SJSU SAN JOSÉ STATE UNIVERSITY

Charles W. Davidson College of Engineering

Department of Computer Engineering

Real-Time Embedded System Co-Design

CMPE 146 Section 1

Fall 2024

Digital-to-Analog Converter

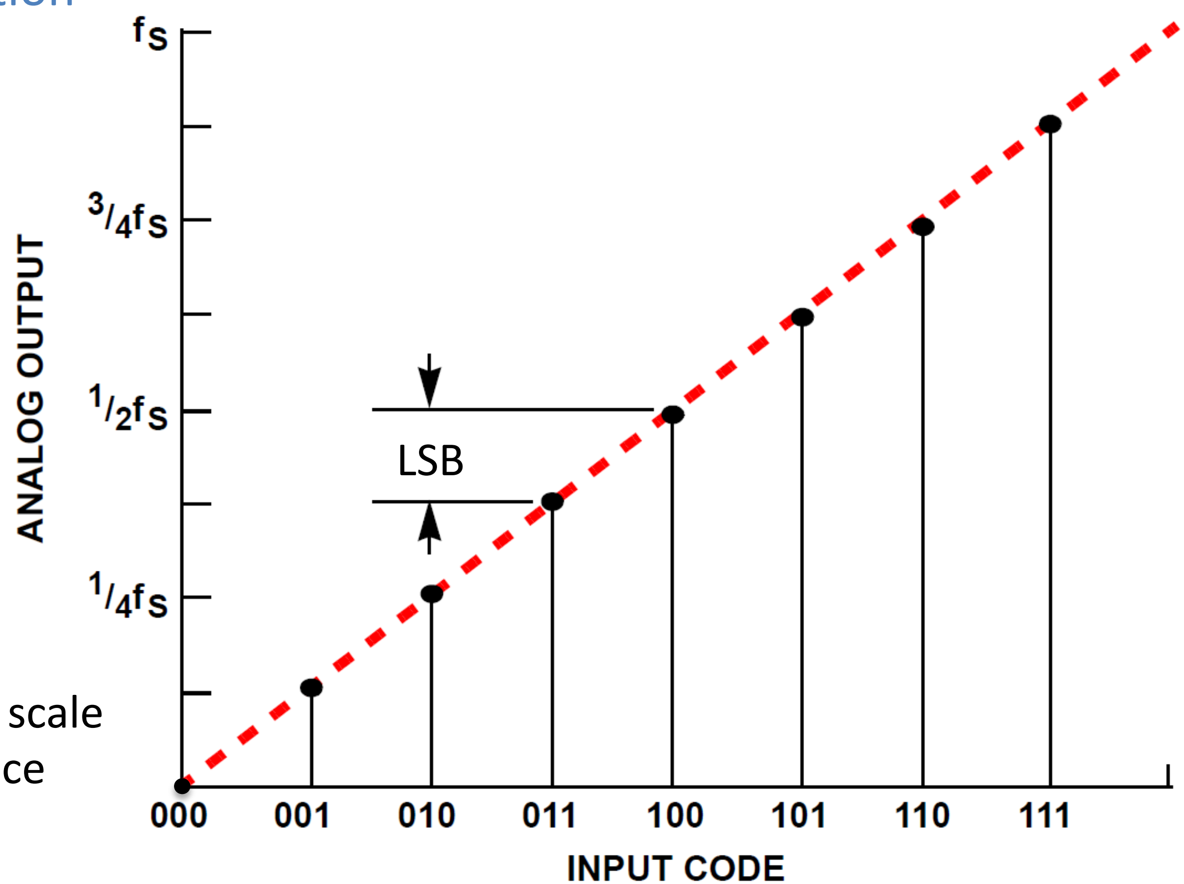
Digital-to-Analog Conversion

- Most of the signals in real world is analog or continuous
- Digital computers processes or store signals in digital or discrete form
- A conversion process is needed to convert a signal’s digital form to an analog form that can be applied to the real world
  - For example, a computer converts the signals stored in a music file to sound
- Digital-to-Analog Converter (DAC)
  - Converts a digital word to an analog voltage that is a proportion of a reference voltage

