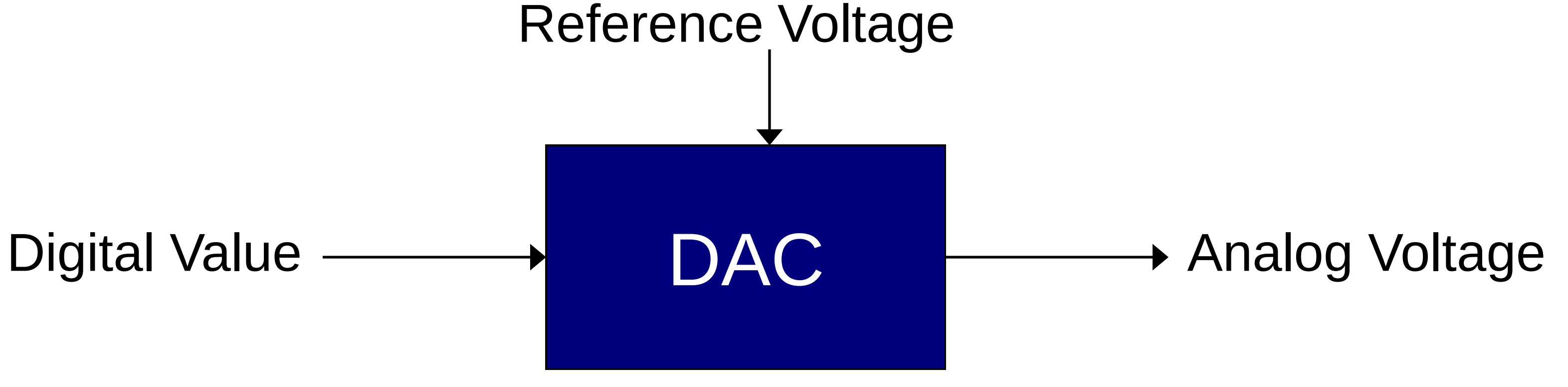
Digital to Analog Converters (DAC)

Outline

- Purpose
- Types
- Performance Characteristics
- Applications

Purpose

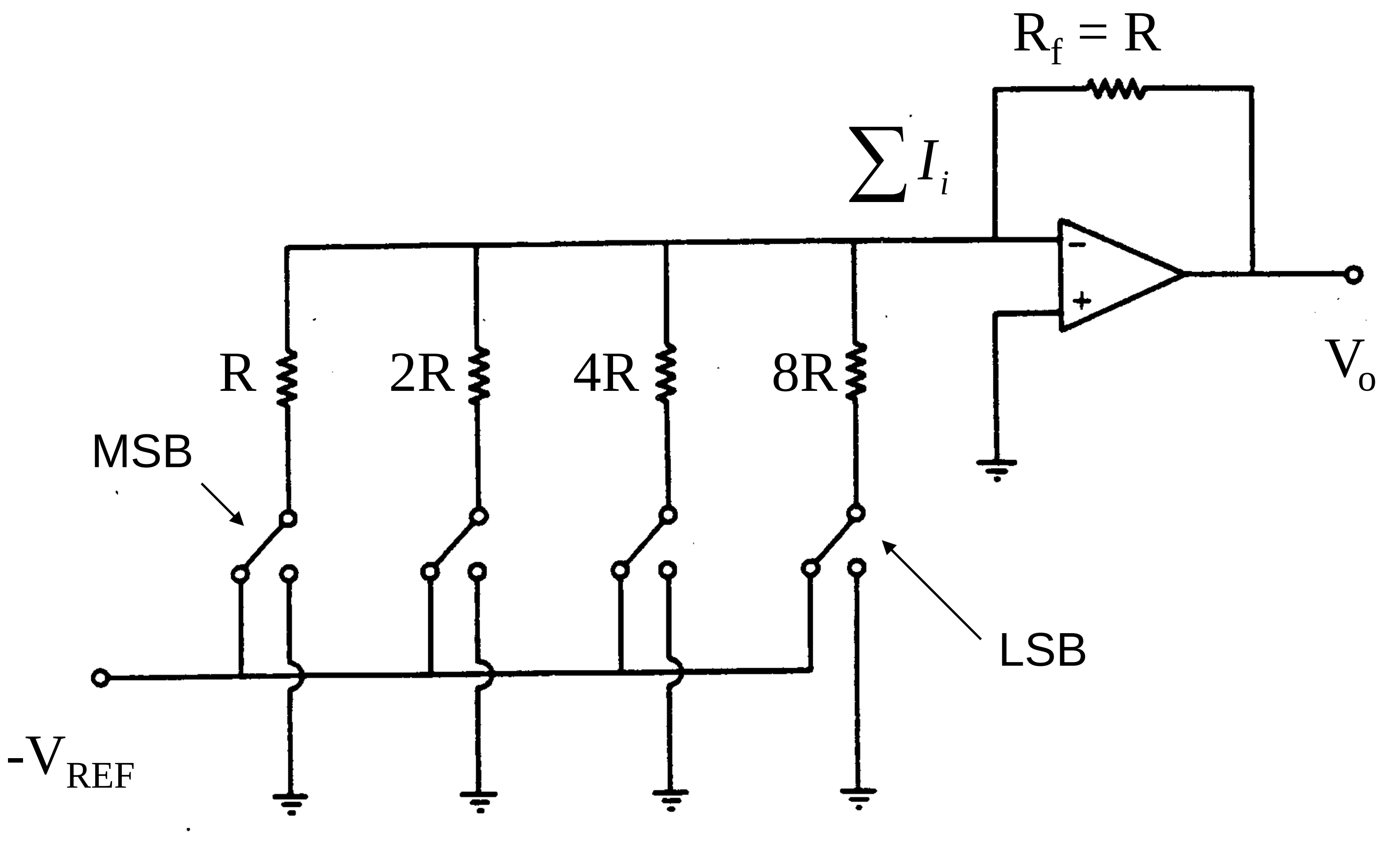
- To convert digital values to analog voltages
- Performs inverse operation of the Analog-to-Digital Converter (ADC)
- $V_{OUT} \propto \text{Digital Value}$



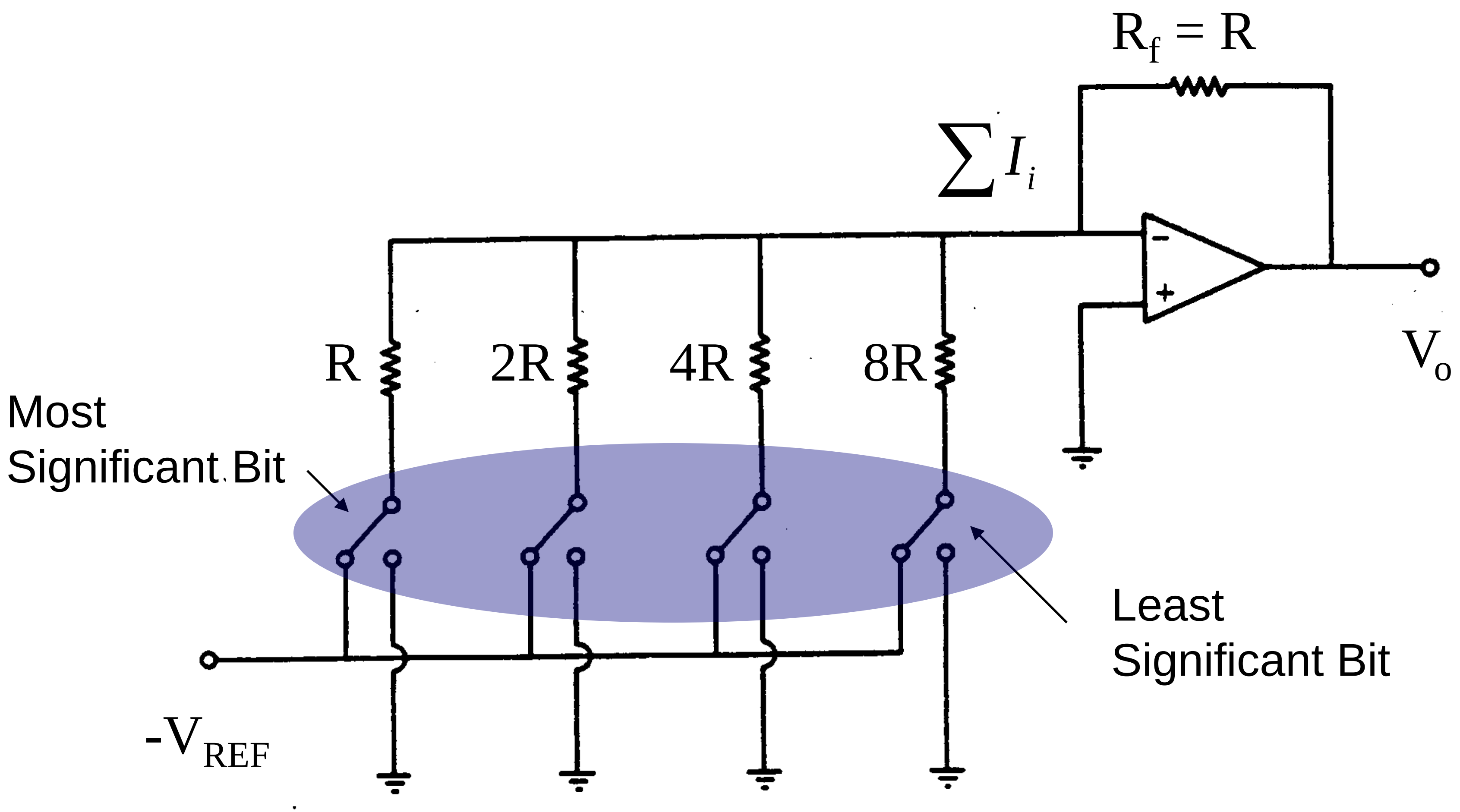
DACs

- Types
  - Binary Weighted Resistor
  - R-2R Ladder
  - Multiplier DAC
    - The reference voltage is constant and is set by the manufacturer.
  - Non-Multiplier DAC
    - The reference voltage can be changed during operation.
- Characteristics
  - Comprised of switches, op-amps, and resistors
  - Provides resistance inversely proportion to significance of bit

