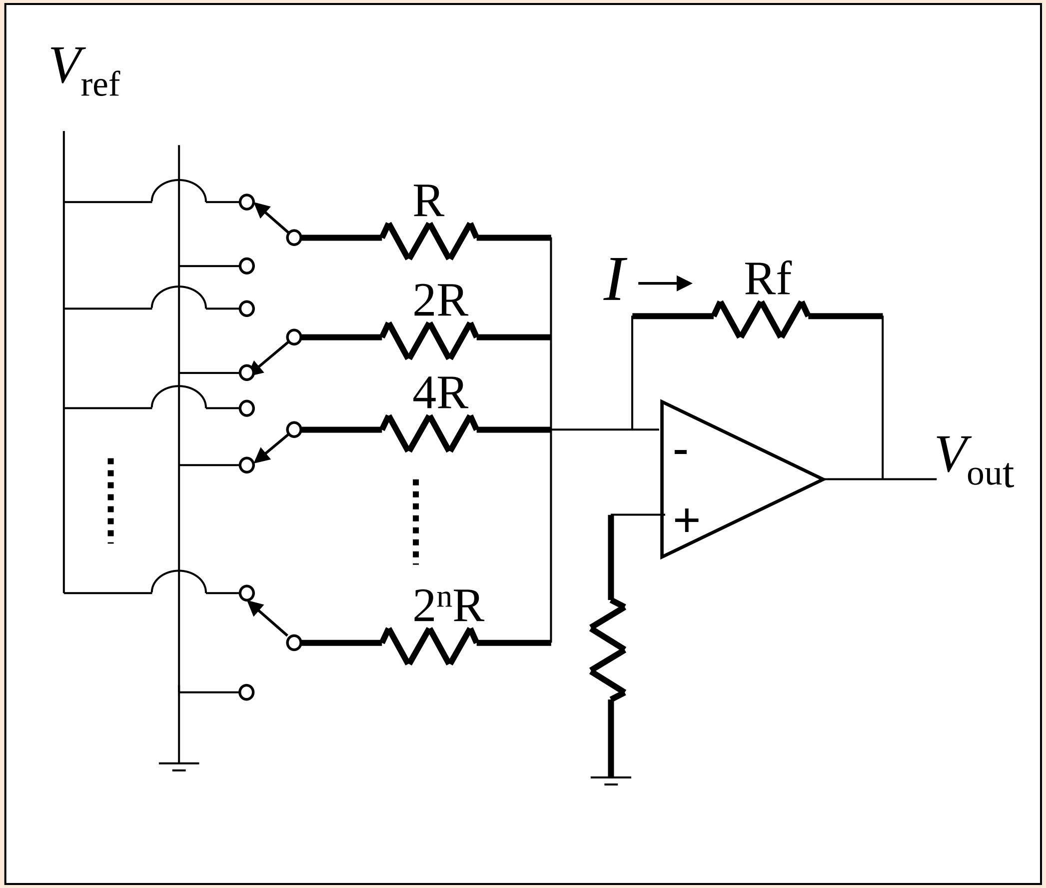
- Many types of DACs available.
- Usually switches, resistors, and op-amps used to implement conversion
- Two Types:
  - – Binary Weighted Resistor
  - – R-2R Ladder

Binary Weighted Resistor

- Utilizes a summing op-amp circuit
- Weighted resistors are used to distinguish each bit from the most significant to the least significant
- Transistors are used to switch between V_{ref} and ground (bit high or low)

Binary Weighted Resistor

- Assume Ideal Op-amp
- No current into op-amp
- Virtual ground at inverting input
- $V_{out} = -IR_f$

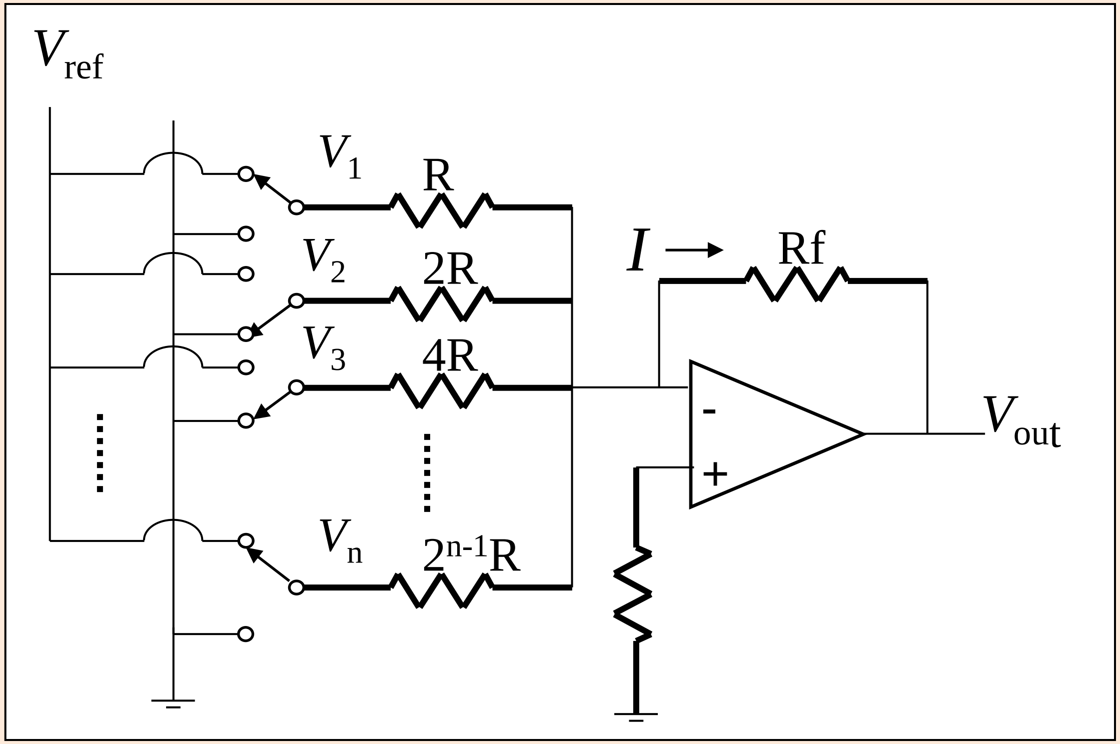


Binary Weighted Resistor

Voltages V_1 through V_n are either V_{ref} if corresponding bit is high or ground if corresponding bit is low