Ideal DAC

An example of a 3-bit DAC

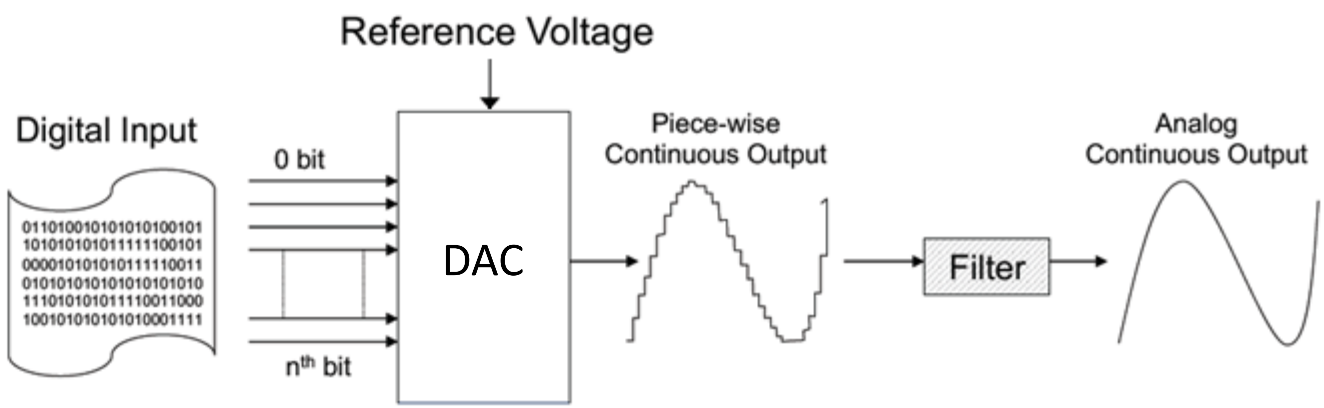
- The smallest resolvable output voltage is 1 LSB (Least Significant Bit) which is equal to $f_S/2^3$ or $f_S/8$
- The output voltage has 8 discrete values representing a discrete linear transfer function



f_S = full scale reference voltage

Support Components

- Voltage reference
  - Provides DAC a precise reference voltage to produce the correct output voltages
- Filter
  - DAC produces a constant voltage level at a regular interval
  - Filter smooths out the jagged form of the piece-wise output signal
  - Essentially a low-pass filter to produce a smooth analog output signal
    - Interpolates the signal between two successive output voltage levels
    - Removes the high-frequency components



- Quite often, the filter's output is connected to the input of a driver circuit that interfaces with the off-board component, e.g., motor, speaker

