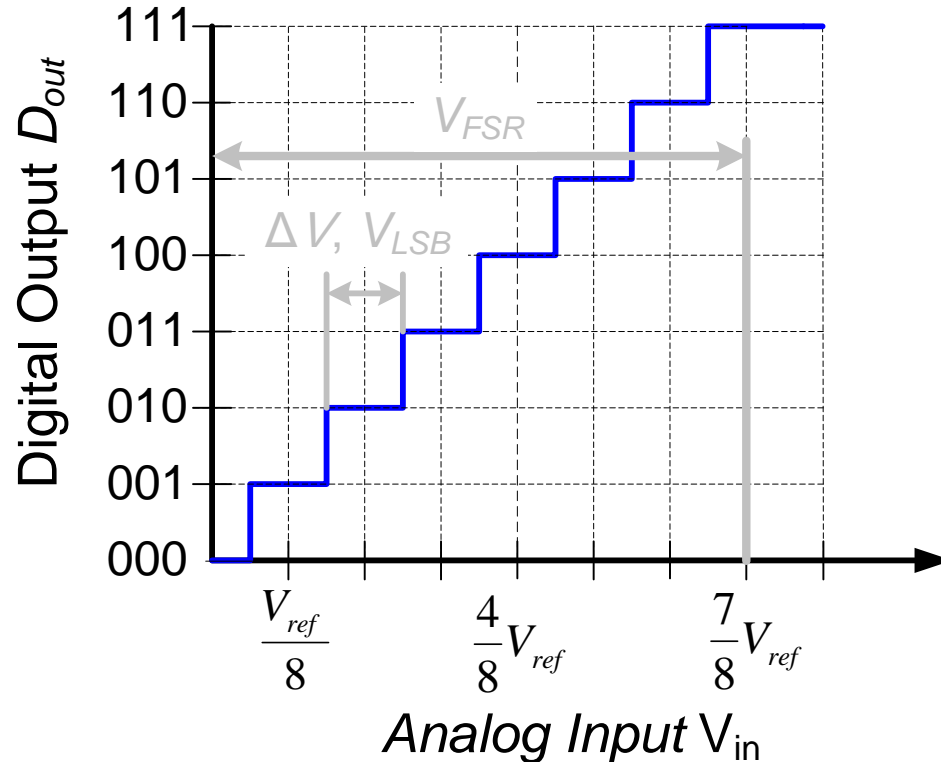# ELG4139: Converters

Analog to Digital Converters (ADCs)   Digital to Analog Converters (DACs)


Any analog quantity can be represented by a binary number. Longer binary numbers provide higher resolution, which gives a more accurate representation of the analog quantity.

Analog to Digital Converters

Objective: Representing an analog varying physical quantity by a sequence of discrete numerical values.

01 07 10 15 09 03 00 05

Analog

Digital

Sample
& Hold

f_{sample}
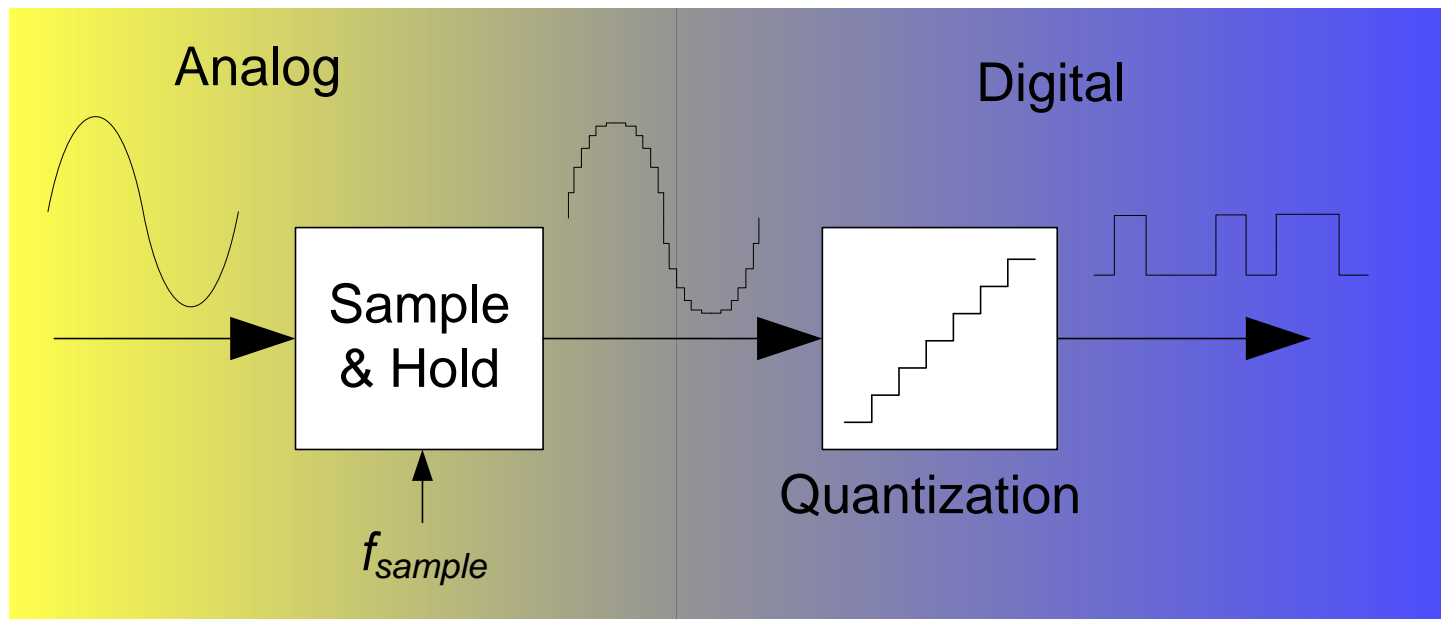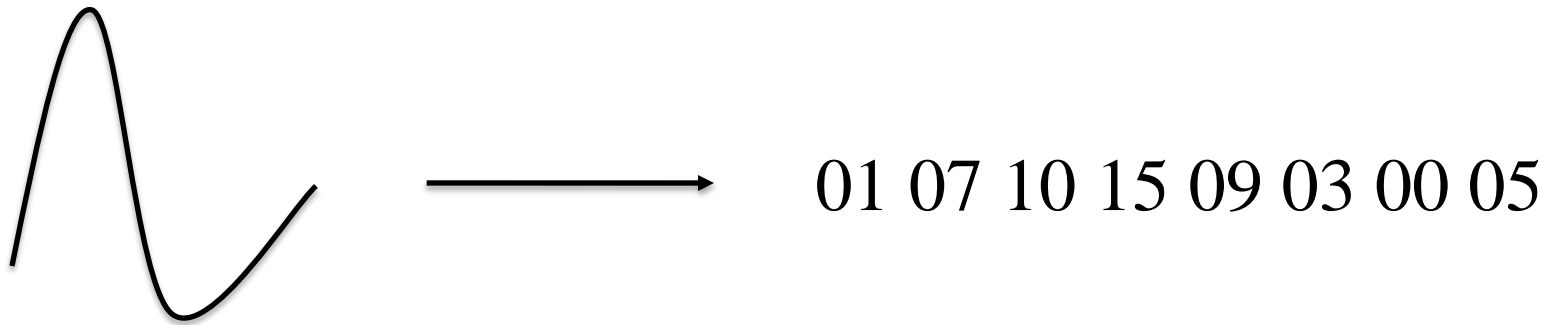
Quantization