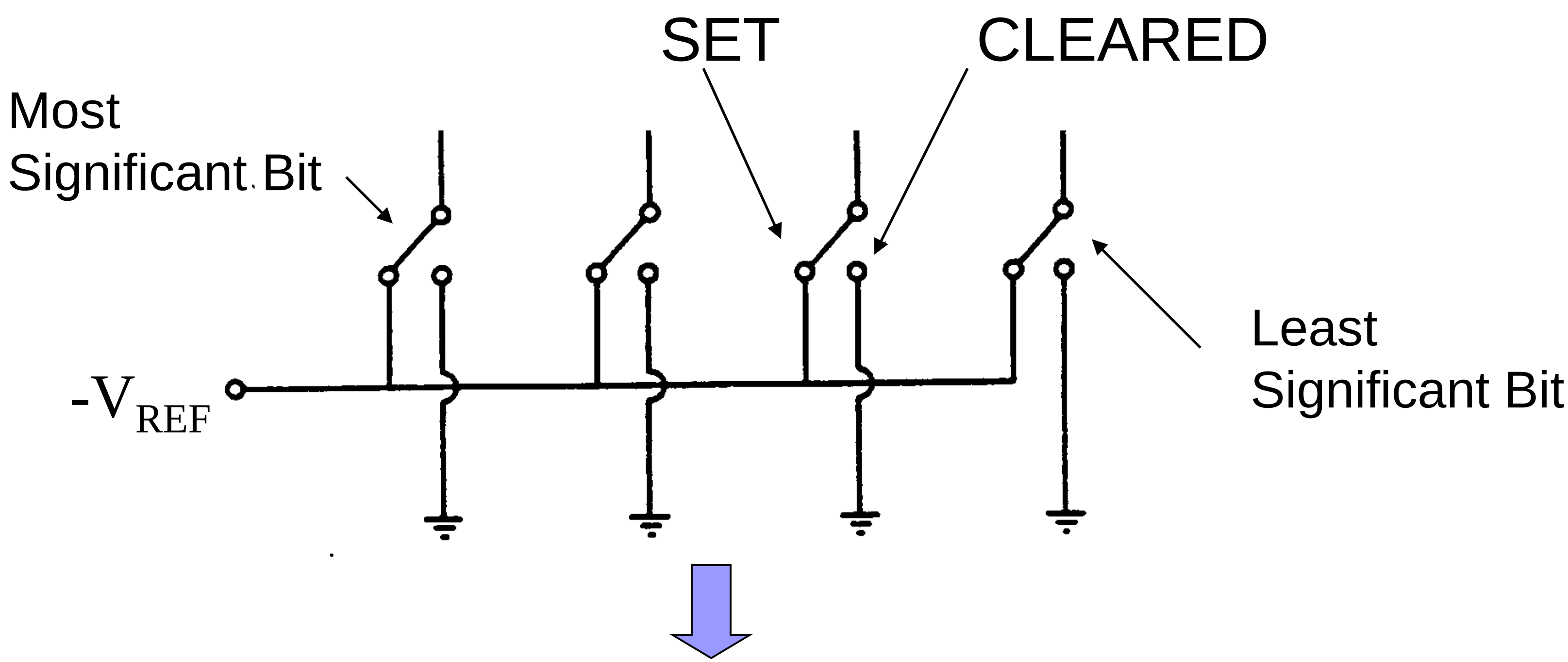
Binary Weighted Resistor



Binary Representation



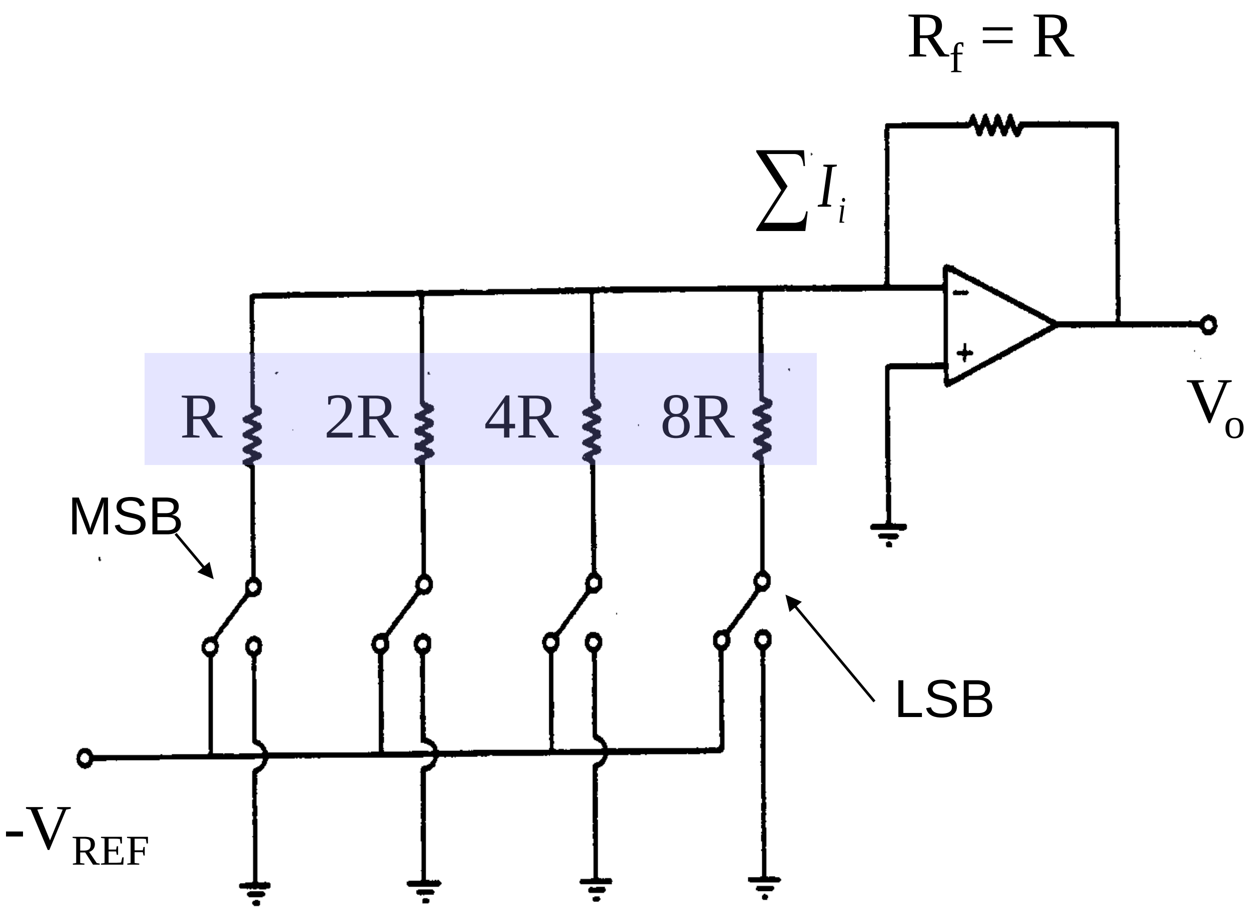
Binary Representation



$(\; 1 \quad 1 \quad 1 \quad 1 \;)_2 = (\; 15 \;)_{10}$

Binary Weighted Resistor

- "Weighted Resistors" based on bit
- Reduces current by a factor of 2 for each bit



Binary Weighted Resistor

- Result:

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

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

  - B_i = Value of Bit i

Binary Weighted Resistor

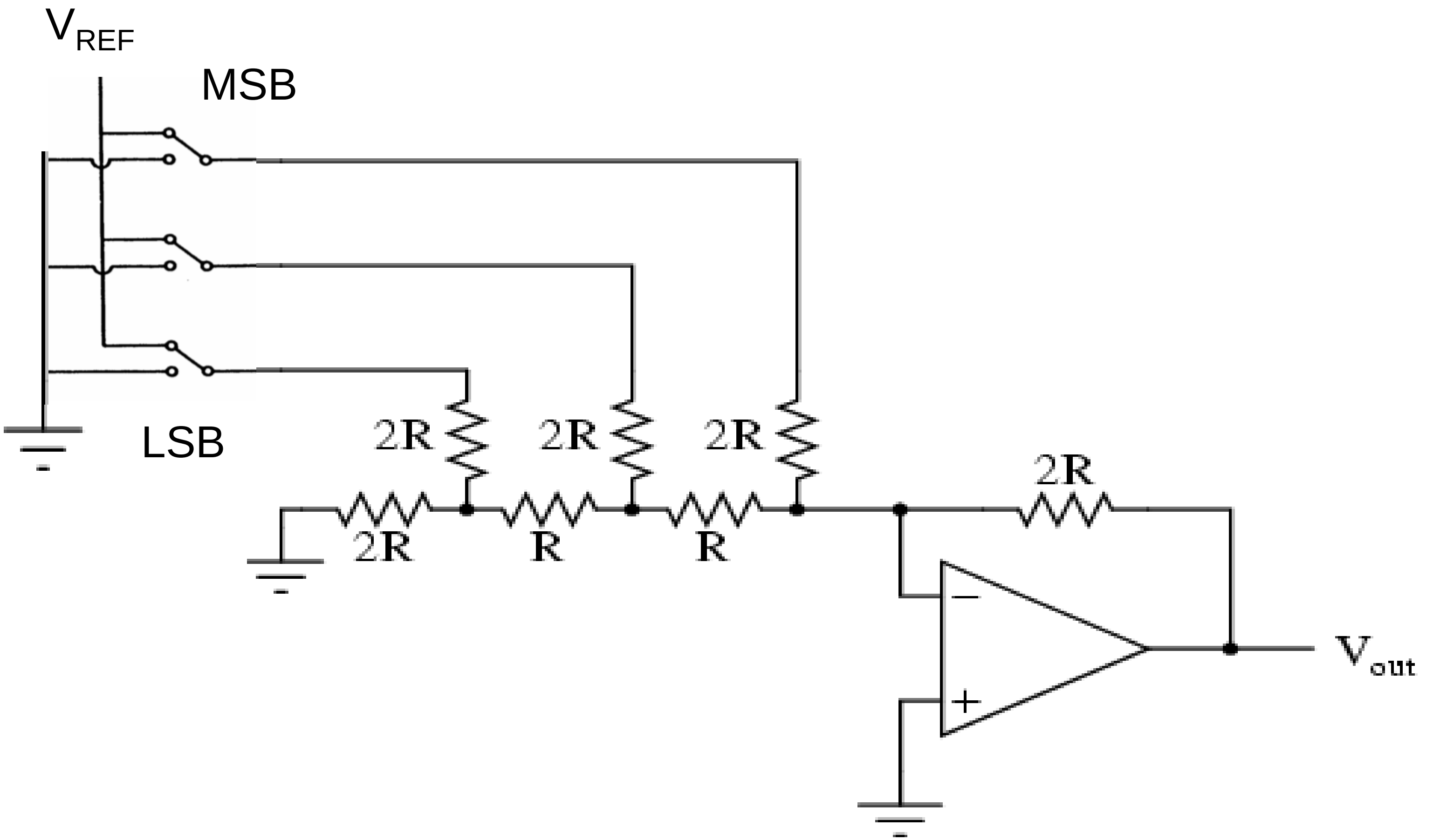
- More Generally:

$$V_{OUT} = V_{REF} \sum \frac{B_i}{2^{n-i-1}}$$

$$= V_{REF} \cdot \text{Digital Value} \cdot \text{Resolution}$$

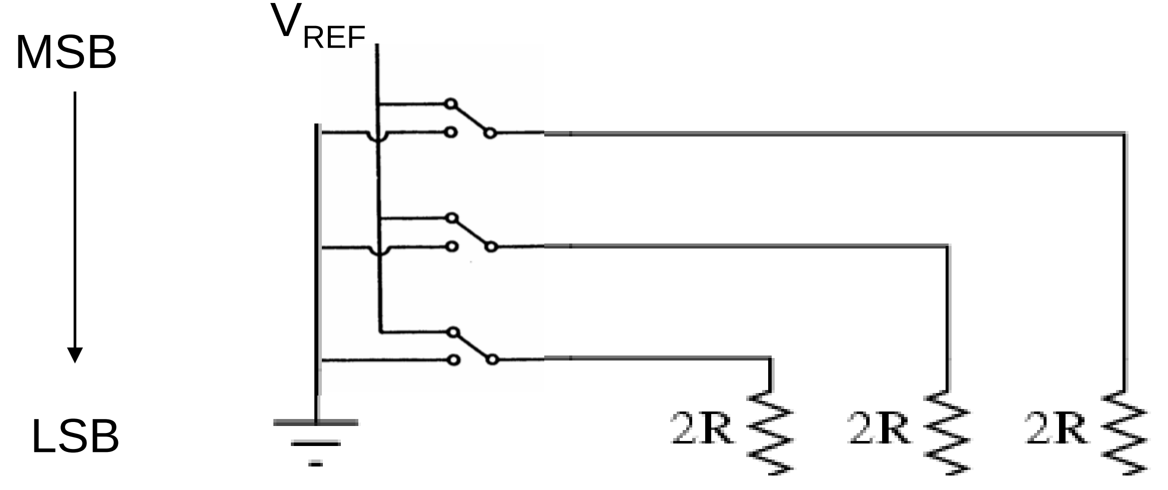
  - B_i = Value of Bit i
  - n = Number of Bits

R-2R Ladder



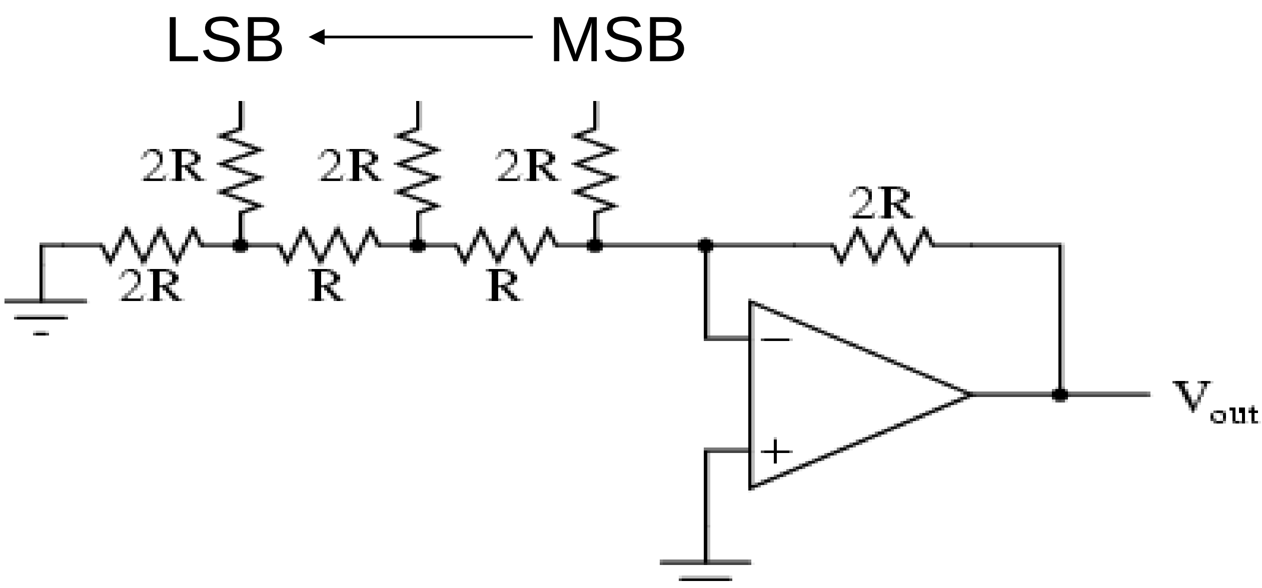
R-2R Ladder

- Same input switch setup as Binary Weighted Resistor DAC
- All bits pass through resistance of 2R