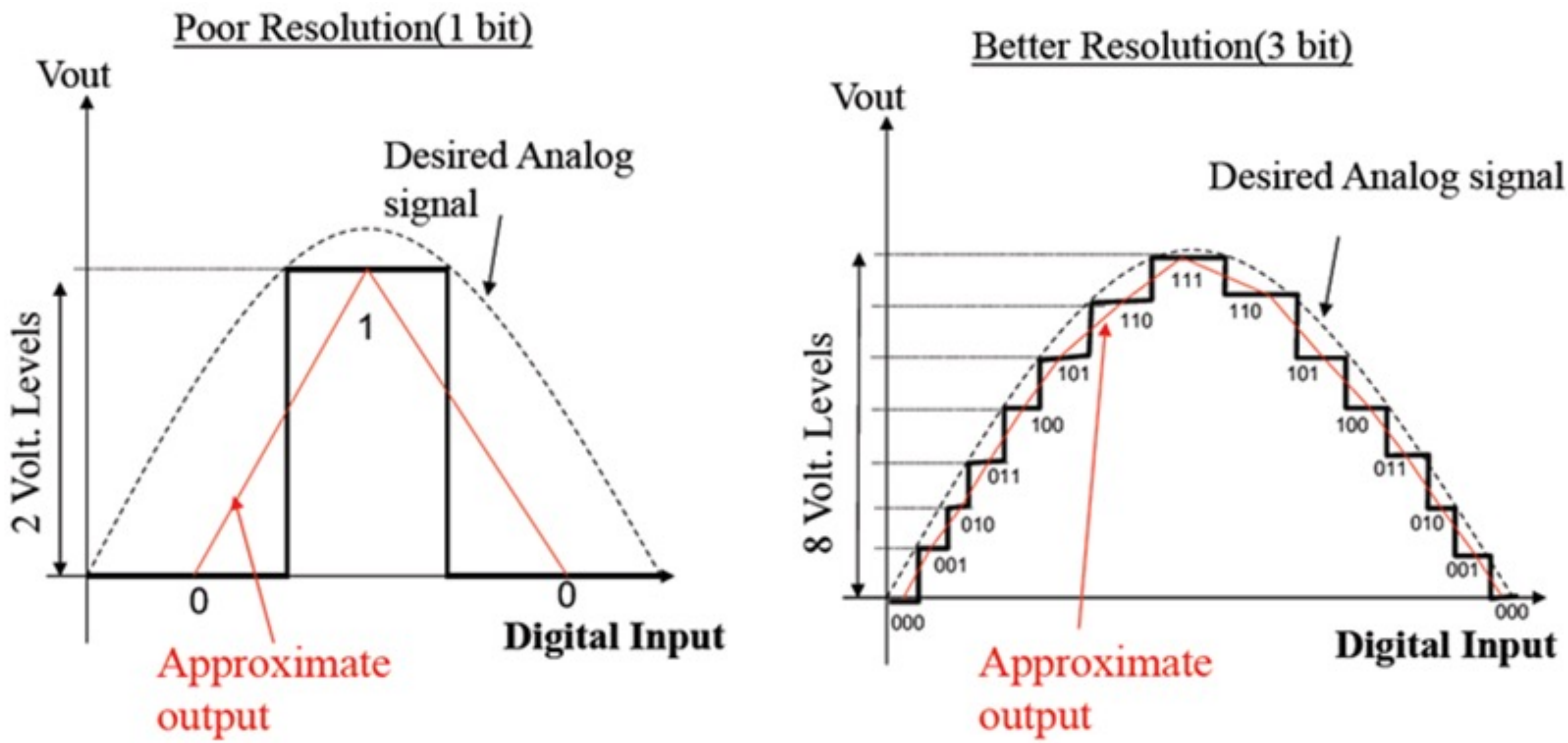
DAC Characteristics

Some important characteristics of DAC

- Resolution
- Nonlinearity
- Monotonicity
- Settling Time
- Update Rate

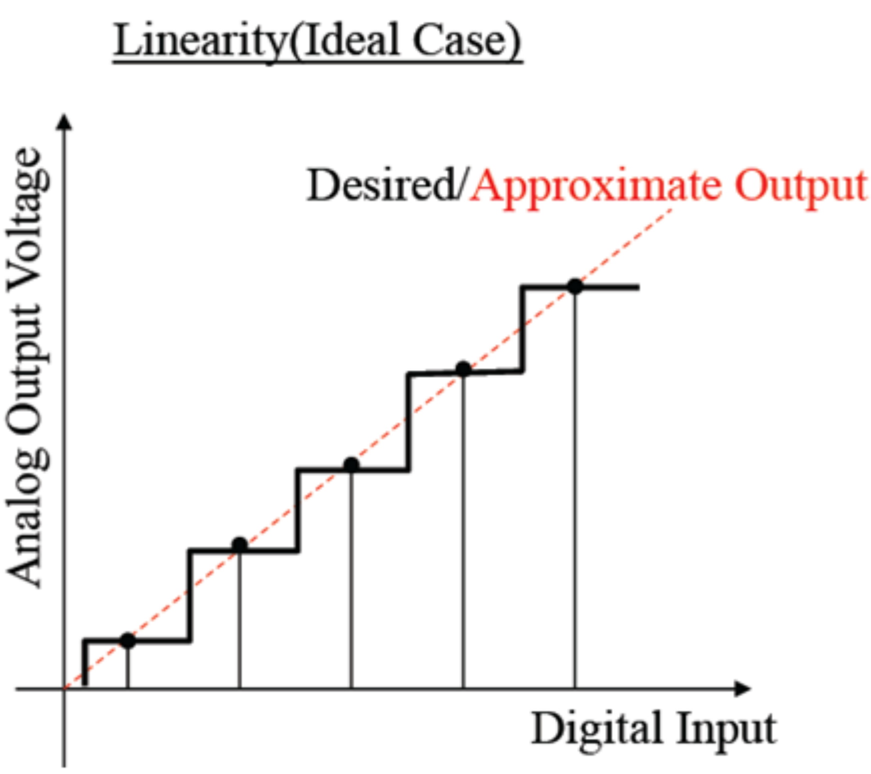
Resolution

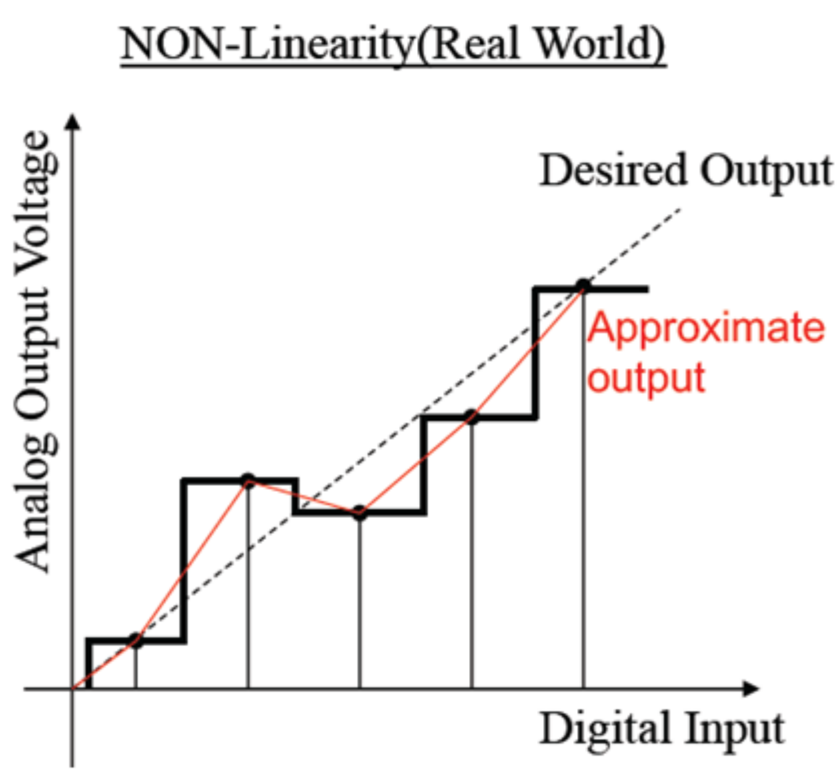
- Resolution of a DAC is the number of bits representing the digital values
- Affects the amount of variance in output voltage for every change of the LSB in the digital input
  - A measure of how closely we can approximate the desired output signal