Digitization Process
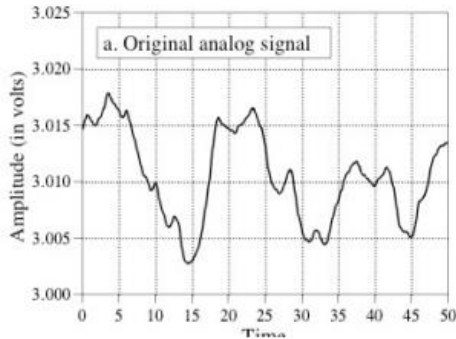
We will look into two stages of the ADC process: *sample and hold* and *quantization*. *After* that, the signal is *encoded* into bits.
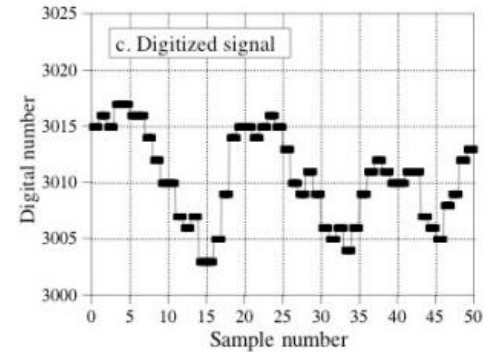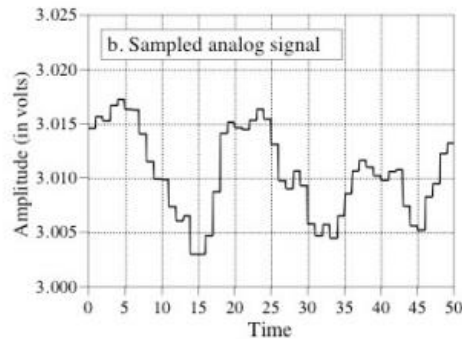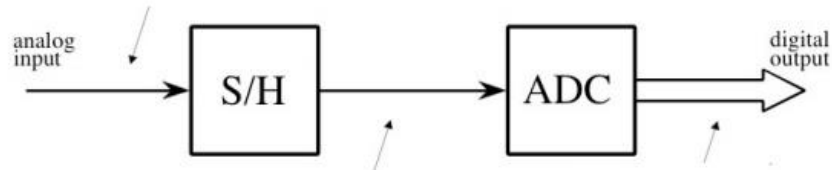
Sample-and-Hold

A number of problems exist with the previous sample and hold circuit

Load placed on the input of the circuit by charging the capacitor during the sample phase.

Current flowing from the capacitor used in the conversion will reduce the voltage stored on the capacitor

sample/hold
control line
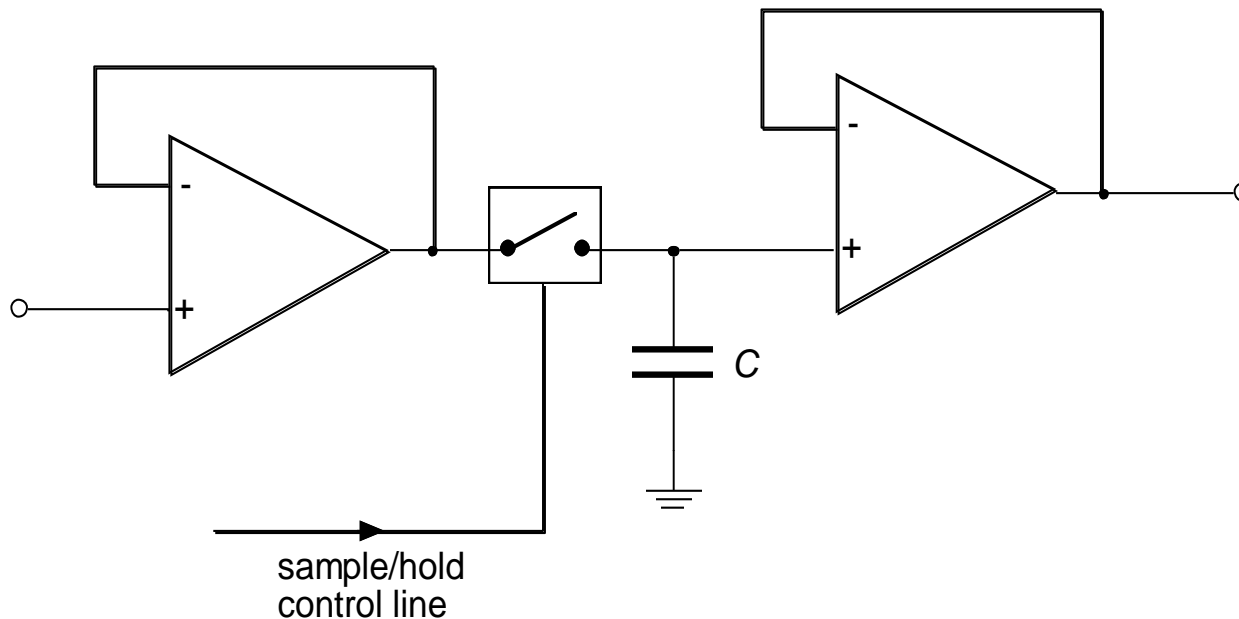
Sample and Hold Circuits