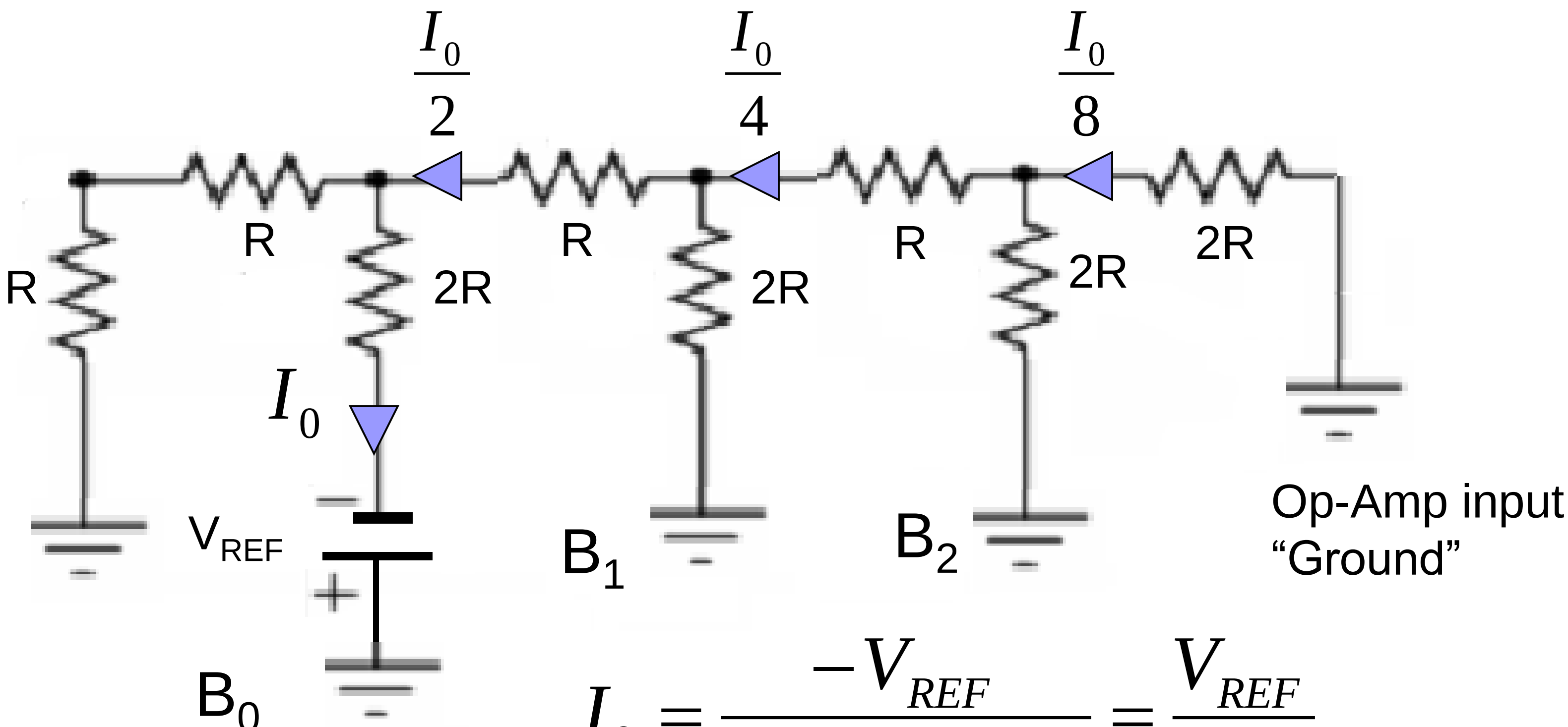
R-2R Ladder

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



R-2R Ladder

- The current is divided by a factor of 2 at each node
- Analysis for current from $(001)_2$ shown below



$$I_0 = \frac{-V_{REF}}{2R + 2R \| 2R} = \frac{V_{REF}}{3R}$$

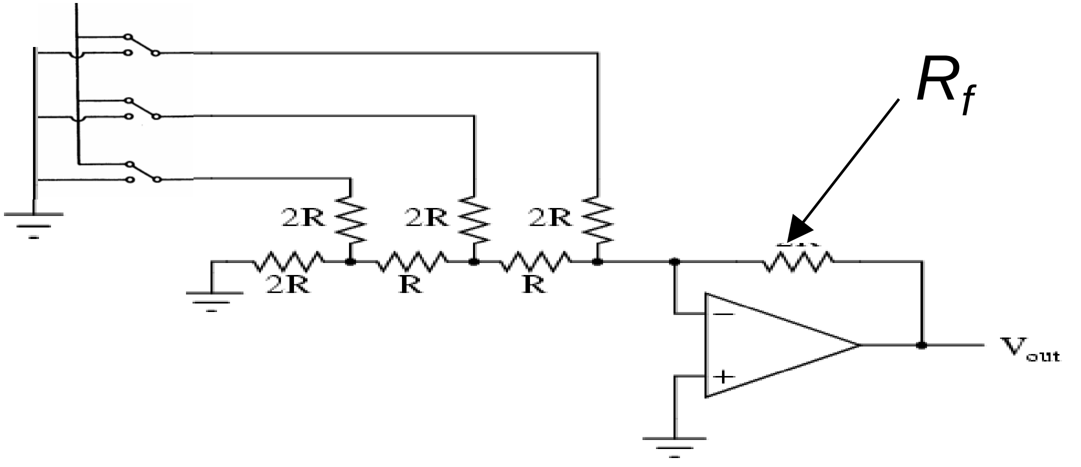
R-2R Ladder

- Result:

$$I = \frac{V_{REF}}{3R}\left(\frac{B_2}{2} + \frac{B_1}{4} + \frac{B_0}{8}\right)$$

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

  - B_i = Value of Bit i



R-2R Ladder

- If R_f = 6R, V_{OUT} is same as Binary Weighted:

$$I = \frac{V_{REF}}{3R} \sum \frac{B_i}{2^{n-i}}$$

$$V_{OUT} = V_{REF} \sum \frac{B_i}{2^{n-i-1}}$$

  - B_i = Value of Bit i

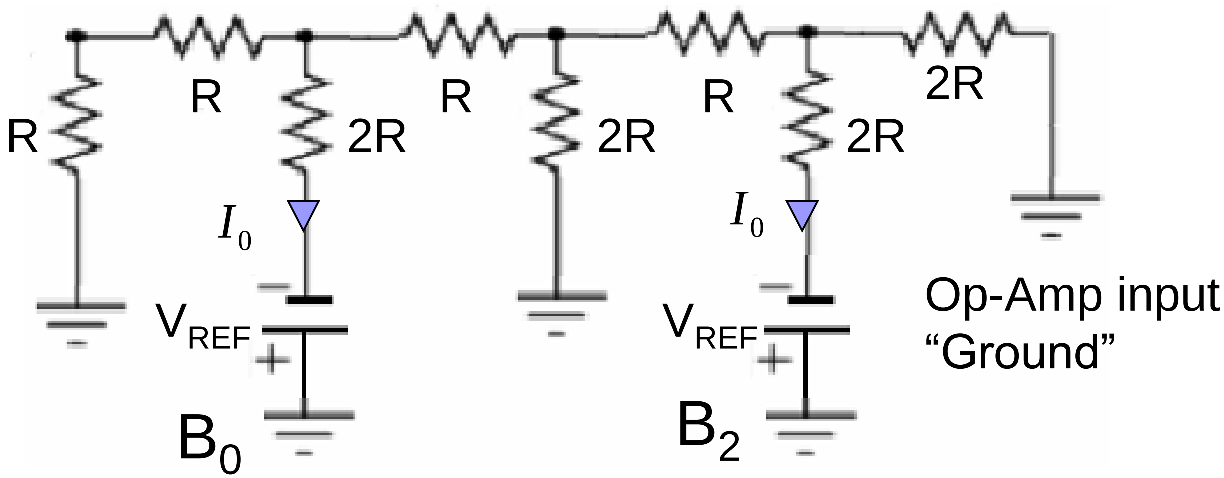
R-2R Ladder

- Example:
  - Input = $(101)_2$
  - V_{REF} = 10 V
  - R = 2 Ω
  - R_f = 2R

$$I_0 = \frac{-V_{REF}}{2R + 2R \| 2R} = \frac{V_{REF}}{3R} = -1.67\ \text{mA}$$

$$I_{op-amp} = \frac{I_0}{8} + \frac{I_0}{2} = -1.04\ \text{mA}$$

$$V_{OUT} = -I_{op-amp} R_f = 4.17\ \text{V}$$



Pros & Cons

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

Digital to Analog Converters

- Performance Specifications
- Common Applications

-Performance Specifications

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

- Resolution: is the amount of variance in output voltage for every change of the LSB in the digital input.
- How closely can we approximate the desired output signal(Higher Res. = finer detail=smaller Voltage divisions)
- A common DAC has a 8 - 12 bit Resolution