V_1 is most significant bit

V_n is least significant bit



MSB

LSB

$$V_{out} = -IR_f = -R_f\left(\frac{V_1}{R} + \frac{V_2}{2R} + \frac{V_3}{4R} + \cdots \frac{V_n}{2^{n-1}R}\right)$$

Binary Weighted Resistor

If $R_f = R/2$

$$V_{out} = -IR_f = -\left(\frac{V_1}{2} + \frac{V_2}{4} + \frac{V_3}{8} + \cdots \frac{V_n}{2^n}\right)$$

For example, a 4-Bit converter yields

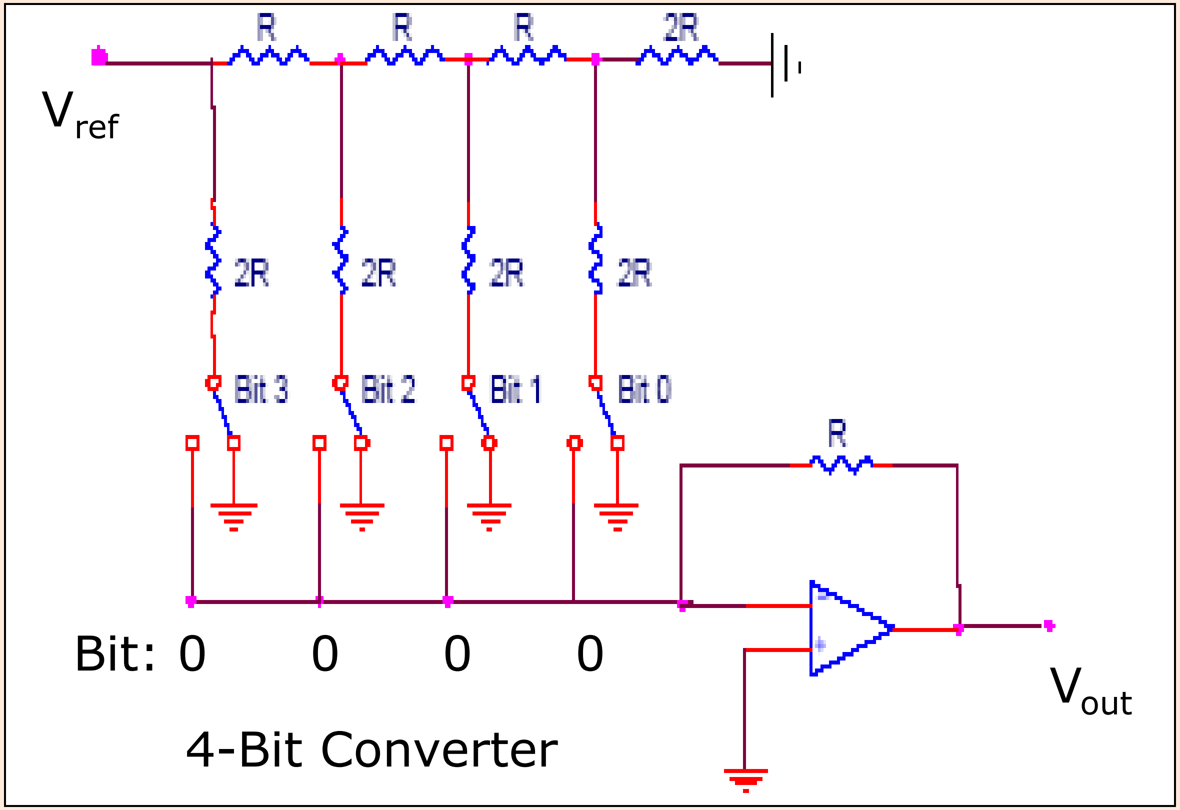
$$V_{out} = -V_{ref}\left(b_3\frac{1}{2} + b_2\frac{1}{4} + b_1\frac{1}{8} + b_0\frac{1}{16}\right)$$

Where b_3 corresponds to Bit-3, b_2 to Bit-2, etc.

Binary Weighted Resistor

- Advantages
  - Simple Construction/Analysis
  - Fast Conversion
- Disadvantages
  - Requires large range of resistors (2000:1 for 12-bit DAC) with necessary high precision for low resistors
  - Requires low switch resistances in transistors
  - Can be expensive. Therefore, usually limited to 8-bit resolution.