- Sample and hold circuits hold signal constant for conversion
- A sample and a hold device (mostly switch and capacitor) Demands:
  - Small RC-settling-time (voltage over hold capacitor has to be fast stable at < 1 LSB)
  - Exact switching point
  - Stable voltage over hold capacitor
  - No charge injection by the switch.
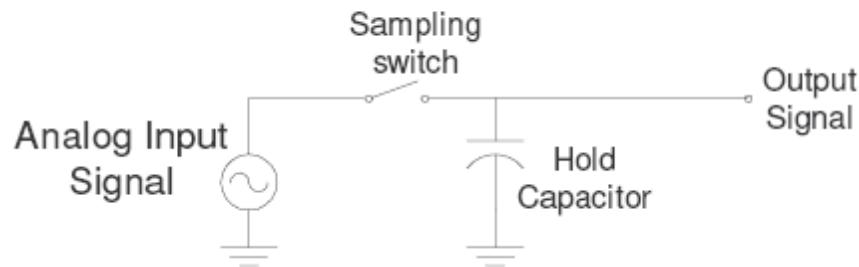
If you can exactly reconstruct the signal from the samples, then you have done a proper sampling and captured the key signal information
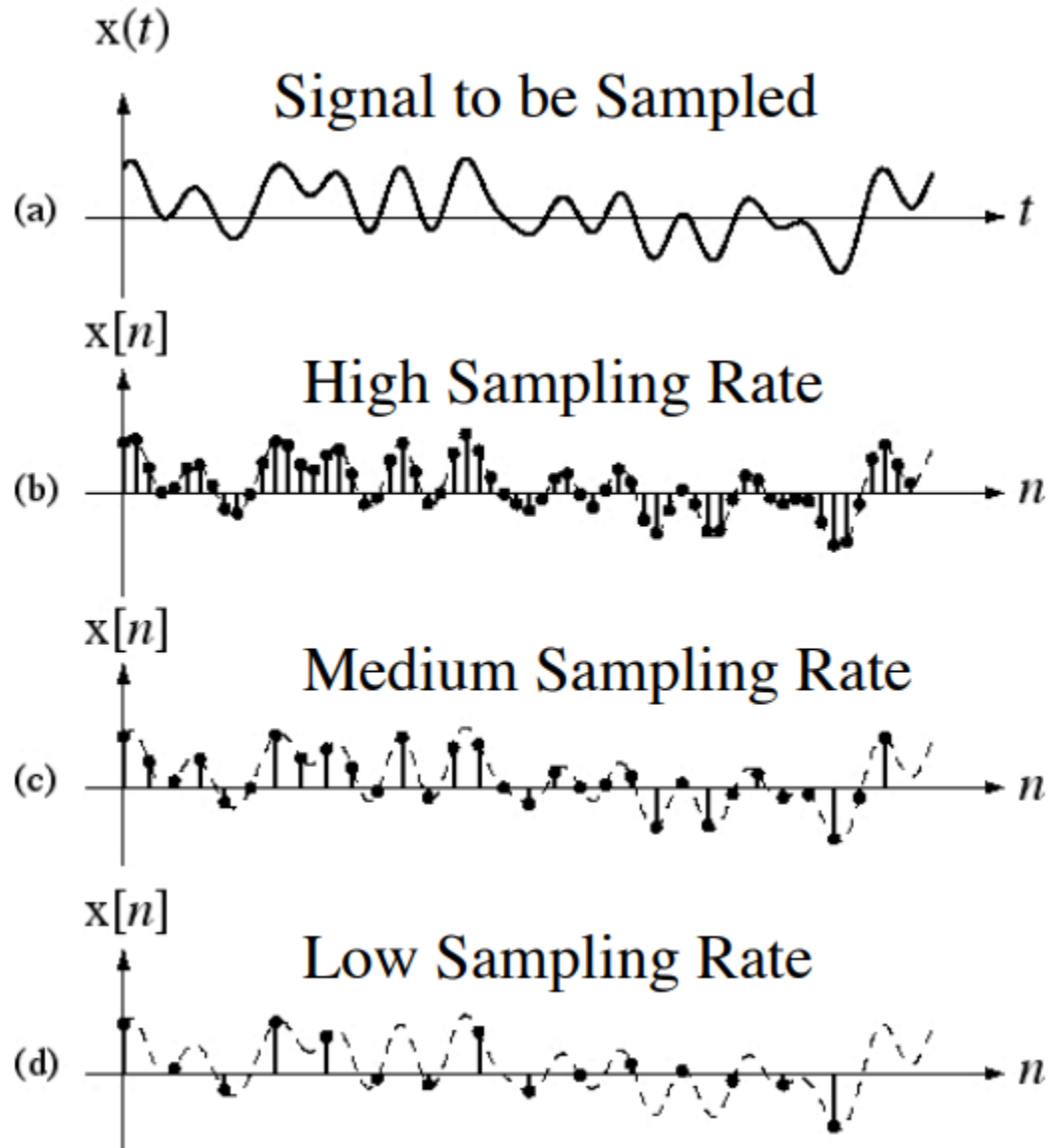
Accuracy
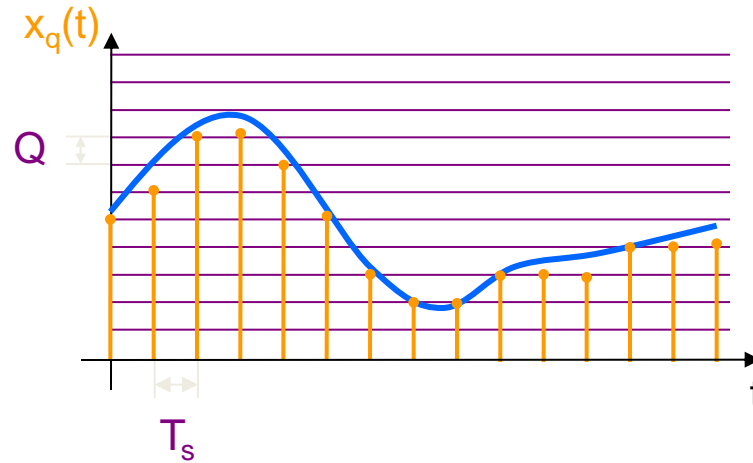
Higher Sampling Rate
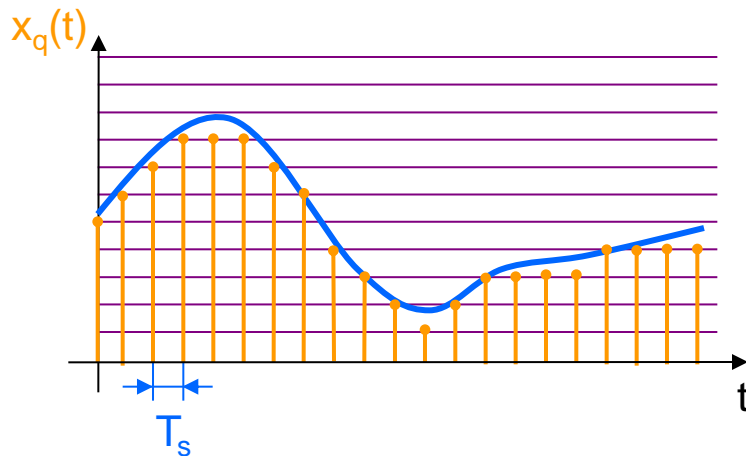
Higher Resolution
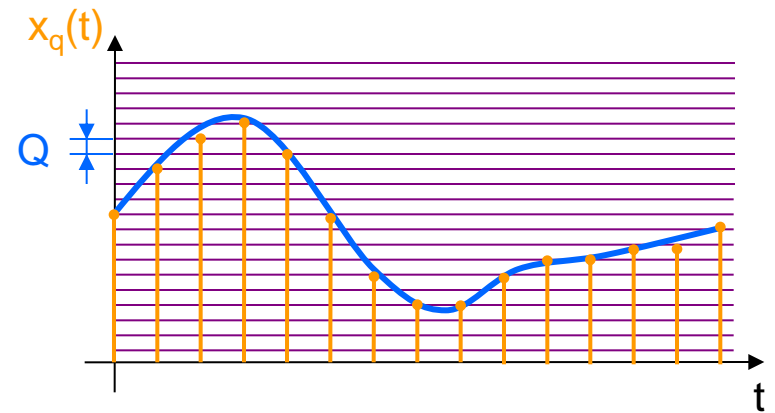
Resolution

Suppose a binary number with N bits is to represent an analog value ranging from 0 to A; There are 2^N possible numbers.

$$\text{Resolution} = A / 2^N$$

Example 1: Temperature range of 0 K to 300 K to be linearly converted to a voltage signal of 0 to 2.5 V, then digitized with an 8-bit A/D converter.

$2.5 / 2^8 = 0.0098$ V, or about 10 mV per step

300 K $/ 2^8 = 1.2$ K per step

Example 2: Temperature range of 0 K to 300 K to be linearly converted to a voltage signal of 0 to 2.5 V, then digitized with a 10-bit A/D converter

$2.5 / 2^{10} = 0.00244$V, or about 2.4 mV per step

300 K $/ 2^{10} = 0.29$ K per step

Is the noise present in the system well below 2.4 mV ?