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

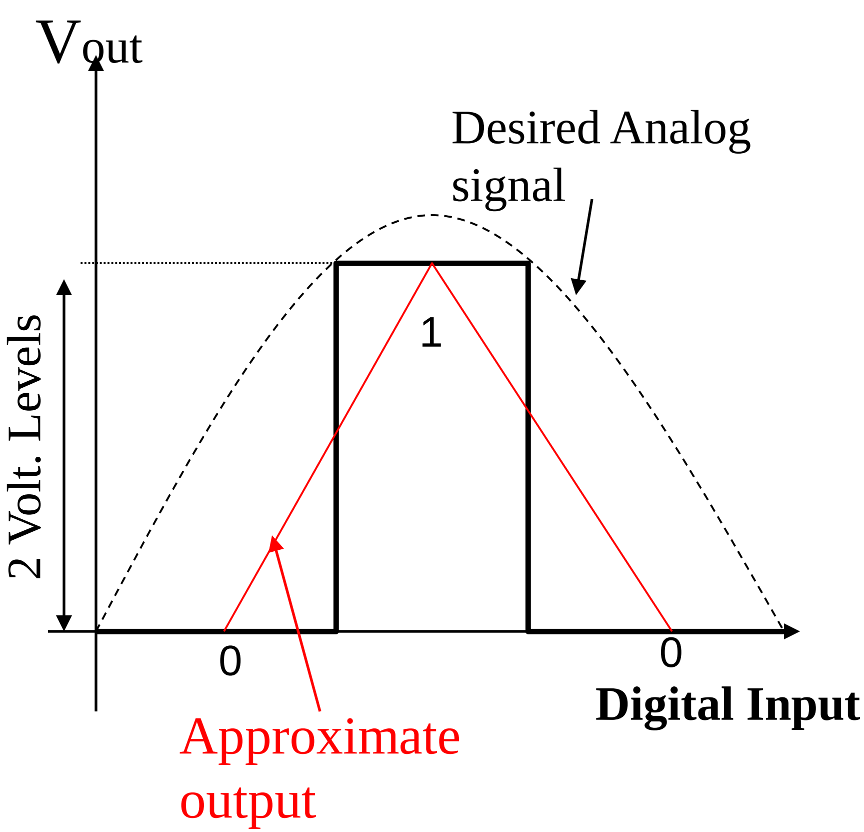
N = Number of bits

Digital to Analog Converters

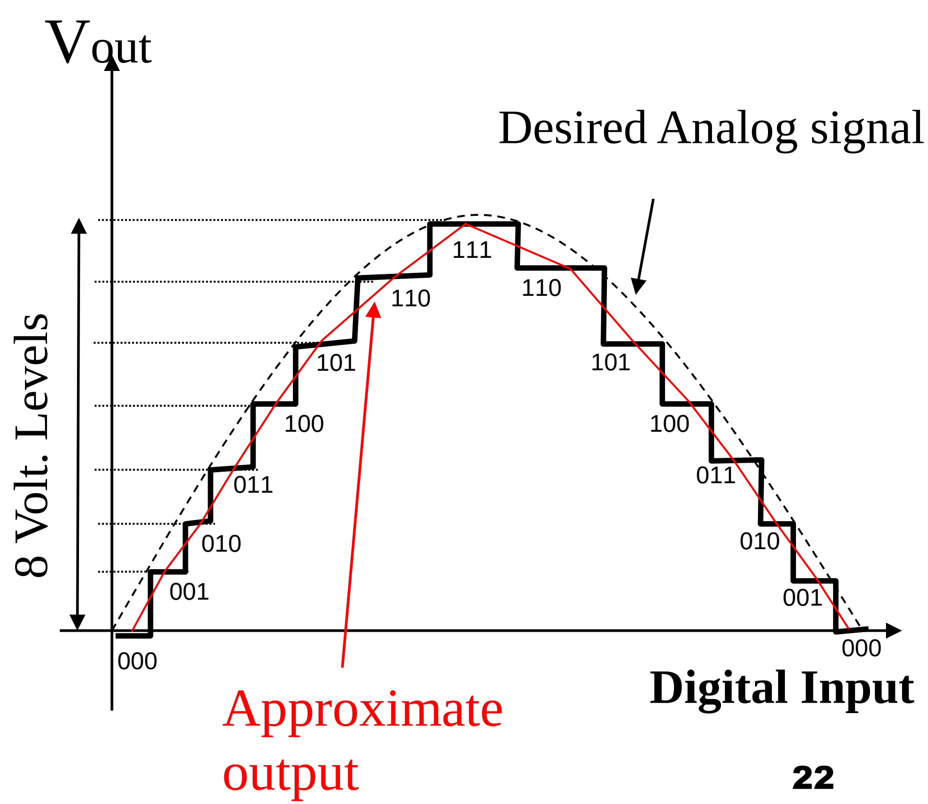
-Performance Specifications

-Resolution

<u>Poor Resolution(1 bit)</u>



<u>Better Resolution(3 bit)</u>



Digital to Analog Converters

-Performance Specifications

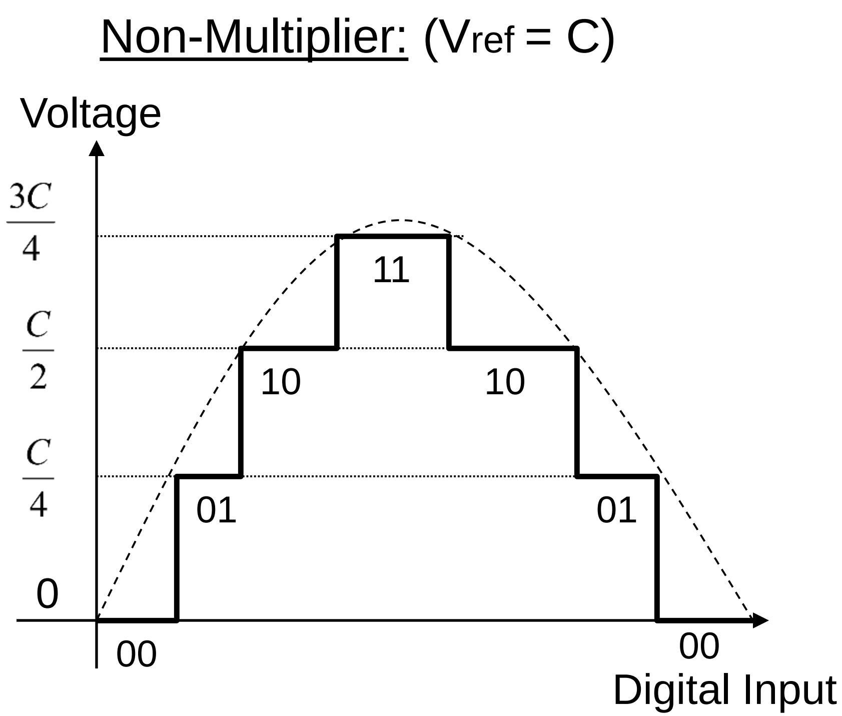
-Reference Voltage

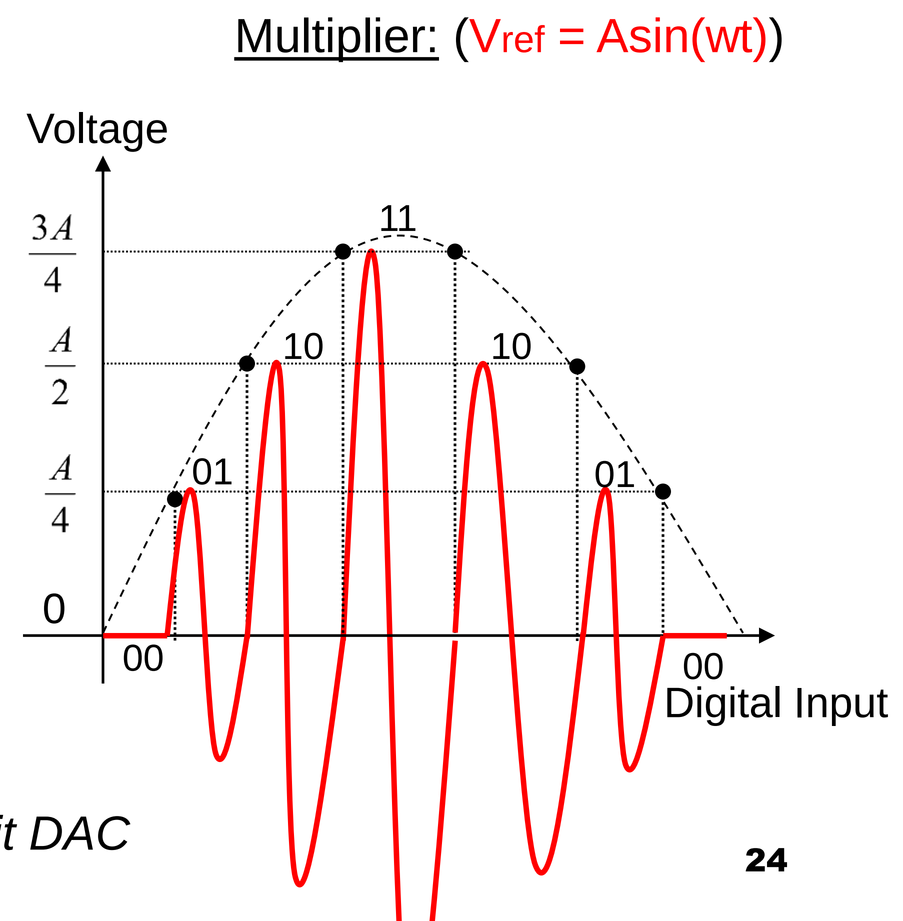
- Reference Voltage: A specified voltage used to determine how each digital input will be assigned to each voltage division.
- Types:
  - Non-multiplier: internal, fixed, and defined by manufacturer
  - Multiplier: external, variable, user specified