R-2R Ladder

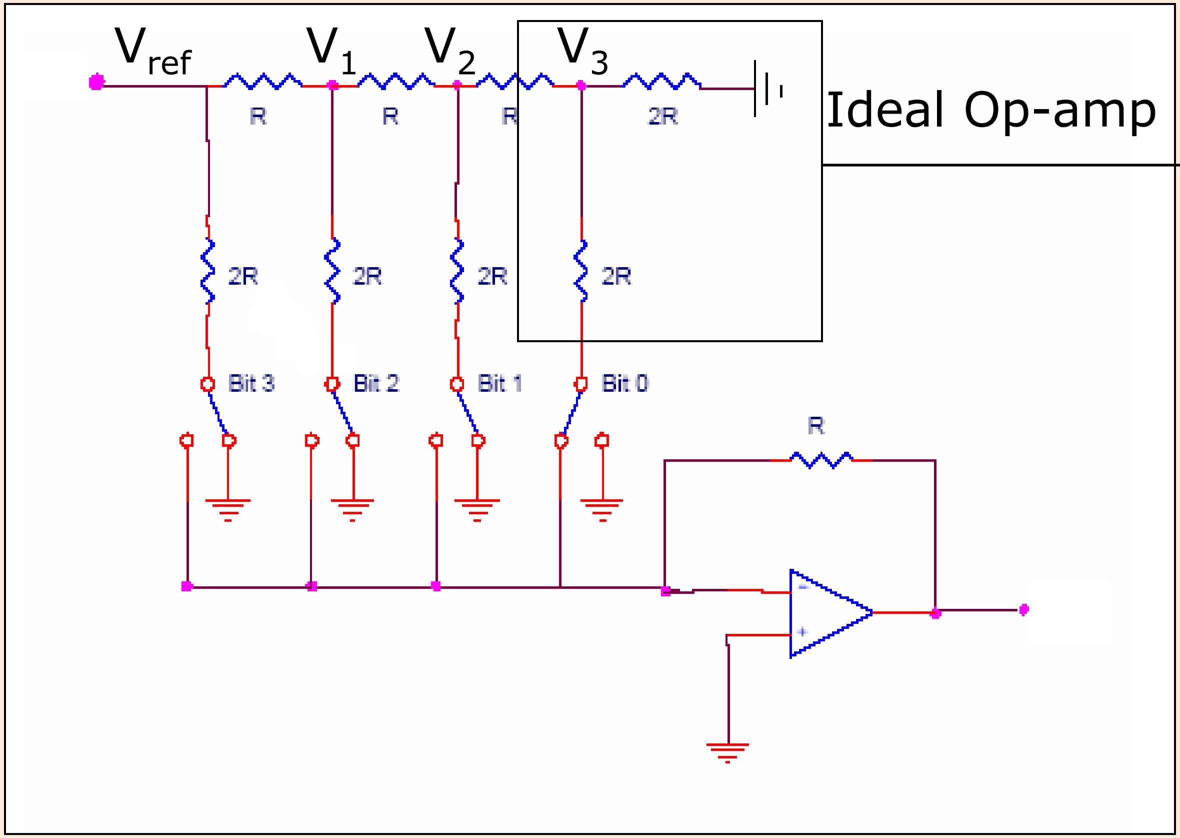


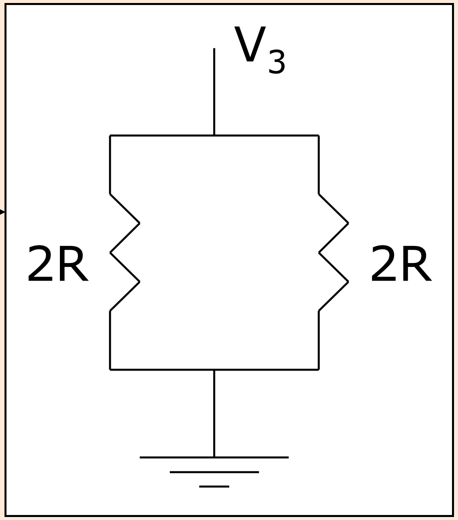
Each bit corresponds to a switch:

If the bit is high, the corresponding switch is connected to the inverting input of the op-amp.

If the bit is low, the corresponding switch is connected to ground.