Successive Approximation ADC

- Generate internal analog signal $V_{D/A}$

- Compare $V_{D/A}$ with input signal V_{in}

- Modify $V_{D/A}$ by $D_0 D_1 D_2 ... D_{N-1}$ until closest possible value to V_{in} is reached
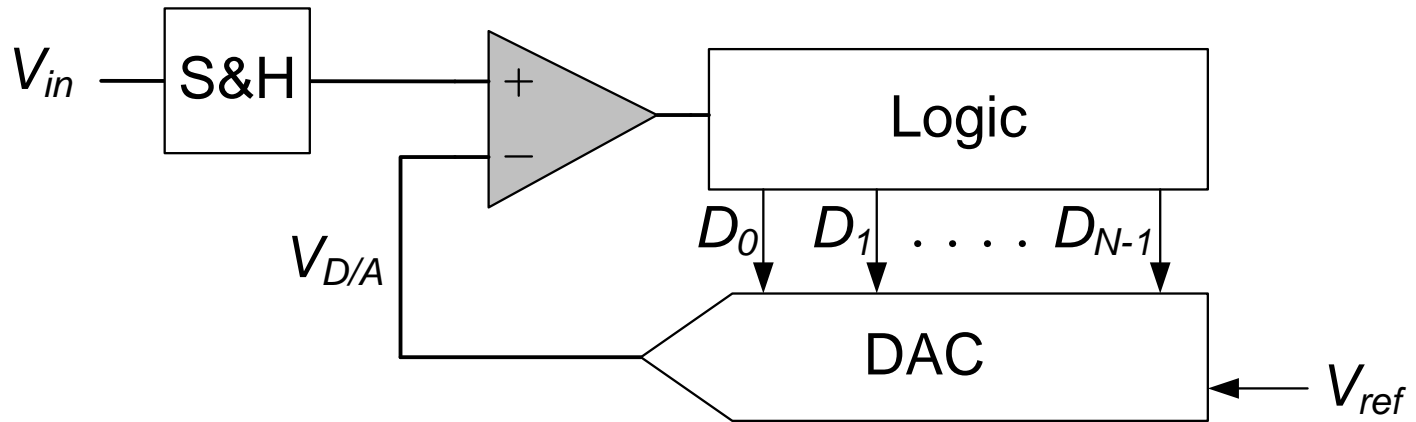
Ladder Comparison

The counter, through a digital-to-analog converter, produces a stair-step of increasing voltage. At each step the input signal is compared to the current step level. If the input is higher, then continue to step, if the input is equal or lesser, then stop and read the counter. The count value is read as numeric value of the input.
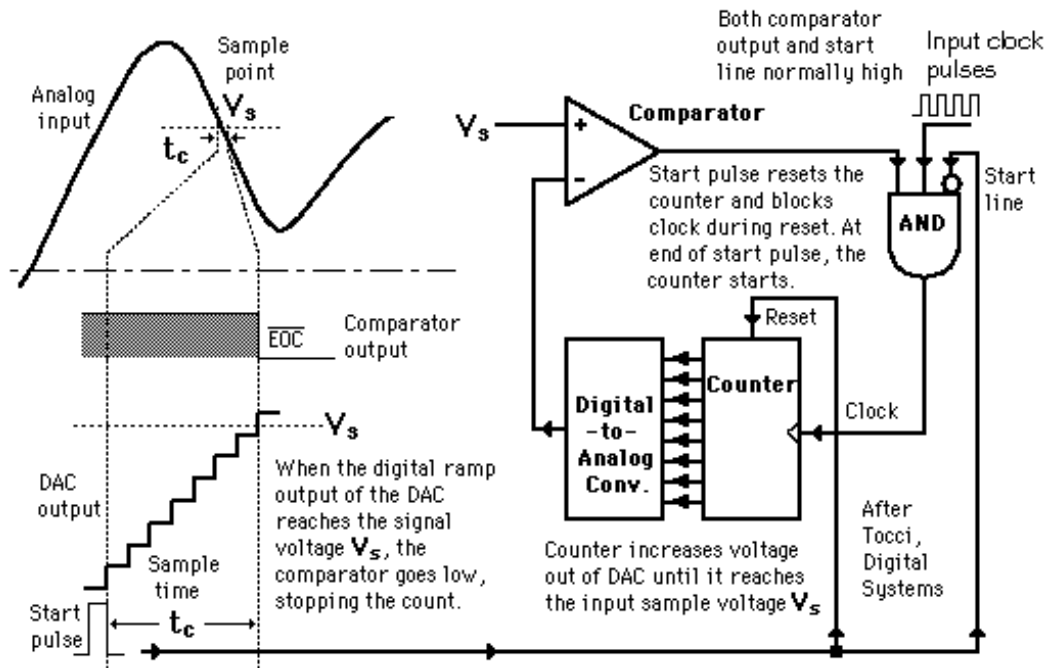
Calculate the maximum conversion time of a 8-bit staircase ramp ADC.
The maximum number of count is $n_c = 28 = 256$. The maximum conversion time is:

$$T_c = \frac{n_c}{f} = \frac{256}{2 \times 10^6} = 128 \times 10^{-6}\, s = 128\mu s$$

Flash ADC
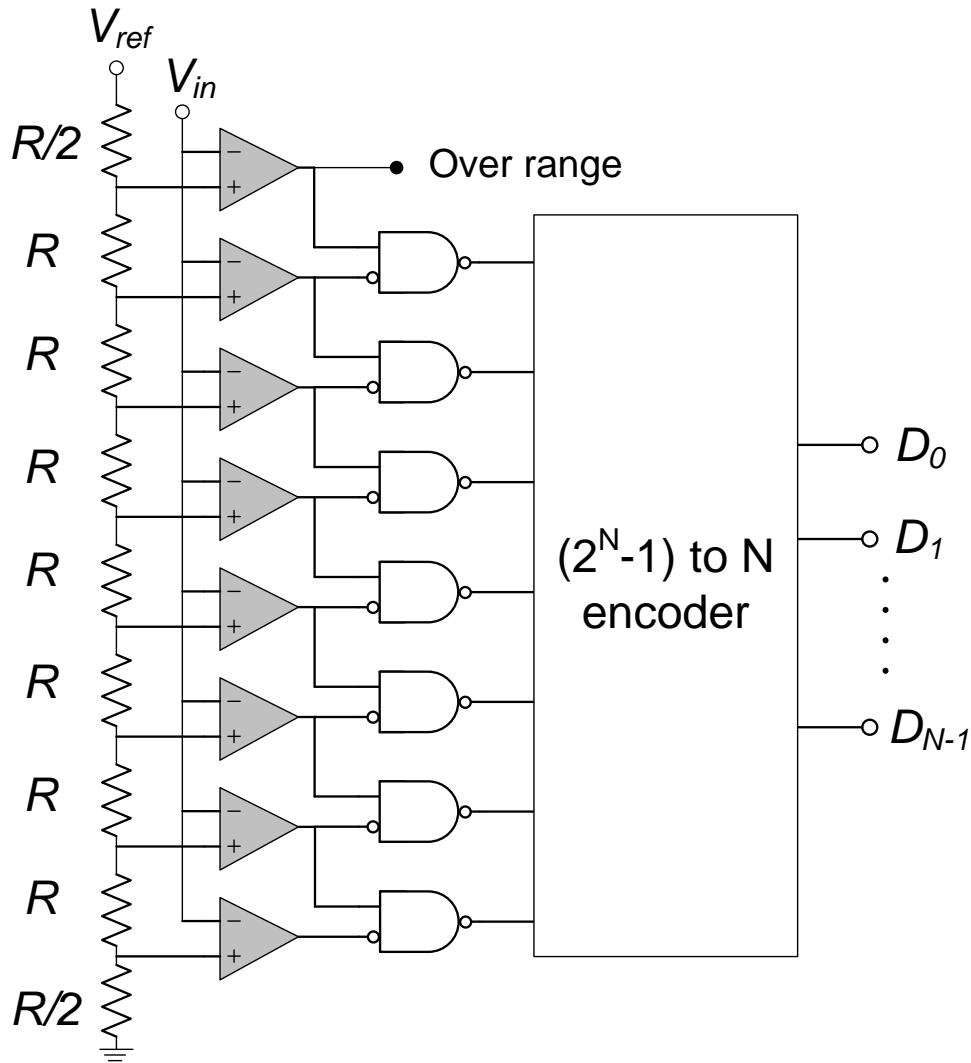
- V_{in} connected with 2^N comparators in parallel
- Comparators connected to resistor string