  - Higher resolution provides smaller voltage division, thus finer detail on output
- Voltage resolution: $V_{LSB} = V_{REF} / 2^N$, where N = Number of bits of digital input



Nonlinearity

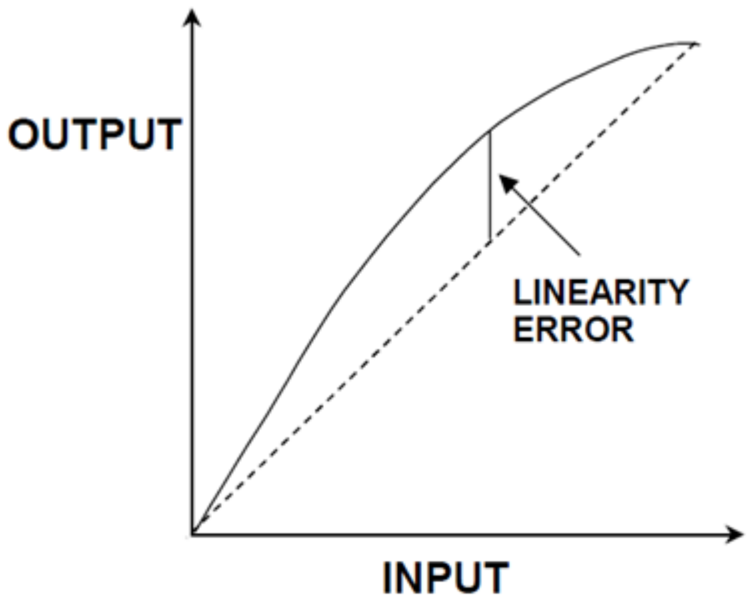
- Error between the desired analog output and the actual output
- Typically expressed in terms of number of LSB's
- Two types of nonlinearity: Integral and differential





Integral Nonlinearity (INL)

- Maximum deviation of the actual transfer function from the ideal straight line through the zero and full-scale points