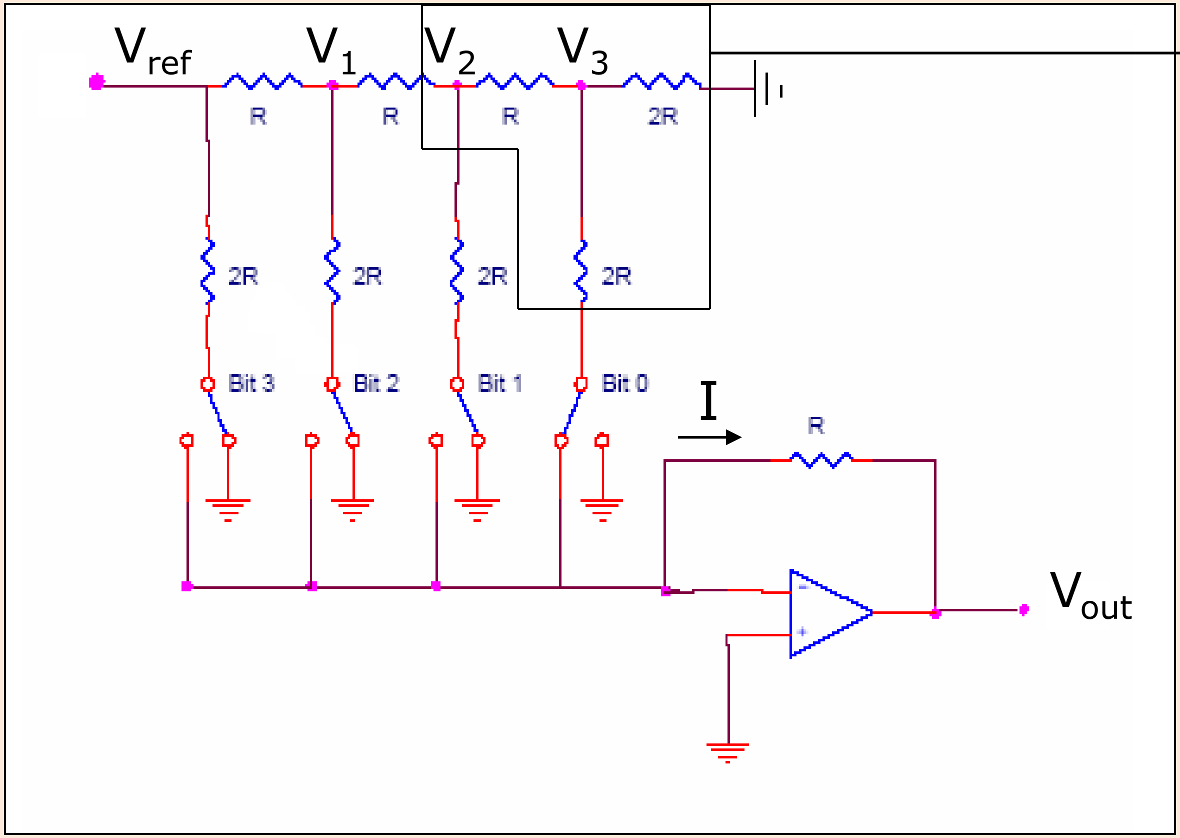
R-2R Ladder

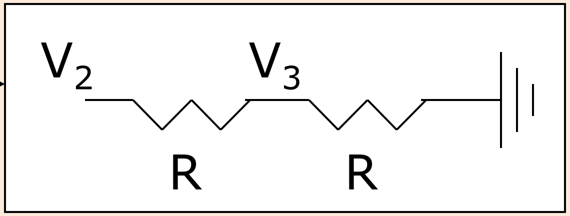




$$R_{eq} = \frac{(2R)(2R)}{(2R+2R)} = R$$

R-2R Ladder





$$V_3 = \left(\frac{R}{R+R}\right)V_2 = \frac{1}{2}V_2$$

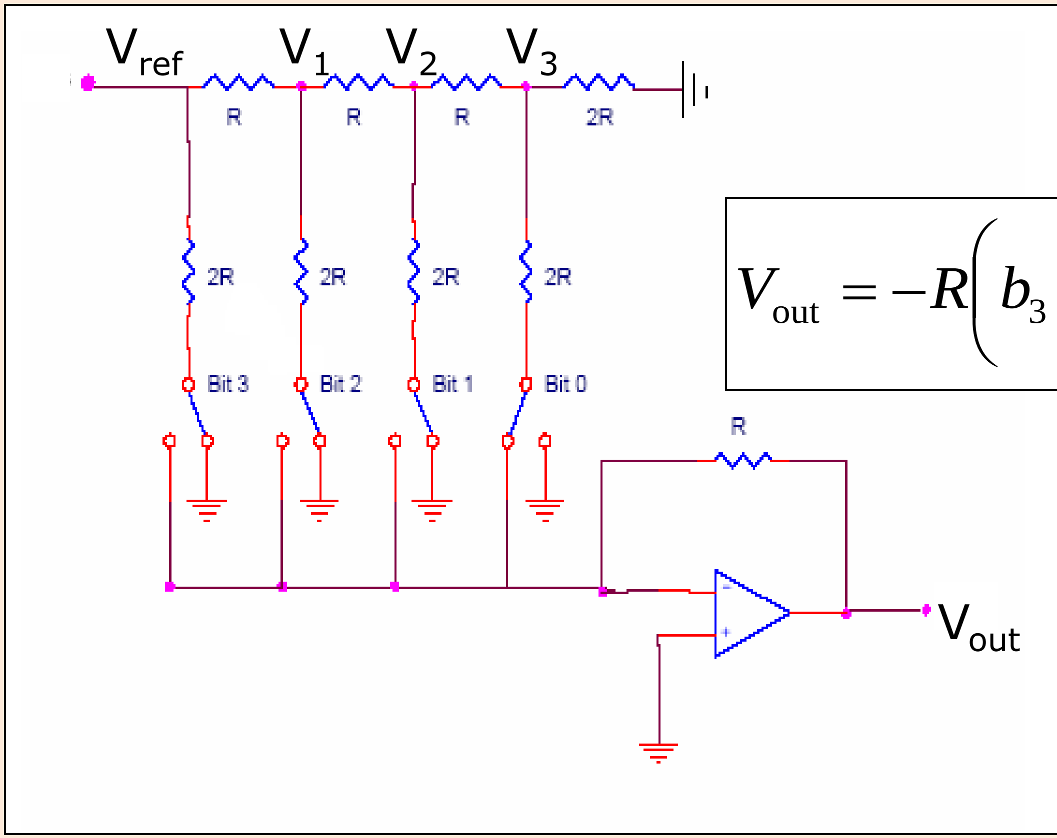
Likewise,

$$V_2 = \frac{1}{2}V_1$$

$$V_1 = \frac{1}{2}V_{ref}$$

$$V_{out} = -IR$$

R-2R Ladder



Results:

$$V_3 = \frac{1}{8}V_{\text{ref}},\ V_2 = \frac{1}{4}V_{\text{ref}},\ V_1 = \frac{1}{2}V_{\text{ref}}$$

$$V_{\text{out}} = -R\left(b_3\frac{V_{\text{ref}}}{2R} + b_2\frac{V_{\text{ref}}}{4R} + b_1\frac{V_{\text{ref}}}{8R} + b_0\frac{V_{\text{ref}}}{16R}\right)$$

Where b_3 corresponds to bit 3, b_2 to bit 2, etc.

If bit n is set, $b_n=1$

If bit n is clear, $b_n=0$

R-2R Ladder

For a 4-Bit R-2R Ladder

$$V_{\text{out}} = -V_{\text{ref}} \left(b_3 \frac{1}{2} + b_2 \frac{1}{4} + b_1 \frac{1}{8} + b_0 \frac{1}{16} \right)$$

For general n-Bit R-2R Ladder or Binary Weighted Resister DAC

$$V_{\text{out}} = -V_{\text{ref}} \sum_{i=1}^{n} b_{n-i} \frac{1}{2^i}$$

R-2R Ladder

- Advantages
  - Only two resistor values (R and 2R)
  - Does not require high precision resistors
- Disadvantage
  - Lower conversion speed than binary weighted DAC

Specifications of DACs

- Resolution
- Speed
- Linearity
- Settling Time
- Reference Voltages
- Errors

Resolution

- Smallest analog increment corresponding to 1 LSB change
- An N-bit resolution can resolve 2^N distinct analog levels
- Common DAC has a 8-16 bit resolution