Over range

(2^N-1) to N encoder

D_0
D_1
D_{N-1}

If	Output
$V_{IN} > V_{REF}$	High
$V_{IN} < V_{REF}$	Low

V_{ref}
V_{in}
R/2
R
R
R
R
R
R
R/2

Binary Encoder

4-to-2 Bit Binary Encoder
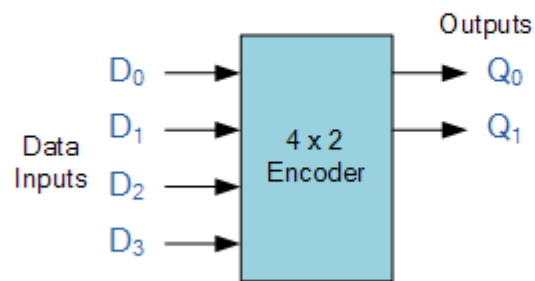
Inputs				Outputs	
D_3	D_2	D_1	D_0	Q_1	Q_0
0	0	0	1	0	0
0	0	1	0	0	1
0	1	0	0	1	0
1	0	0	0	1	1
0	0	0	0	x	x

Priority Encoder

8-to-3 Bit Priority Encoder
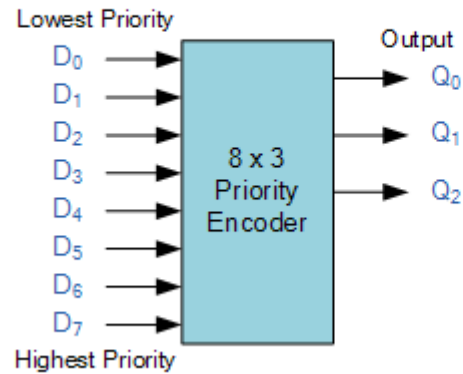
Inputs								Outputs		
D_7	D_6	D_5	D_4	D_3	D_2	D_1	D_0	Q_2	Q_1	Q_0
0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	1	x	0	0	1
0	0	0	0	0	1	x	x	0	1	0
0	0	0	0	1	x	x	x	0	1	1
0	0	0	1	x	x	x	x	1	0	0
0	0	1	x	x	x	x	x	1	0	1
0	1	x	x	x	x	x	x	1	1	0
1	x	x	x	x	x	x	x	1	1	1

Lowest Priority
D_0
D_1
D_2
D_3
8 x 3
Priority
Encoder
D_4
D_5
D_6
D_7
Highest Priority

Output
Q_0
Q_1
Q_2

An ADC is usually in form of an integrated circuit (IC). ADC0808 and ADC0809 are two typical examples of 8-bit ADC with 8-channel multiplexer using successive approximation method for its conversion.
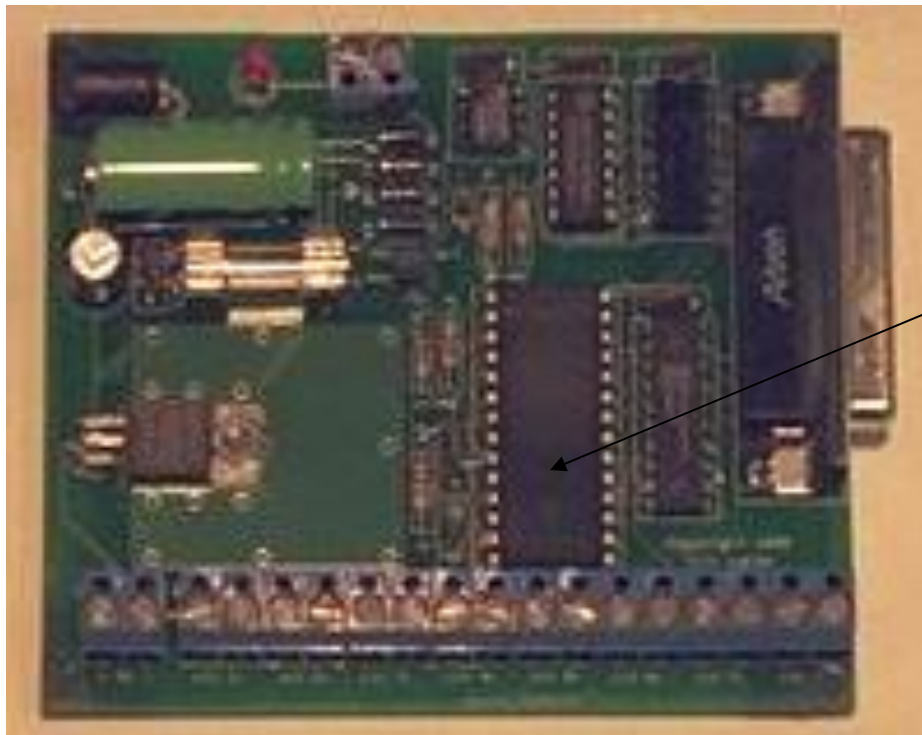
ADC0809
National
Semiconductor

For more information,
http://www.national.com/ads-cgi/viewer.pl/ds/AD/ADC0808.pdf

Selection of ADC

The parameters used in selecting an ADC are very similar to those considered for a DAC selection:

- Error/Accuracy: Quantizing error represents the difference between an actual analog value and its digital representation. Ideally, the quantizing error should not be greater than ± ½ LSB.
- Resolution: ΔV to cause 1 bit change in output
- Output Voltage Range $\Rightarrow$ Input Voltage Range
- Output Settling Time $\Rightarrow$ Conversion Time
- Output Coding (usually binary)

The Nyquist Rate: A signal must be sampled at a rate at least twice that of the highest frequency component that must be reproduced.
Example: Hi-Fi sound (20-20,000 Hz) is generally sampled at about 44 kHz.

Digital to Analog Converters (DACs)
Binary Weighted Resistor

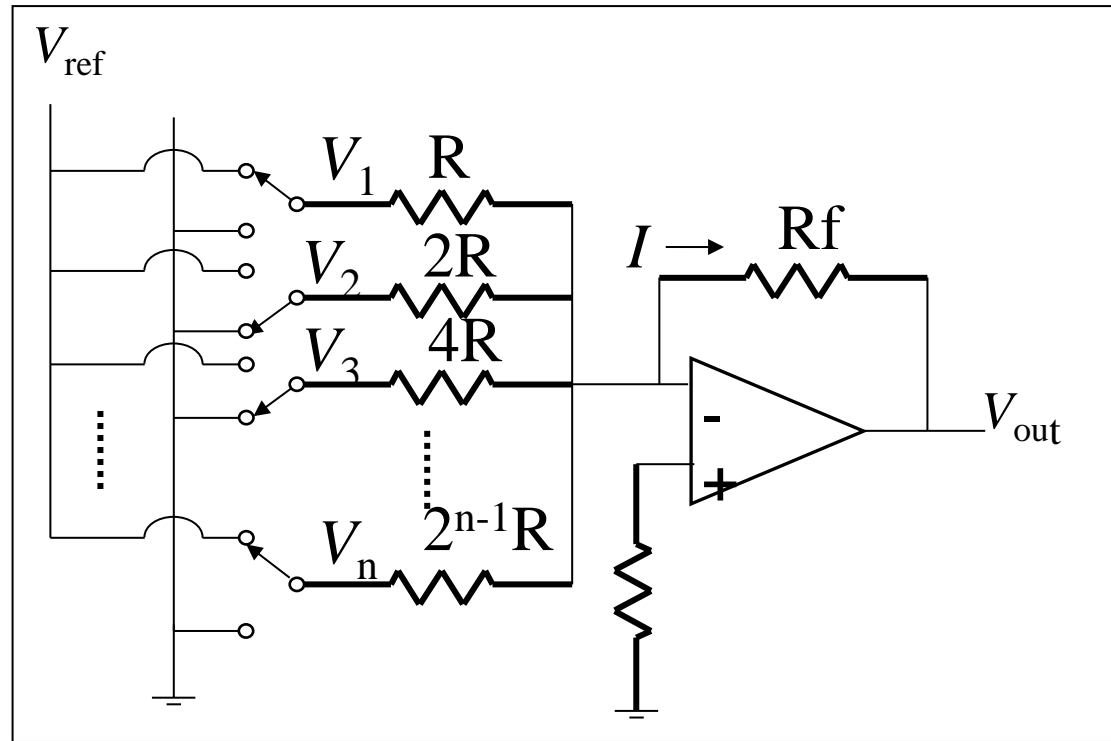Voltages V_1 through V_n are either V_{ref} if corresponding bit is high or ground if corresponding bit is low