Digital to Analog Converters

-Performance Specifications

-Reference Voltage





Assume 2 bit DAC

Digital to Analog Converters

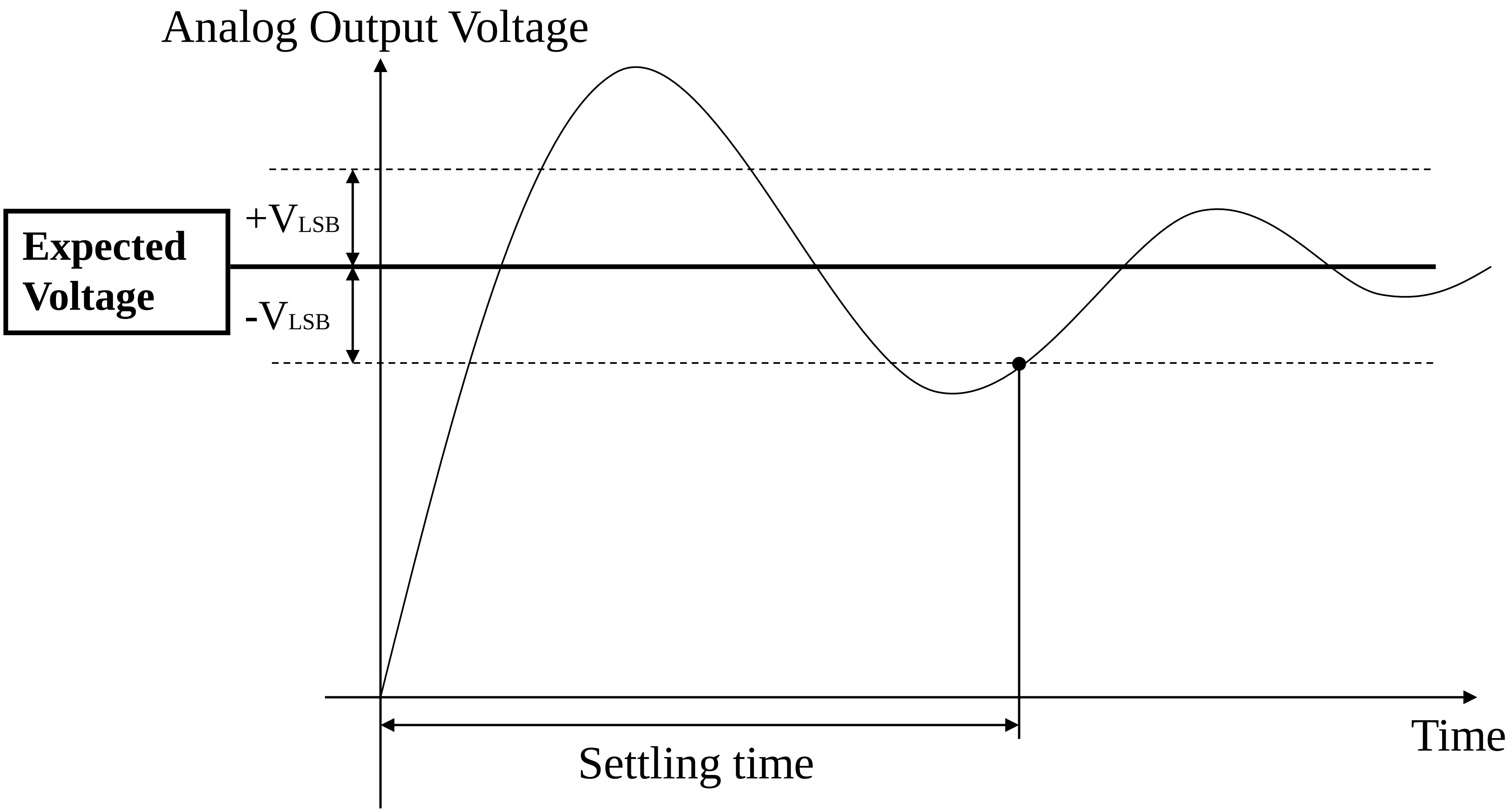
-Performance Specifications

-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. There is a time lag, between the two events.

-Performance Specifications

-Settling Time



Digital to Analog Converters

-Performance Specifications

-Linearity

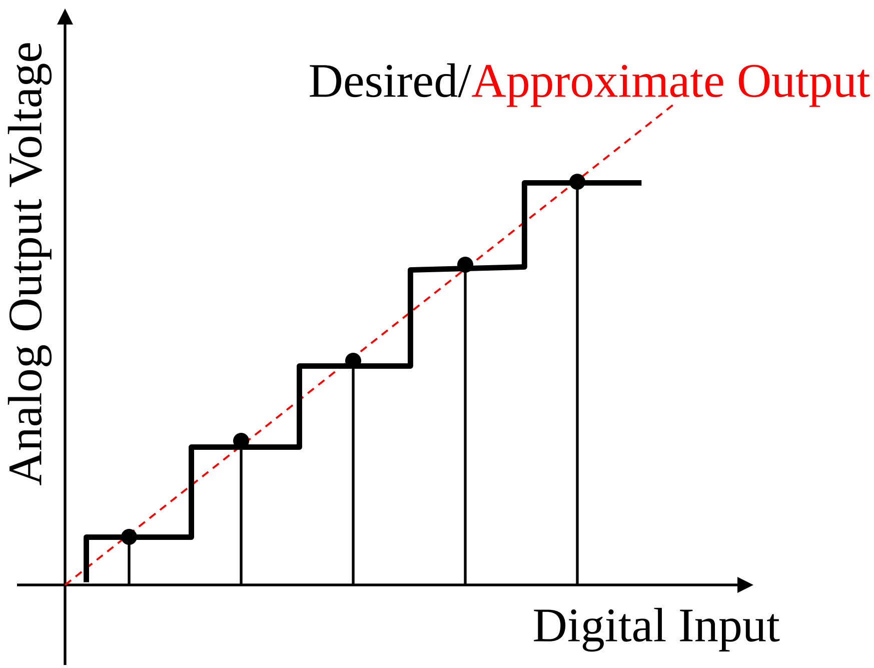
- Linearity: is the difference between the desired analog output and the actual output over the full range of expected values.
- Ideally, a DAC should produce a linear relationship between a digital input and the analog output, this is not always the case.

Digital to Analog Converters

-Performance Specifications

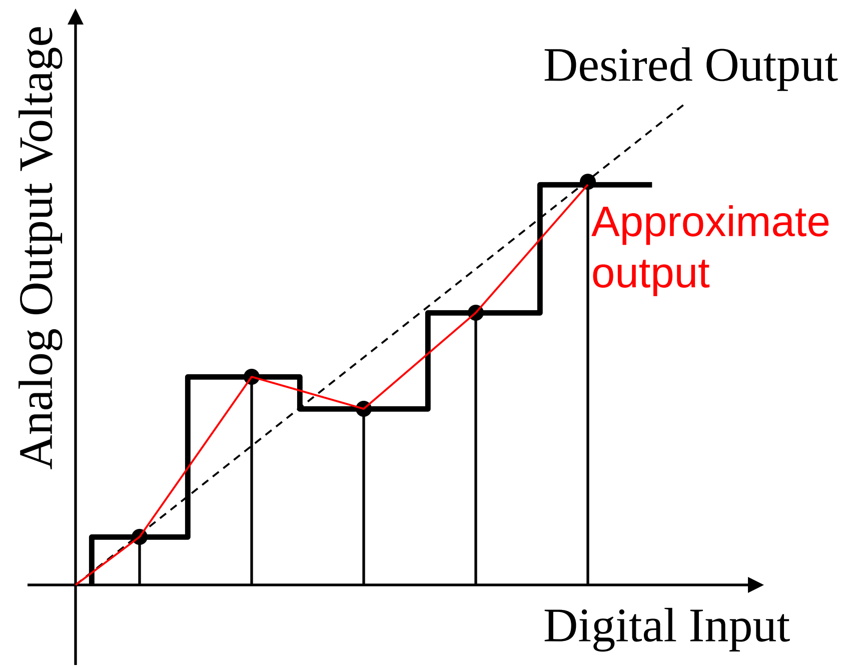
-Linearity

<u>Linearity(Ideal Case)</u>



Perfect Agreement

<u>NON-Linearity(Real World)</u>



Miss-alignment

Digital to Analog Converters

-Performance Specifications

-Speed

- Speed: Rate of conversion of a single digital input to its analog equivalent
- Conversion Rate
  - Depends on clock speed of input signal
  - Depends on settling time of converter