$$\text{Resolution} = V_{LSB} = \frac{V_{ref}}{2^N}$$

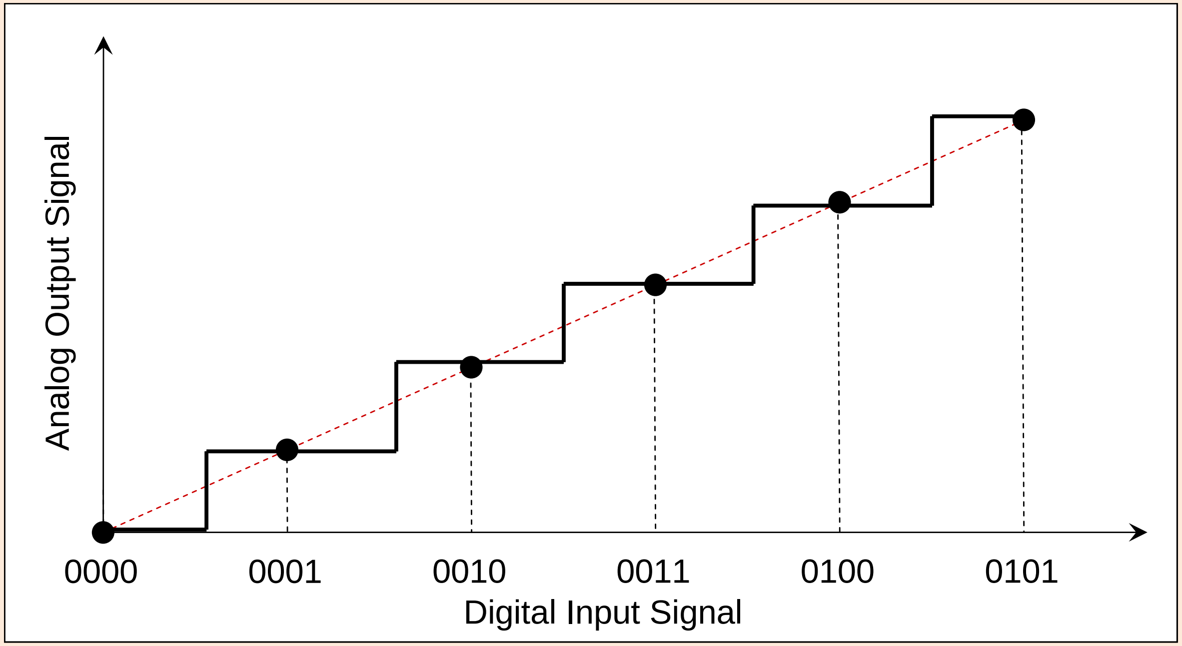
$$\text{where } N = number\,of\ bits$$

Speed

- Rate of conversion of a single digital input to its analog equivalent
- Conversion rate depends on
  - clock speed of input signal
  - settling time of converter
- When the input changes rapidly, the DAC conversion speed must be high.

Linearity

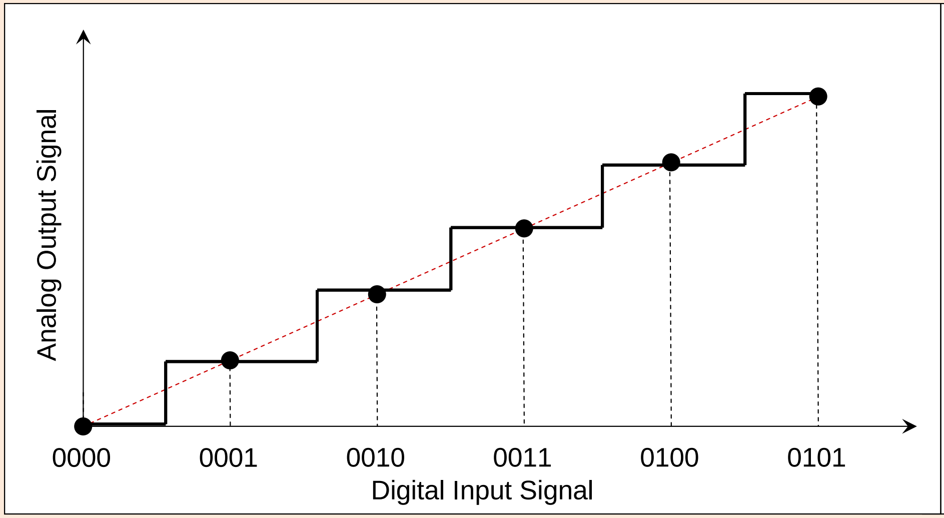
- The difference between the desired analog output and the actual output over the full range of expected values



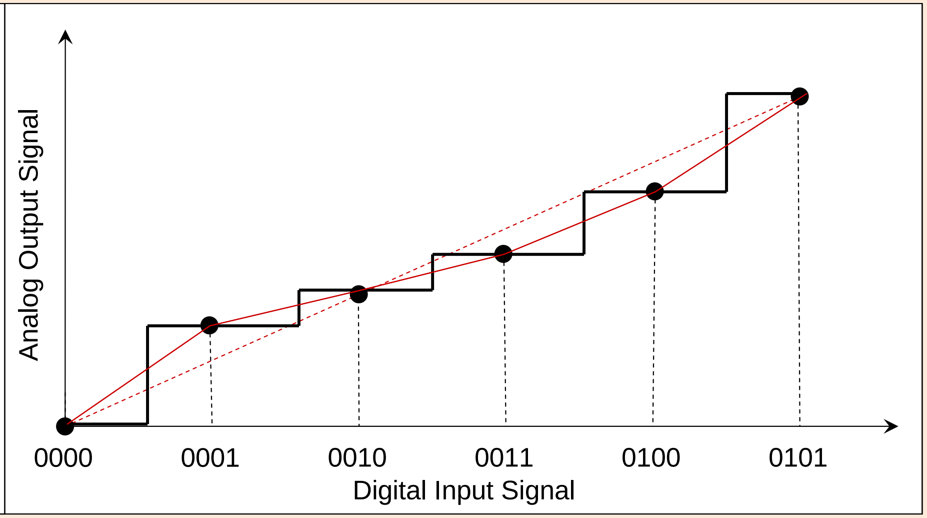
Linearity

- Ideally, a DAC should produce a linear relationship between the digital input and analog output

Linearity (Ideal)

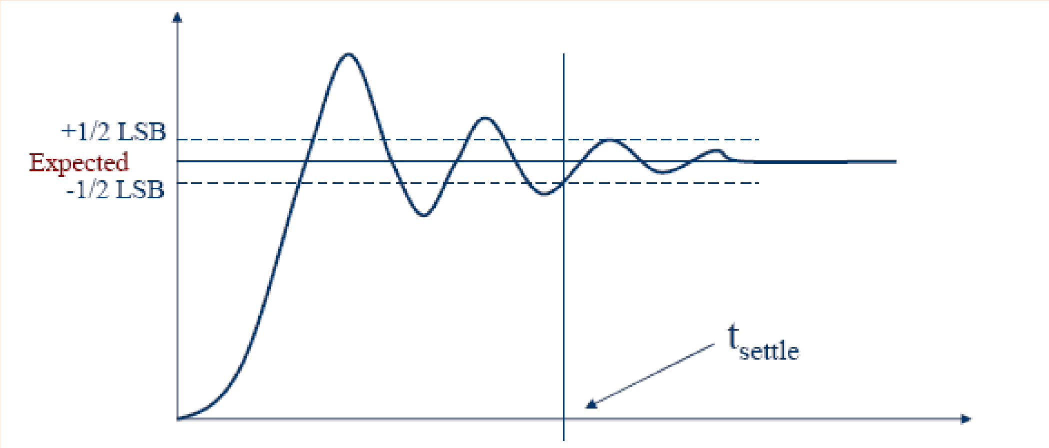


Non-Linearity



Settling Time

- Time required for the output signal to settle within +/- ½ LSB of its final value after a given change in input scale
- Limited by slew rate of output amplifier
- Ideally, an instantaneous change in analog voltage would occur when a new binary word enters into DAC