V_1 is most significant bit

V_n is least significant bit

V_{ref}
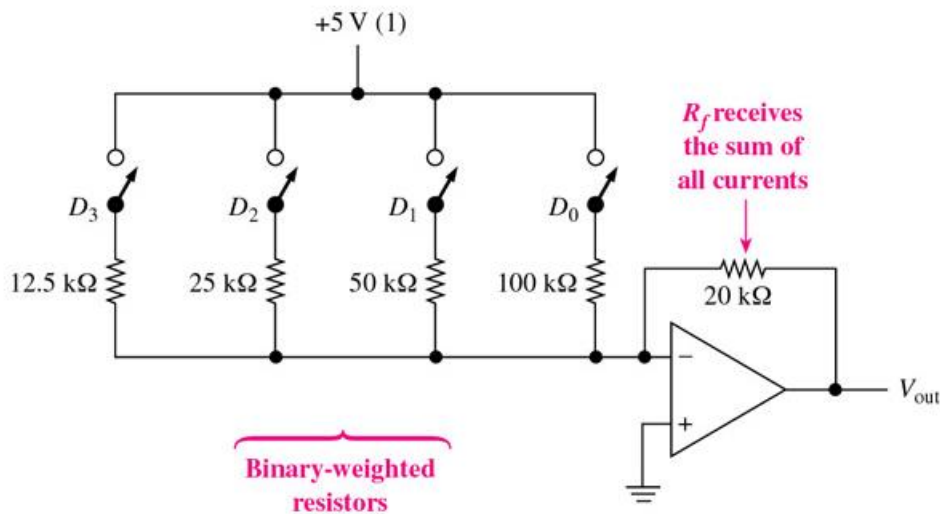
V_1 R
V_2 2R
V_3 4R
$I \rightarrow$ Rf
$2^{n-1}R$
V_n

V_{out}

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 Digital-to-Analog Converters

Sum of the currents from the input resistors; Consider binary weighting factor.

Digital				Analog
D_3	D_2	D_1	D_0	V_{out} $(-V)$
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8
1	0	0	1	9
1	0	1	0	10
1	0	1	1	11
1	1	0	0	12
1	1	0	1	13
1	1	1	0	14
1	1	1	1	15

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
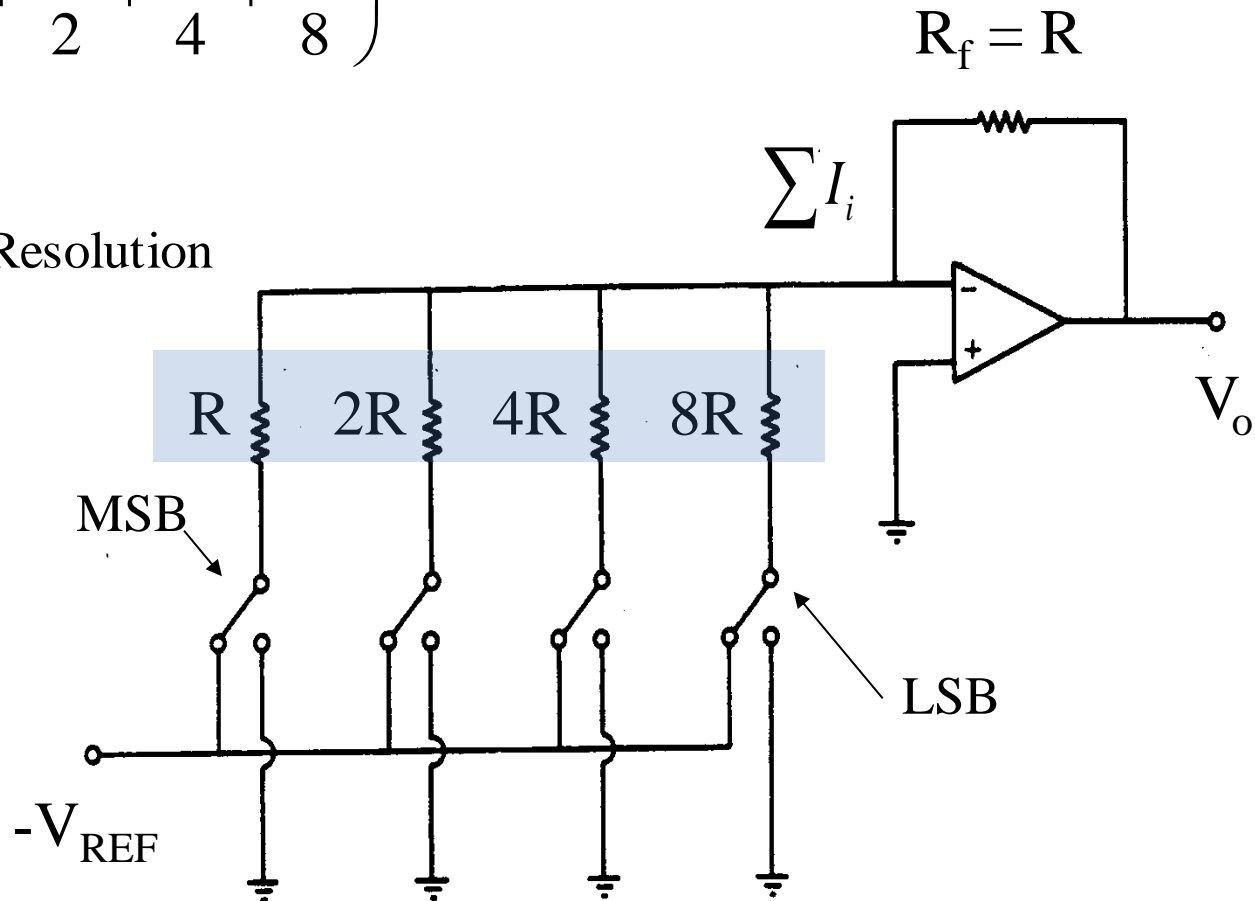
9