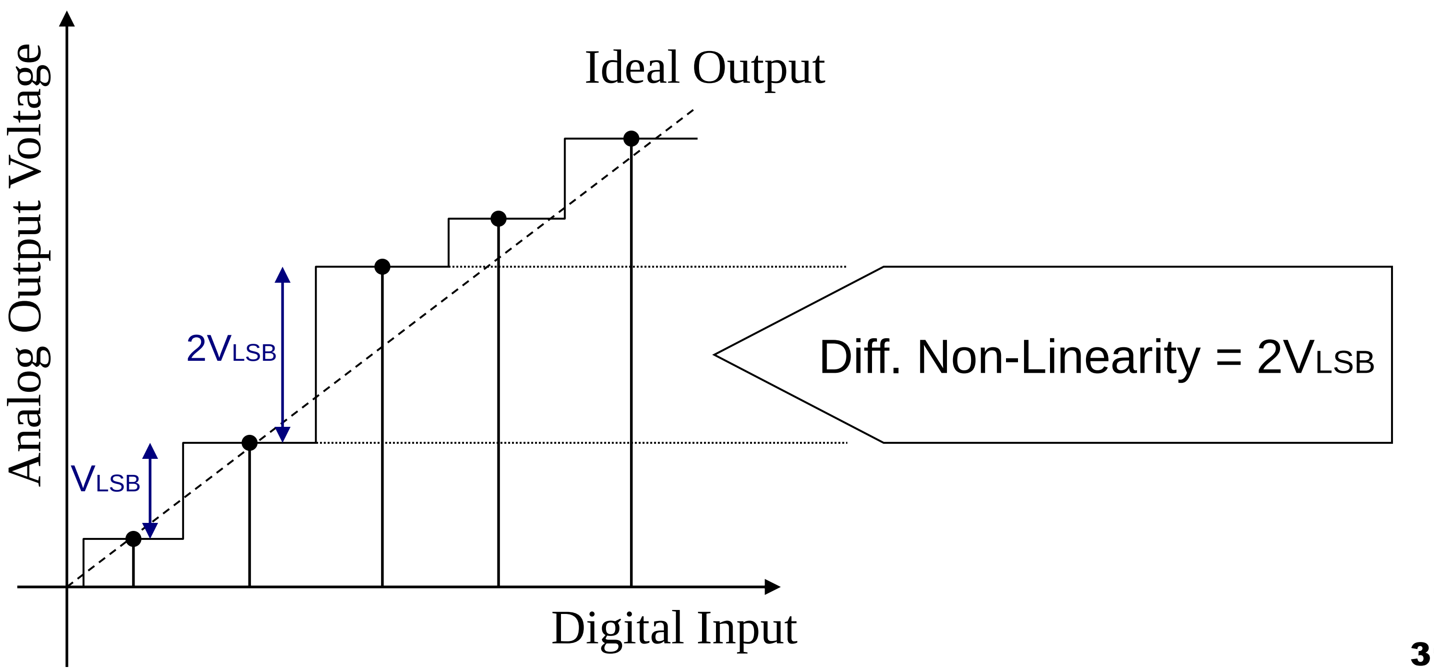
Digital to Analog Converters
-Performance Specifications
-Errors

- Non-linearity
  - Differential
  - Integral
- Gain
- Offset
- Non-monotonicity

-Performance Specifications

-Errors: Differential Non-Linearity

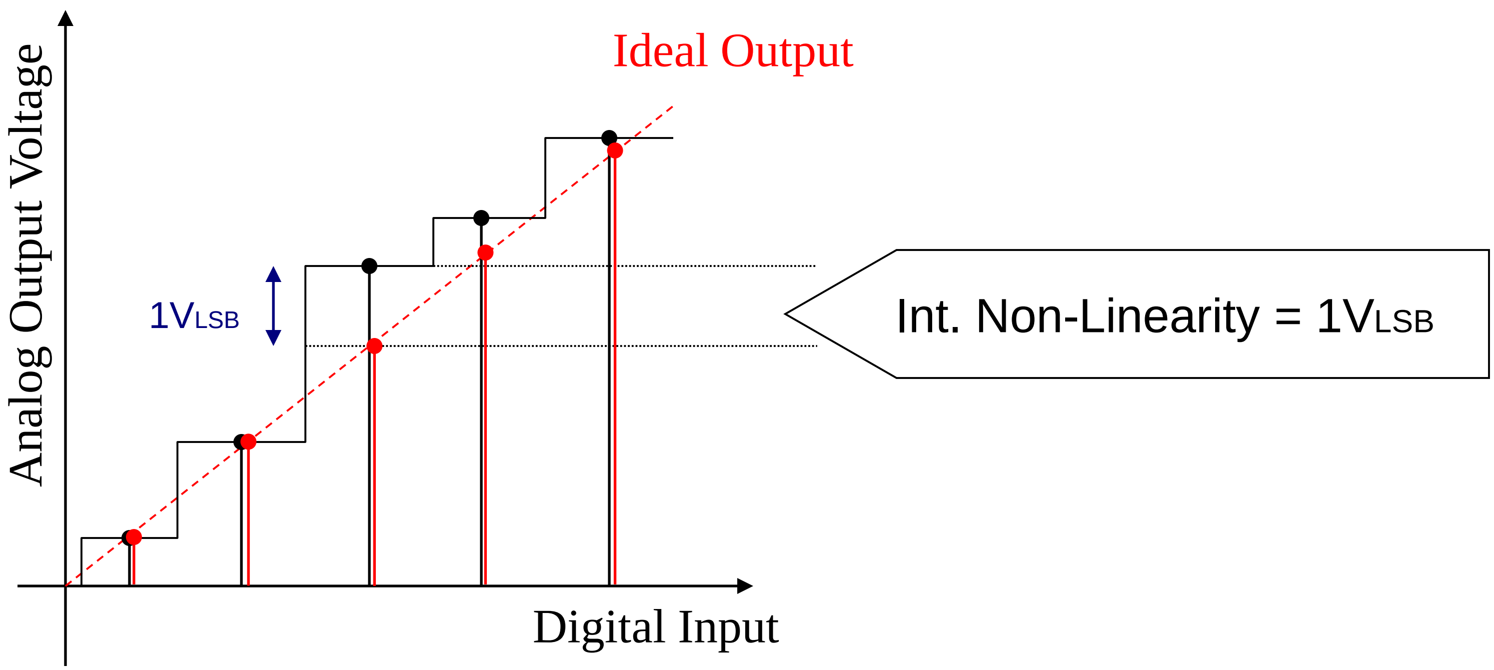
- Differential Non-Linearity: Difference in voltage step size from the previous DAC output (Ideally All DLN's = 1 V_{LSB})



-Performance Specifications

-Errors: Integral Non-Linearity

- Integral Non-Linearity: Deviation of the actual DAC output from the ideal (Ideally all INL's = 0)