Reference Voltages

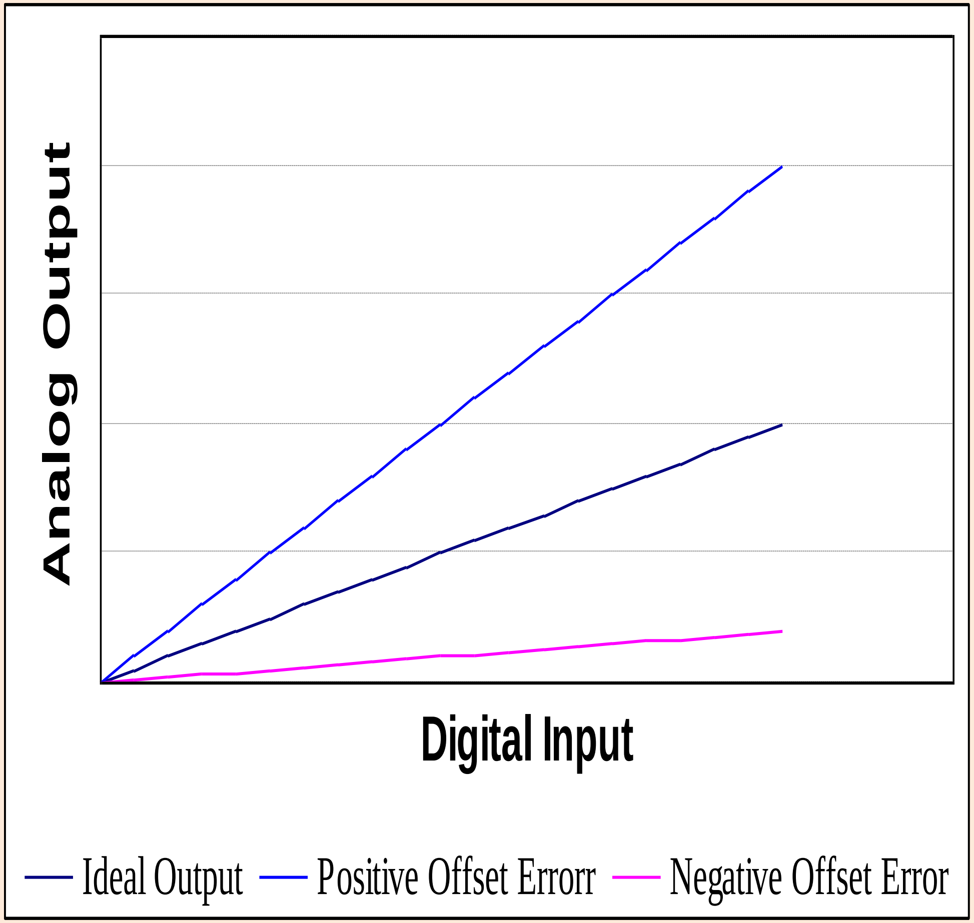
- Used to determine how each digital input will be assigned to each voltage division
- Types:
  - Non-multiplier DAC: Vref is fixed
  - Multiplier DAC: Vref provided by external source

Types of Errors Associated with DACs

- Gain
- Offset
- Full Scale
- Resolution
- Non-Linearity
- Non-Monotonic
- Settling Time and Overshoot