Binary Weighted Resistor

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

$$V_{OUT} = I \cdot R_f = V_{REF}\left(B_3 + \frac{B_2}{2} + \frac{B_1}{4} + \frac{B_0}{8}\right)$$
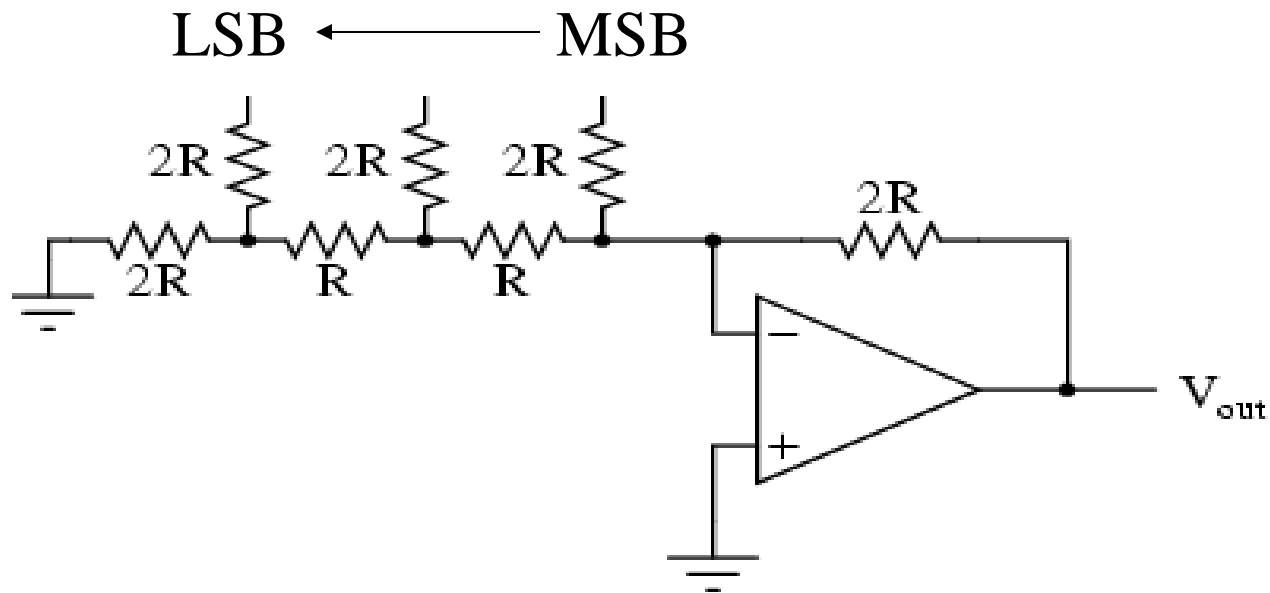
$$V_{OUT} = V_{REF}\sum \frac{B_i}{2^{n-i-1}}$$

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

$R_f = R$

$\sum I_i$

R   2R   4R   8R
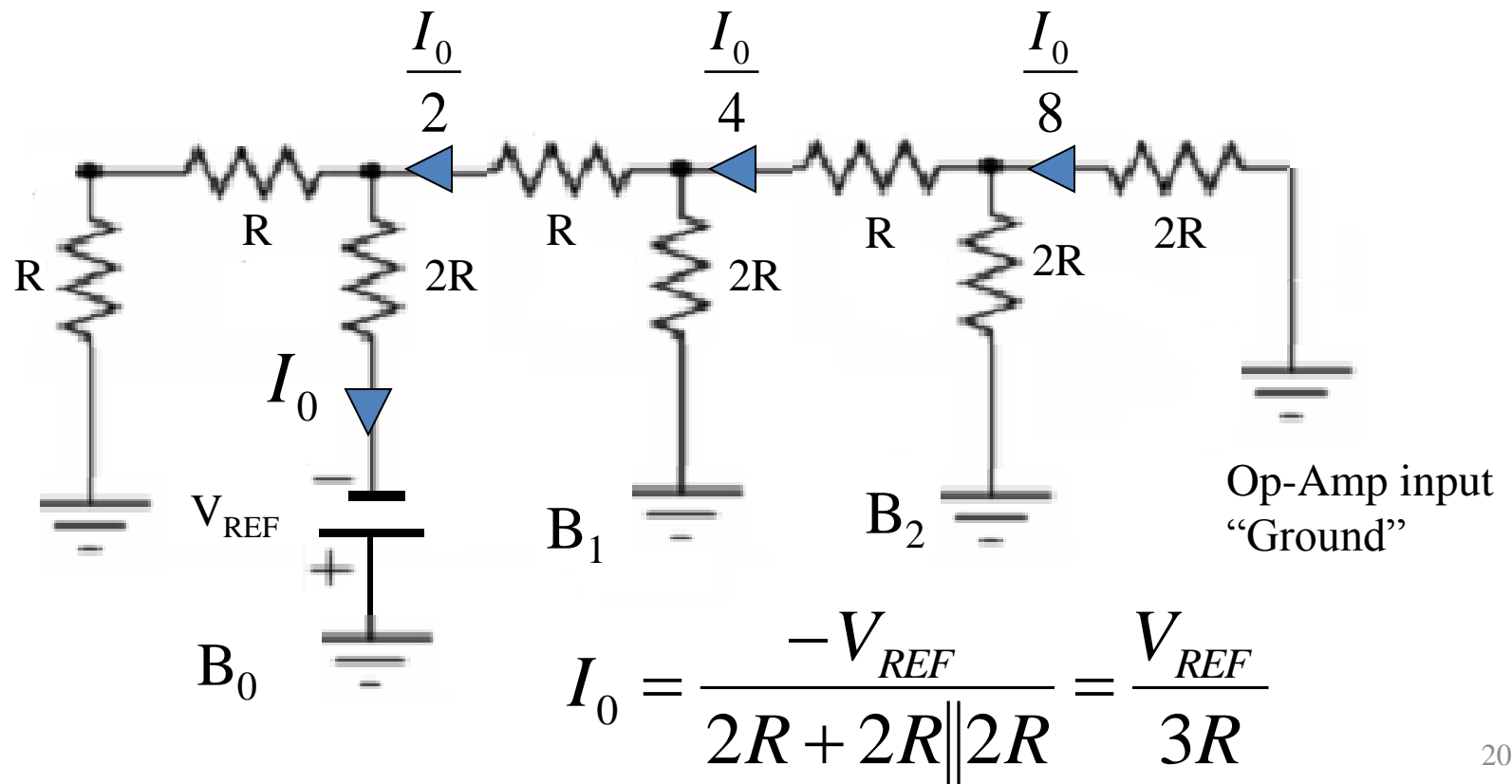
MSB

LSB

$-V_{REF}$

V_o

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: An Example

Find the output voltage of the Op-Amp for the following DAC
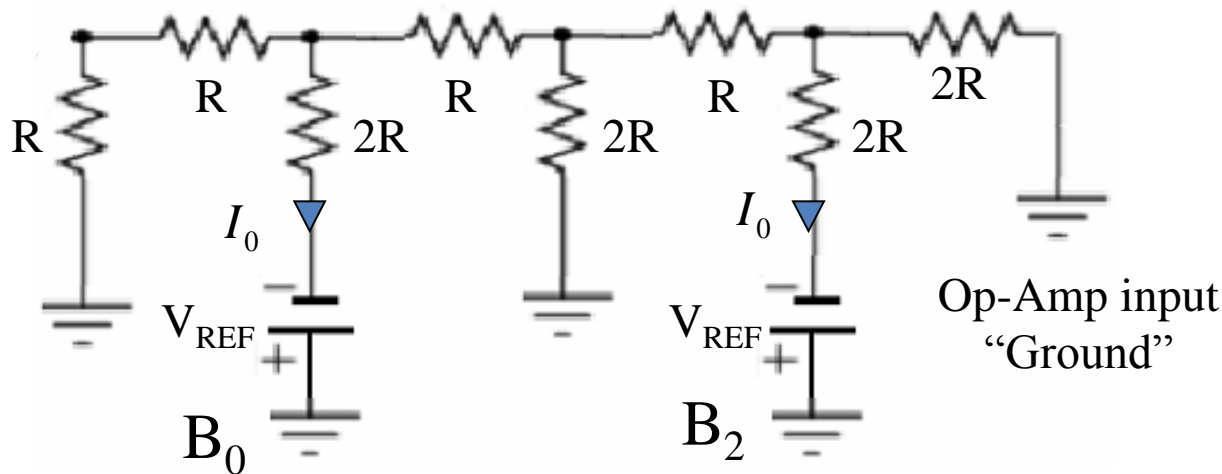
- Given Values
  - Input = $(101)_2$
  - $V_{REF} = 10$ V
  - R = 2 Ω
  - $R_f = 2R$