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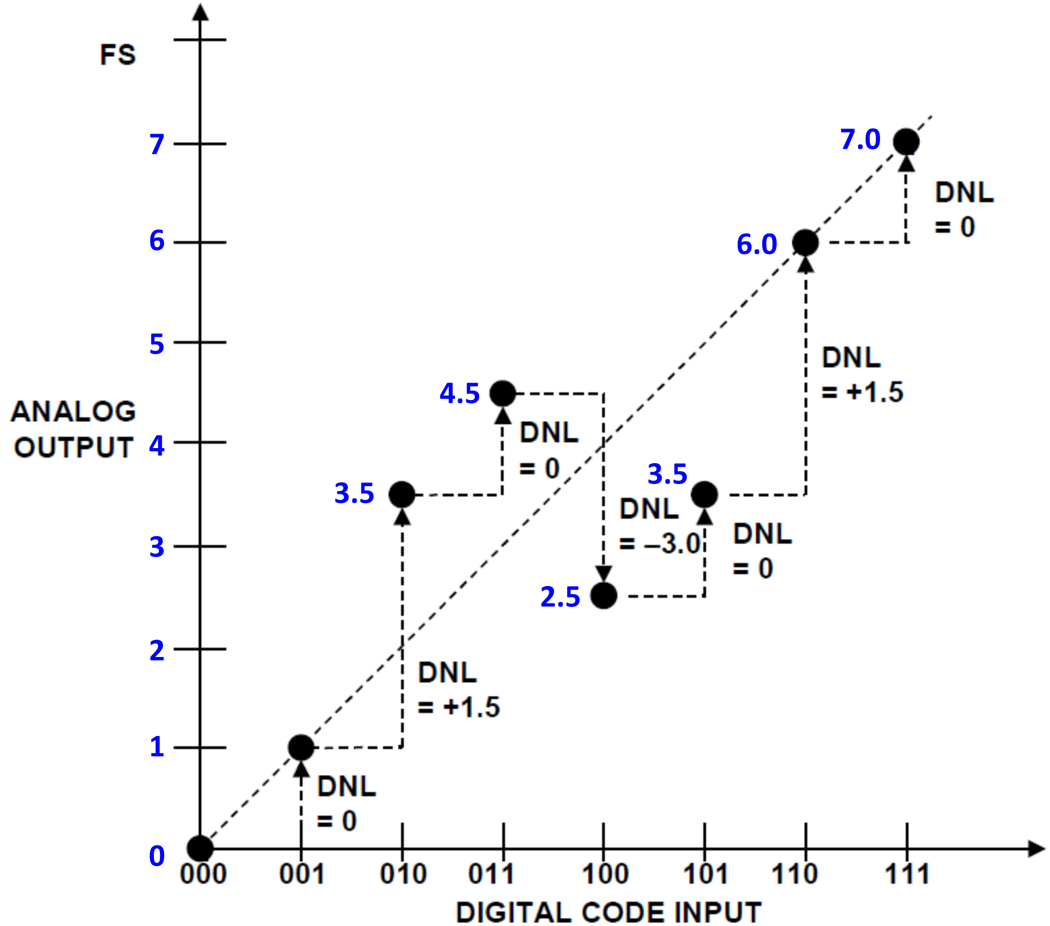
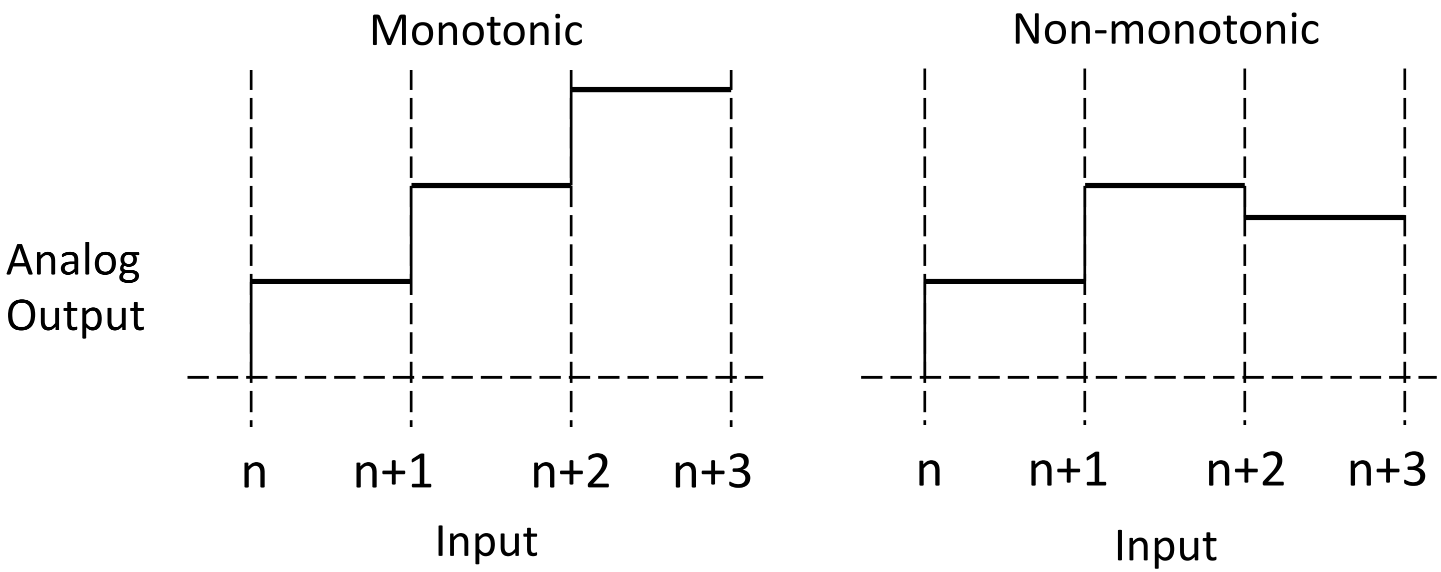
Differential Nonlinearity (DNL)

- Maximum deviation of an actual analog output step, between adjacent input codes, from the ideal step value of +1 LSB
- An ideal DAC response would have analog output values exactly one code (LSB) apart, i.e., DNL = 0