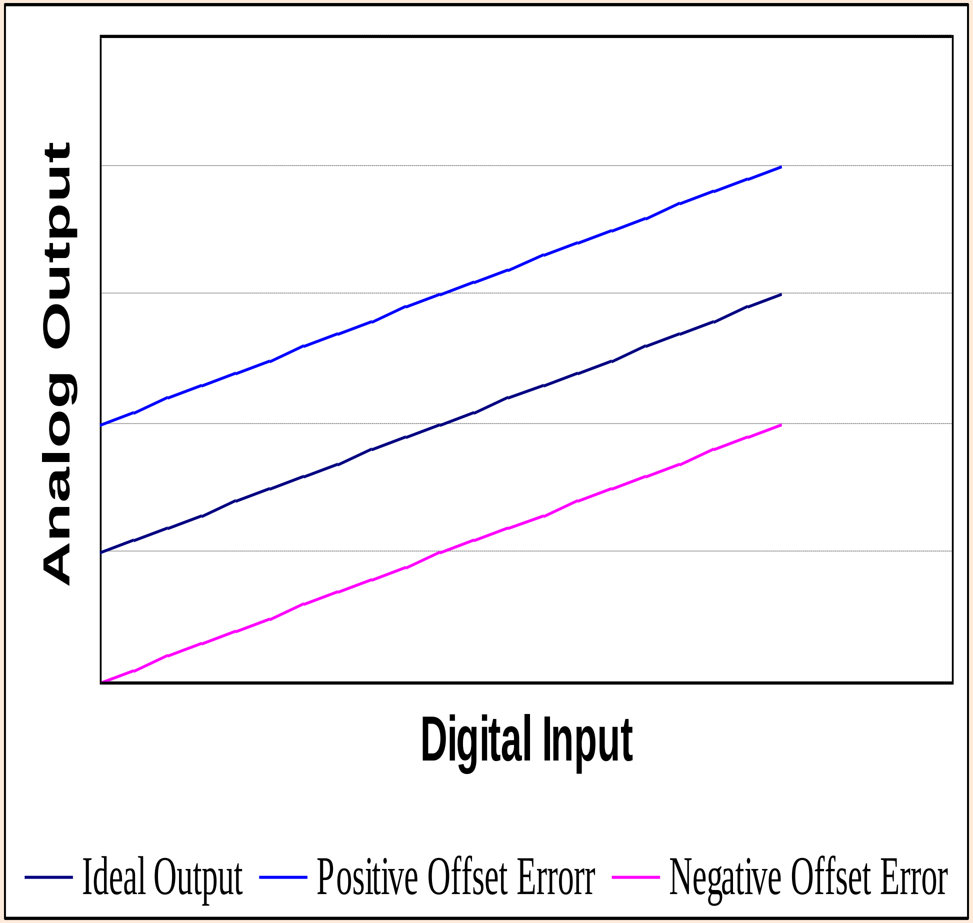
Gain Error

- Occurs when the slope of the actual output deviates from the ideal output



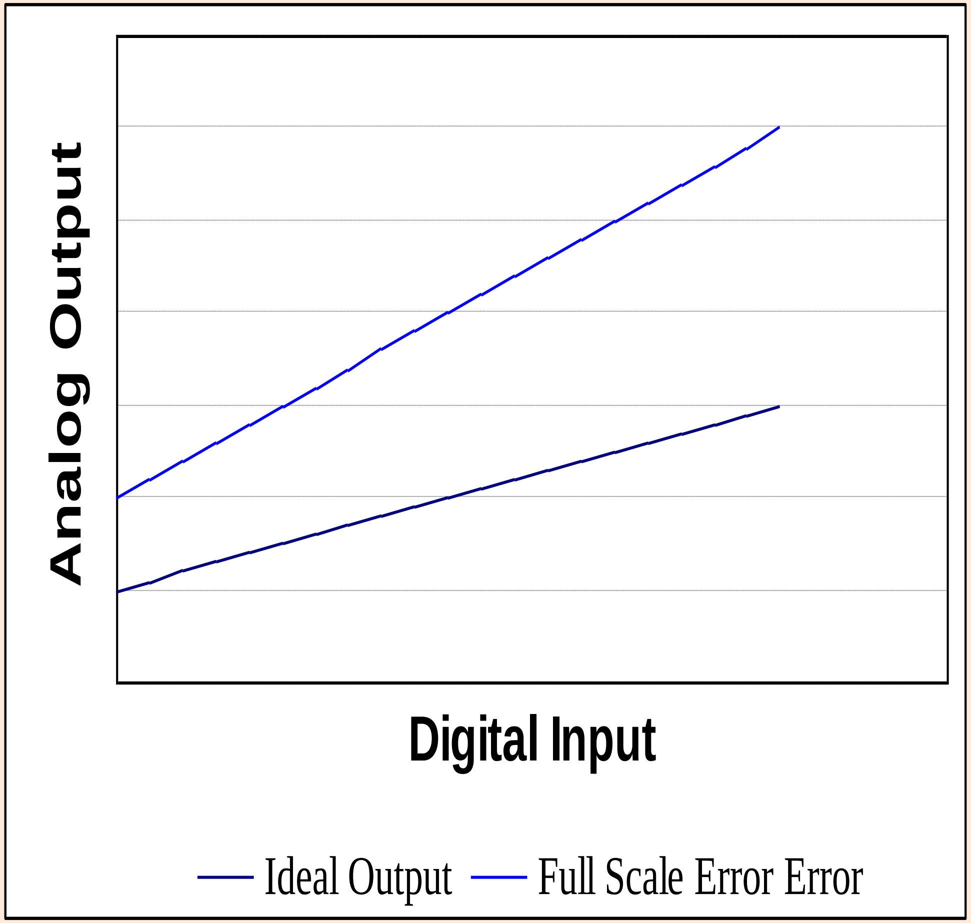
Offset Error

- Occurs when there is a constant offset between the actual output and the ideal output