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

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

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

Op-Amp input "Ground"

Resolution

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

Poor Resolution(1 bit)

Vout

Desired Analog signal

2 Volt. Levels

1

0   0

Digital Input

Approximate output

Better Resolution(3 bit)

Vout

Desired Analog signal

8 Volt. Levels

111
110   110
101   101
100   100
011   011
010   010
001   001
000   000
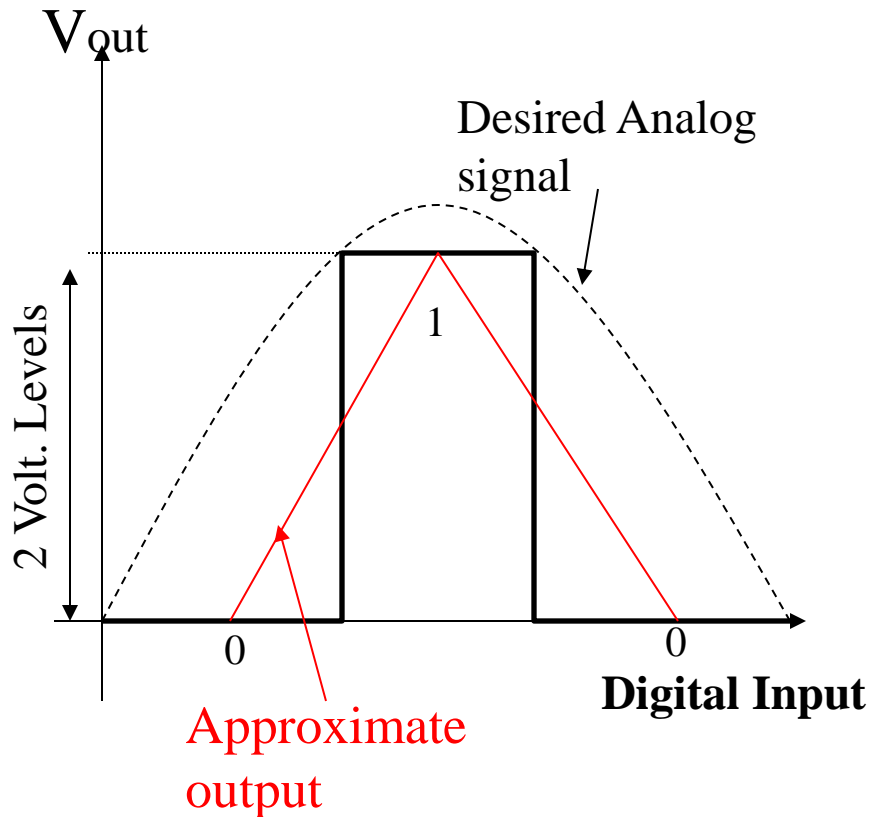
Digital Input

Approximate output
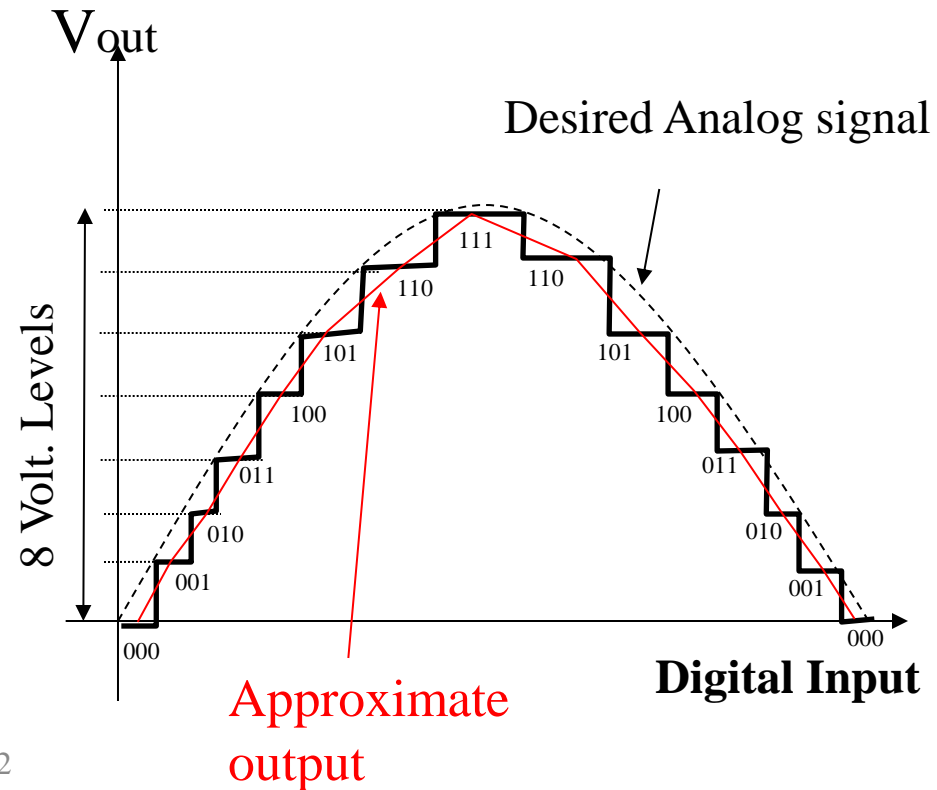
Digital to Analog Converters
Selection Criteria of DAC

Resolution

The number of bits making up the input data word that will ultimately determine the output step voltage as a percentage of full-scale output voltage.

Example: Calculate the resolution of an 8-bit DAC.

Resolution = 8 bits

Percentage resolution = $\dfrac{1}{2^8} \times 100\% = \dfrac{1}{256} \times 100\% = 0.391\%$

Output Voltage Range

This is the difference between the maximum and minimum output voltages expressed in volts.

Example: Calculate the output voltage range of a 4-bit DAC if the output voltage is +4.5V for an input of 0000 and +7.5V for an input of 1111.

Output voltage range = 7.5 – 4.5 = 3.0V

Summary

- Operational amplifiers are important building blocks in analog-to-digital (A/D) and digital-to-analog (D/A) converters. They provide a means for summing currents at the input and converting a current to a voltage at the output of converter circuits.

- The methods of A/D conversion used are many! In the successive method, bits are tested to see if they contribute an equivalent analog value that is greater than the analog input to be converted. If they do, they are returned to zero. After all bits are tested, the ones that are left ON are used as the final digital equivalent to the analog input.

- The R/2R ladder D/A converter uses only two different resistor values, no matter how many binary input bits are included. This allows for very high resolution and ease of fabrication in integrated-circuit form.

- The DAC0808 (or MC1408) IC is an 8-bit D/A converter that uses the R/2R ladder method of conversion. It accepts 8 binary input bits and outputs an equivalent analog current. Having 8 input bits means that it can resolve up to 256 unique binary values into equivalent analog values.