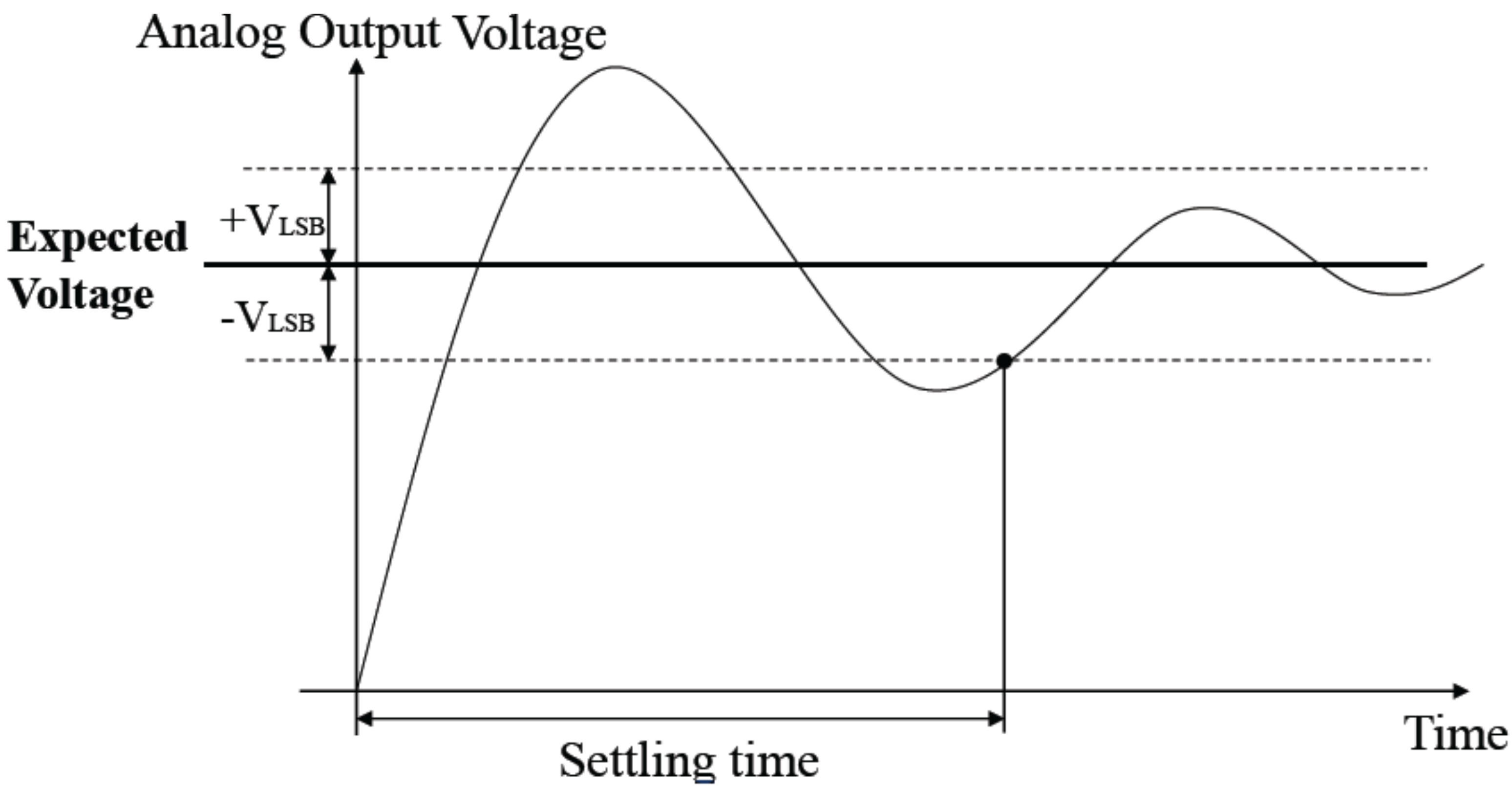
Monotonicity

- In a monotonic DAC, the analog output always increases or remains the same as the digital input increases
  - The analog output never decreases during the input sequence
- If the analog output decreases at any point during the input sequence, a DAC is said to be non-monotonic
- Important property in many control applications where the direction of movement of an object is determined by the DAC
  - If the DAC behaves in a non-monotonic fashion, the object will be moved in the wrong direction



Settling Time

- Interval between the output voltage starts to change and it settles within $\pm 1V_{LSB}$ of the expected value



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Update Rate

- The maximum speed at which the DAC circuitry can operate and still produce correct output
  - Typically expressed in number of samples per second or simply Hz
- Depends on
  - How fast the input digital code can be updated
  - Conversion speed