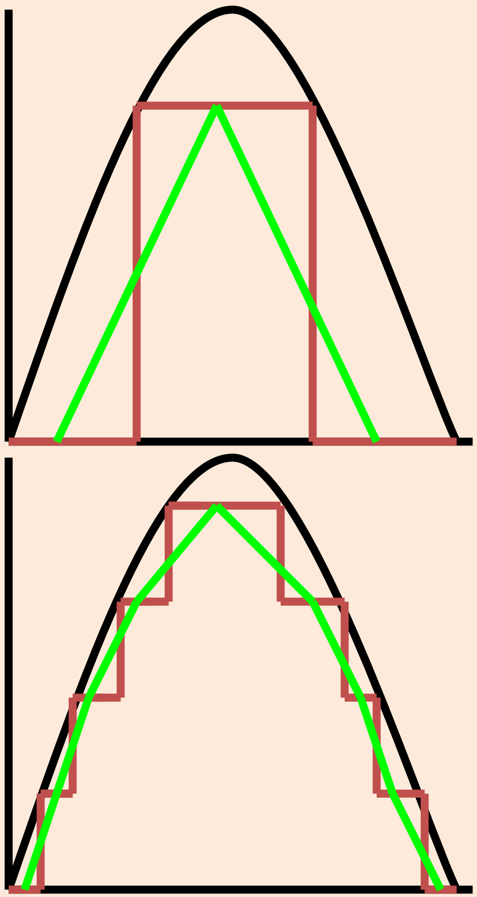
Full Scale Error

- Occurs when the actual signal has both gain and offset errors



Resolution Error

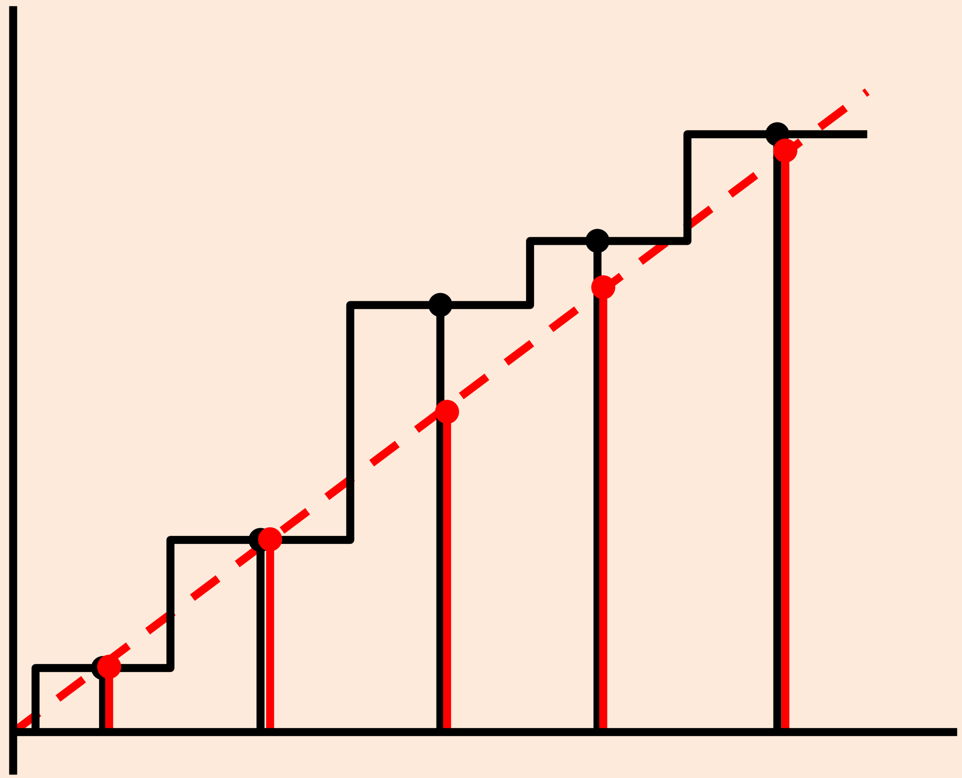
- Poor representation of ideal output due to poor resolution
- Size of voltage divisions affect the resolution



Non-Linearity Error

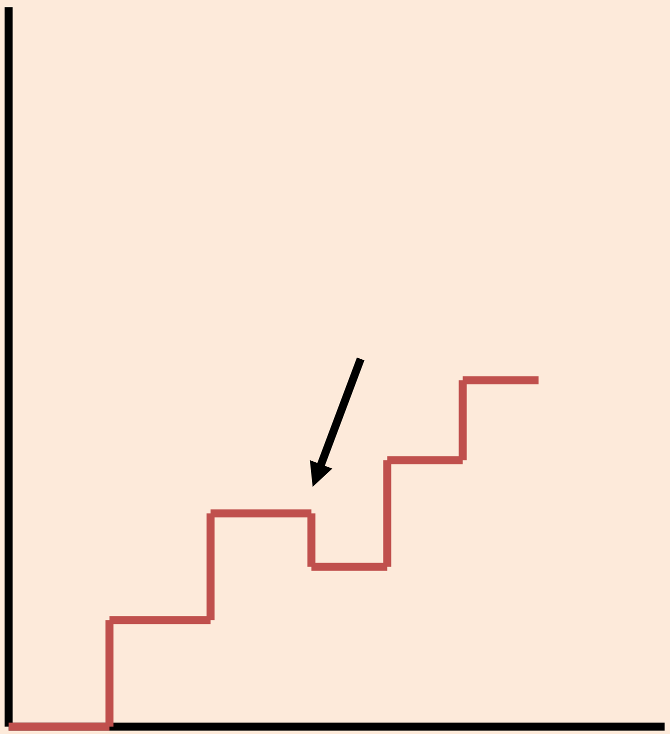
- Occurs when analog output of signal is non-linear
- Two Types
  - Differential – analog step-sizes changes with increasing digital input (measure of largest deviation; between successive bits
  - Integral – amount of deviation from a straight line after offset and gain errors removed; on concurrent bits

Non-Linearity Error, cont.



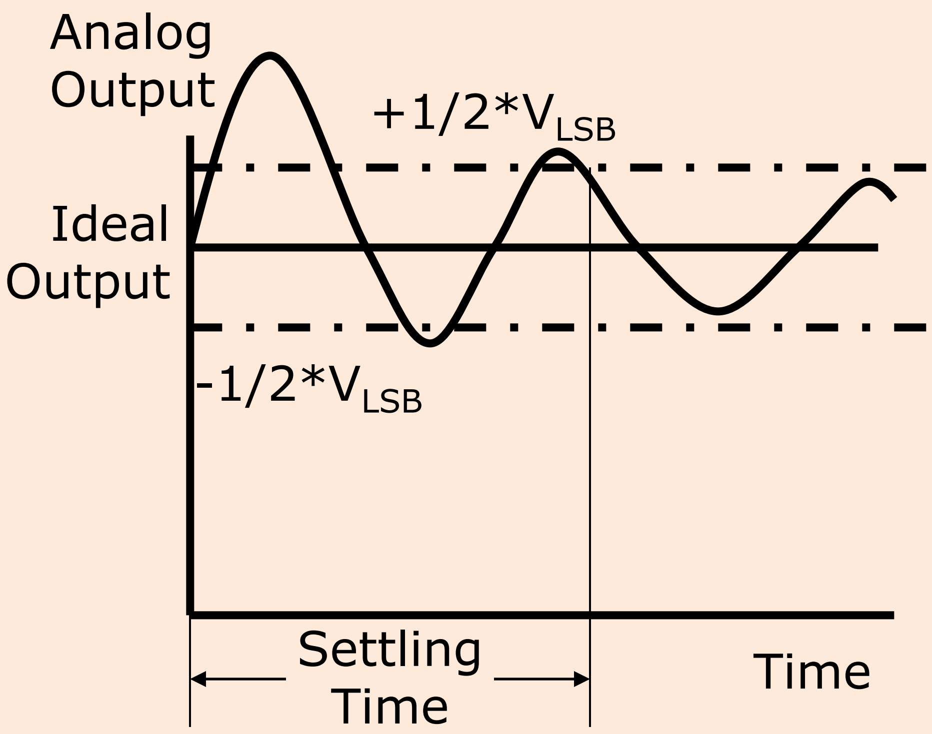
Non-Monotonic Error

- Occurs when an increase in digital input results in a decrease in the analog output



Settling Time and Overshoot Error

- Settling Time – time required for the output to fall with in +/- ½ V_{LSB}
- Overshoot – occurs when analog output overshoots the ideal output



Applications

- Digital Motor Control
- Computer Printers
- Sound Equipment (e.g. CD/MP3 Players, etc.)
- Electronic Cruise Control
- Digital Thermostat

References

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THANK YOU