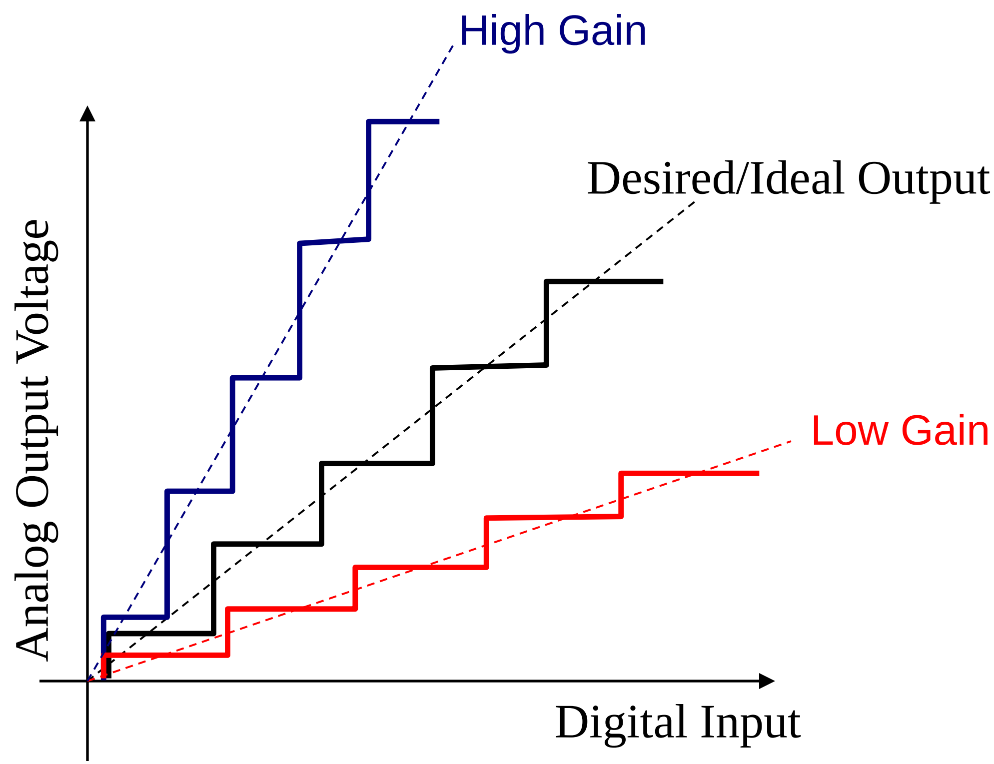
-Performance Specifications

-Errors: Gain

- Gain Error: Difference in slope of the ideal curve and the actual DAC output

High Gain Error: Actual slope greater than ideal

Low Gain Error: Actual slope less than ideal

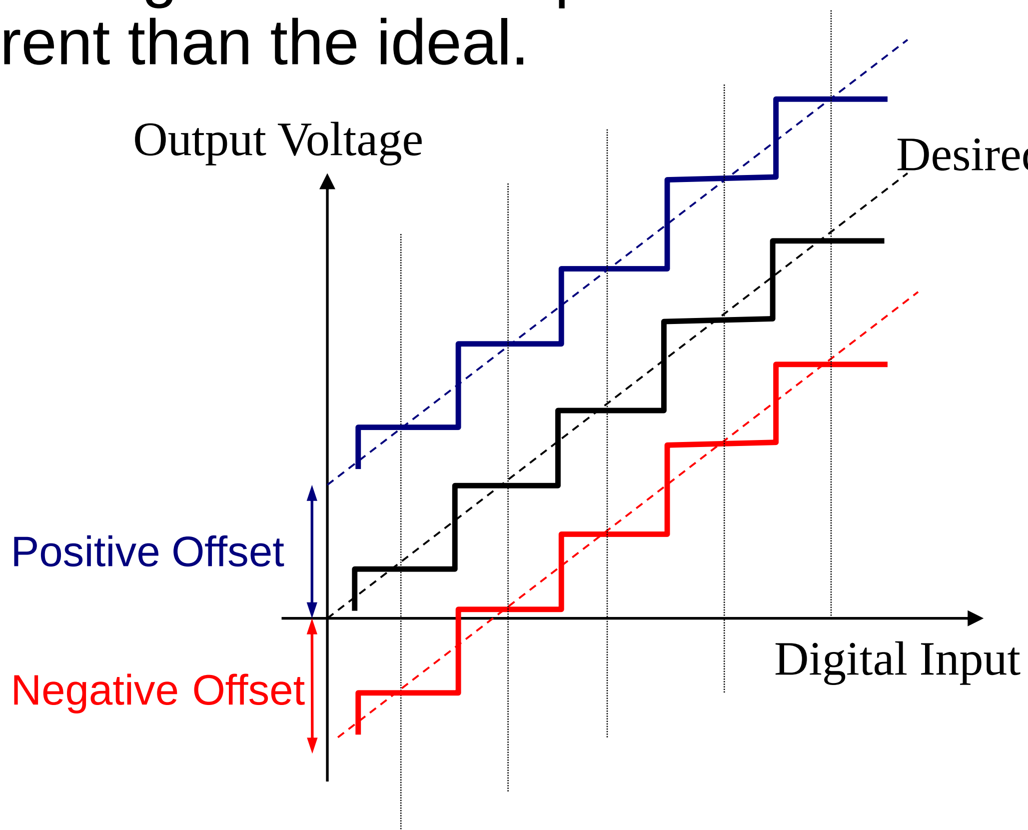


Digital to Analog Converters

-Performance Specifications

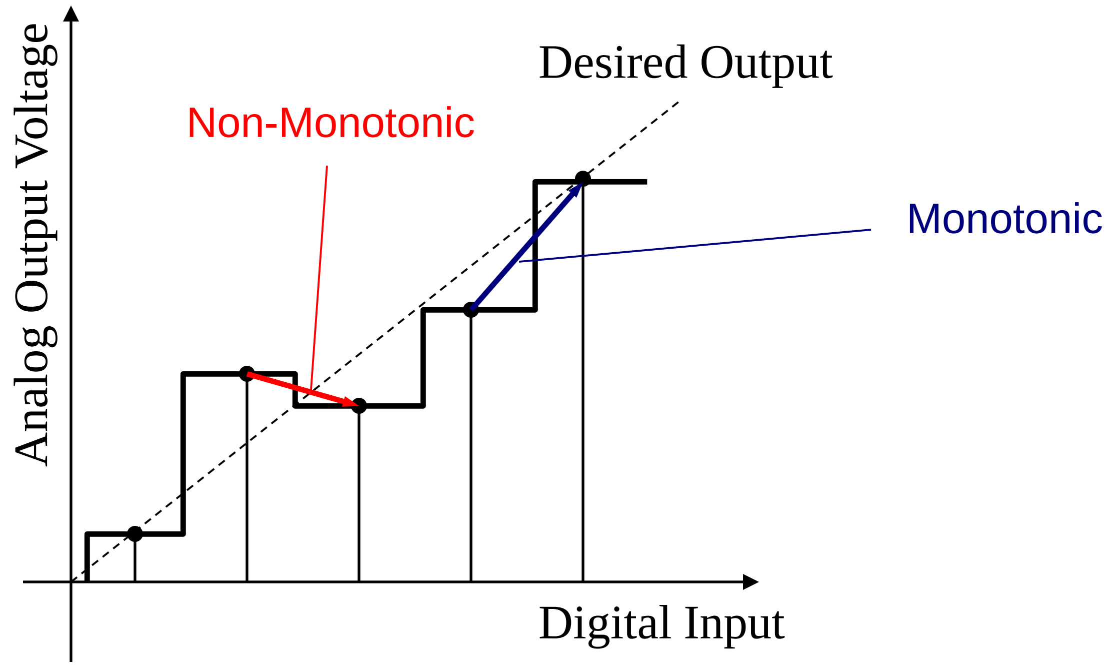
-Errors: Offset

- Offset Error: A constant voltage difference between the ideal DAC output and the actual.
  - The voltage axis intercept of the DAC output curve is different than the ideal.



-Errors: Non-Monotonicity

- Non-Monotonic: A decrease in output voltage with an increase in the digital input



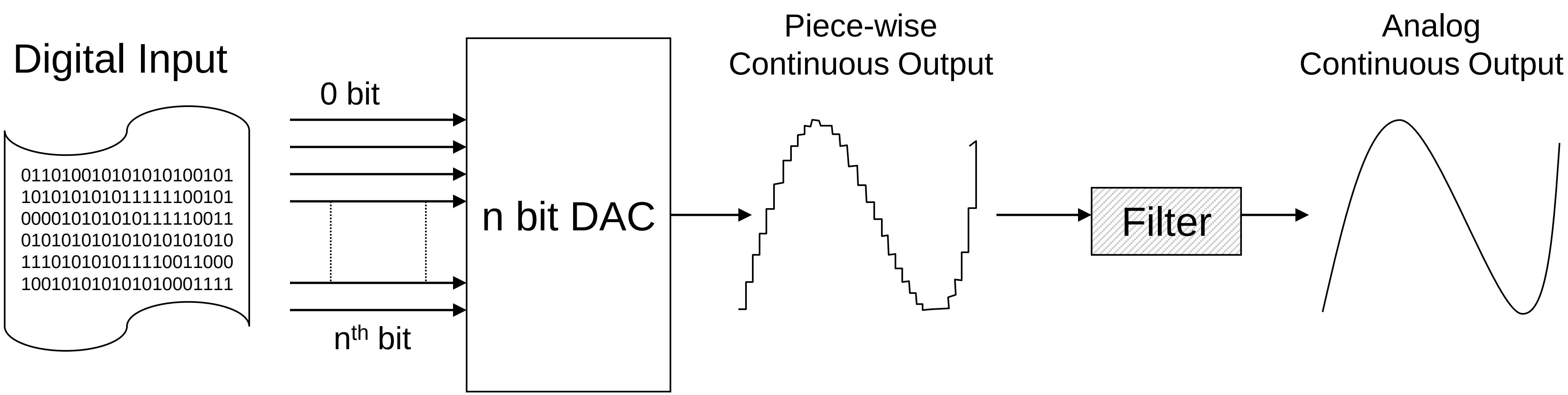
Digital to Analog Converters

-Common Applications

- Generic use
- Circuit Components
- Digital Audio
- Function Generators/Oscilloscopes
- Motor Controllers

Digital to Analog Converters
-Common Applications
-Generic

- Used when a continuous analog signal is required.
- Signal from DAC can be smoothed by a Low pass filter



Digital to Analog Converters

-Common Applications

-Circuit Components

- Voltage controlled Amplifier
  - digital input, External Reference Voltage as control
- Digitally operated attenuator
  - External Reference Voltage as input, digital control
- Programmable Filters
  - Digitally controlled cutoff frequencies

Digital to Analog Converters

-Common Applications

-Digital Audio

- CD Players
- MP3 Players
- Digital Telephone/Answering Machines

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1. http://electronics.howstuffworks.com/cd.htm
2. http://accessories.us.dell.com/sna/sna.aspx?c=us&cs=19&l=en&s=dhs&~topic=odg_dj
3. http://www.toshiba.com/taistsd/pages/prd_dtc_digphones.html

Digital to Analog Converters

-Common Applications

-Function Generators

- Digital Oscilloscopes
  - Digital Input
  - Analog Ouput
- Signal Generators
  - Sine wave generation
  - Square wave generation
  - Triangle wave generation
  - Random noise generation

1

2

1. http://www.electrorent.com/products/search/General_Purpose_Oscilloscopes.html
2. http://www.bkprecision.com/power_supplies_supply_generators.htm

Digital to Analog Converters

-Common Applications

-Motor Controllers

- Cruise Control
- Valve Control
- Motor Control

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1. http://auto.howstuffworks.com/cruise-control.htm
2. http://www.emersonprocess.com/fisher/products/fieldvue/dvc/
3. http://www.thermionics.com/smc.htm