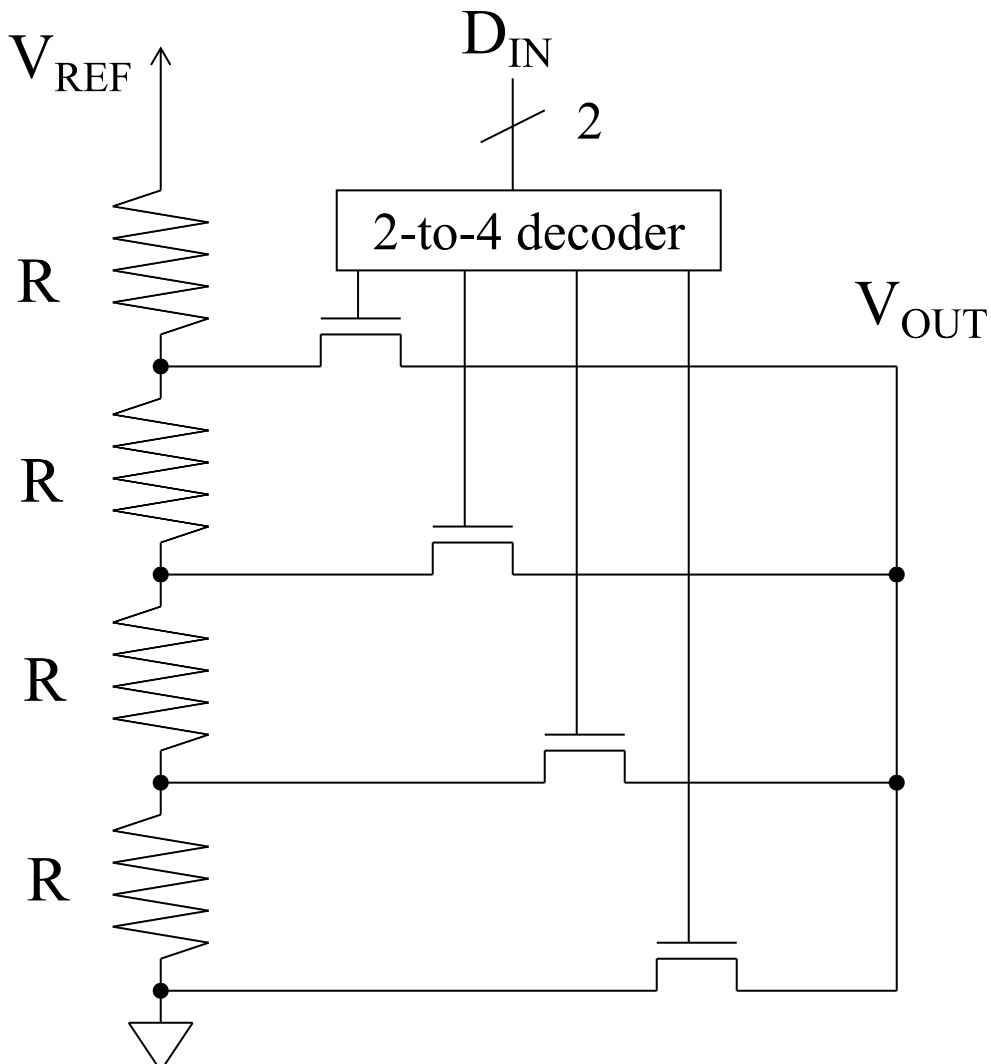
DAC Design

Some basic designs

- Voltage Divider
- Binary-Weighted
- R/2R Ladder

Voltage Divider DAC

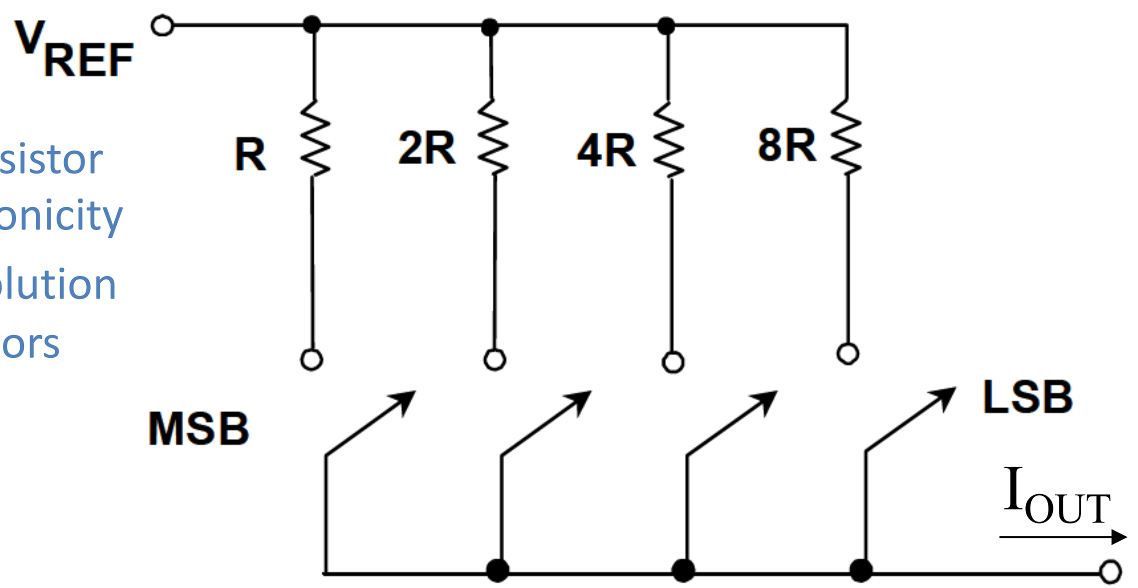
- N-bit DAC consists of
  - 2^N resistors in series
  - 2^N switches
- Input code to the decoder turns on only one of the switches
- Advantages
  - Fast
  - Monotonic (inherently)
- Disadvantage
  - Large number of resistors and switches for high resolutions



2-bit DAC

Binary-Weighted DAC

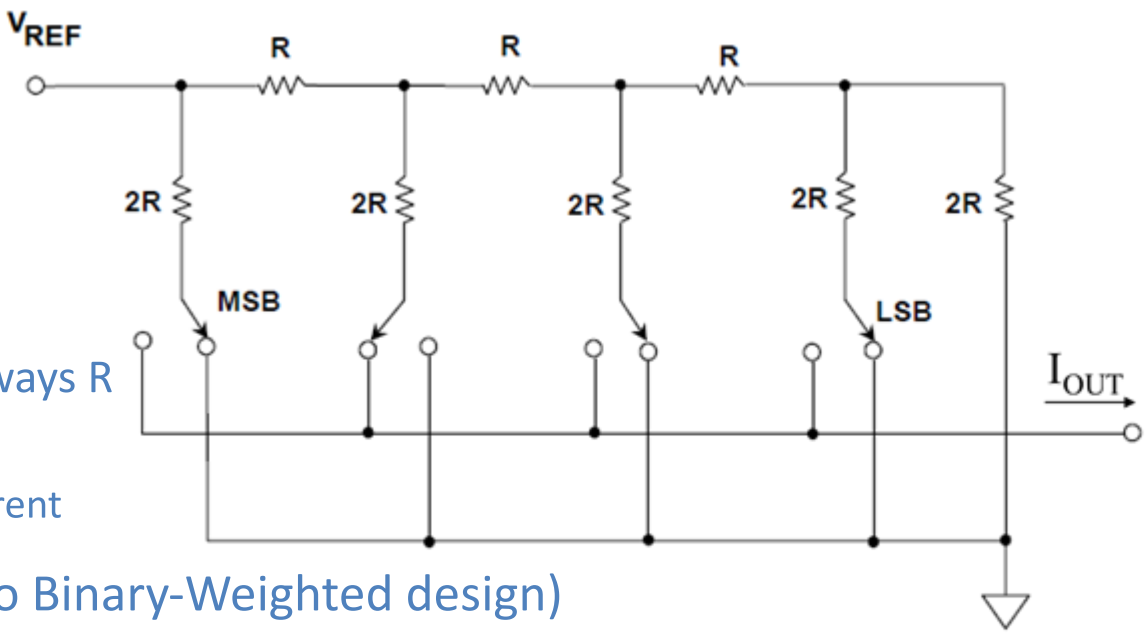
- N-bit DAC consists of
  - N binary-weighted resistors
  - N switches
- Output current I_{OUT} is the sum of individual currents through the resistors
  - Current ratios through resistors: $1:2:4:8:\ldots:2^{N-1}$
- Advantage
  - Few components
- Disadvantages
  - Need to tightly control resistor ratios to maintain monotonicity
  - Hard to achieve high resolution due to variations of resistors



4-bit DAC

R/2R Ladder DAC

- N-bit DAC consists of
  - 2N resistors of only two values in the ratio of 1:2
  - N switches
- Output current I_{OUT} is the sum of individual currents through the higher-value resistors (2R)
  - Current ratios through resistors: $1:2:4:8:....:2^{N-1}$
- Advantages
  - Fewer resistors to trim
  - Scalable
    - Easy to achieve higher number of bits
  - Network impedance is always R
    - Regardless of N
    - Constant reference current



- Disadvantages (compared to Binary-Weighted design)
  - Double the number of resistors
  - More complicated circuitry
    - More wiring, more complicated switches