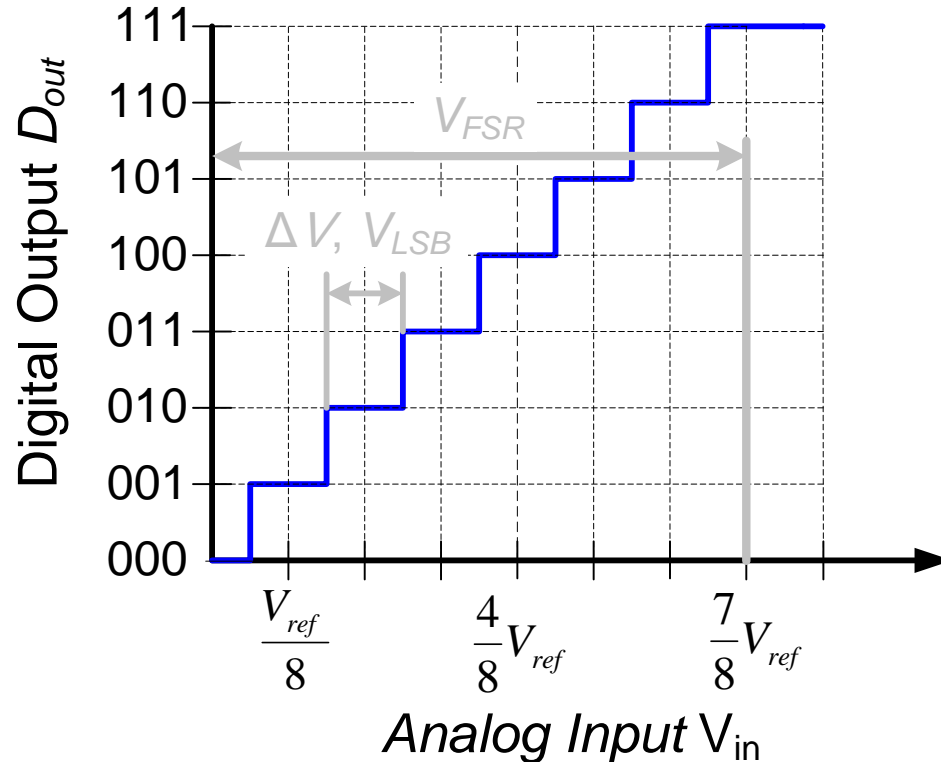


ELG3336: Converters

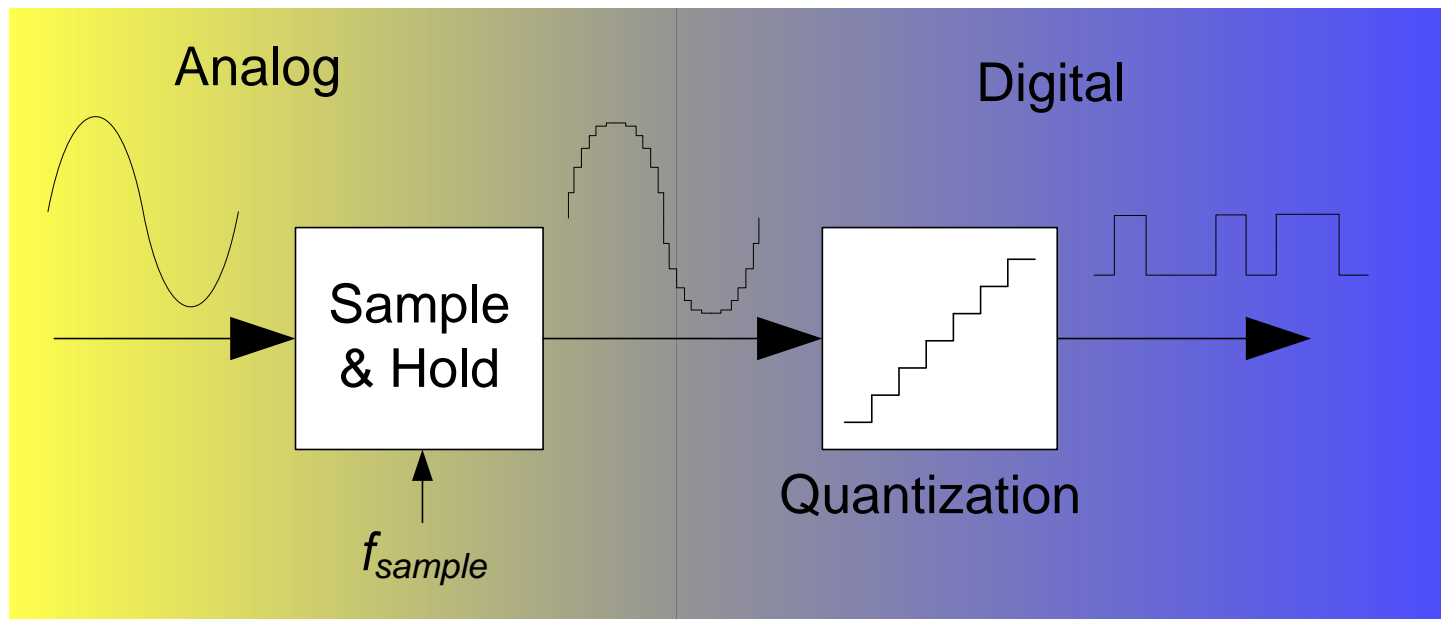
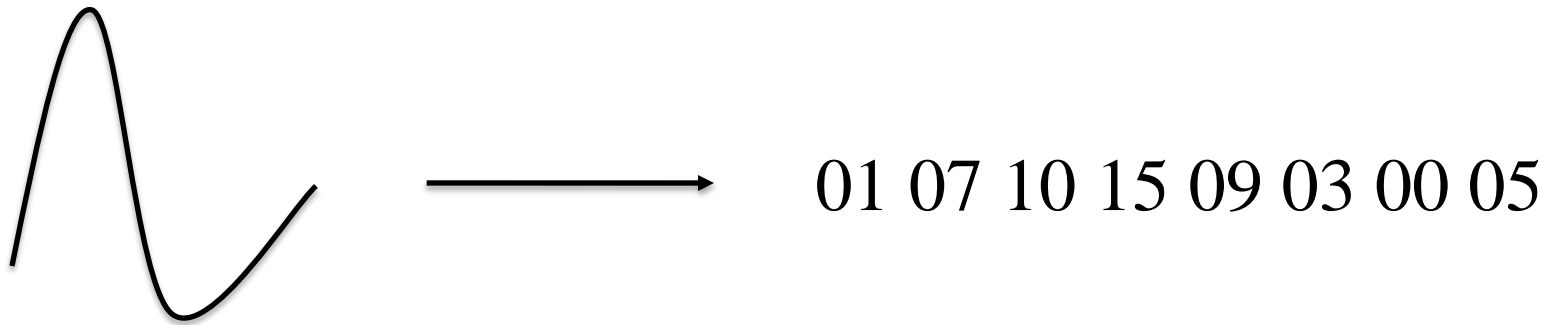
Analog to Digital Converters (ADCs) Digital to Analog Converters (DACs)



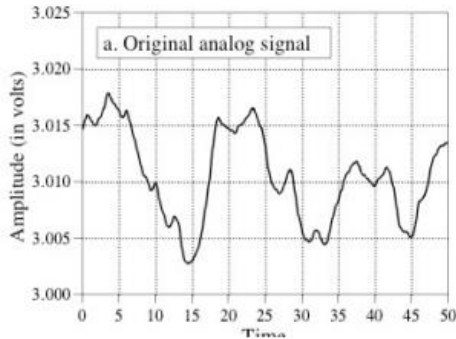
Any analog quantity can be represented by a binary number. Longer binary numbers provide higher resolution, which gives a more accurate representation of the analog quantity.

Analog to Digital Converters

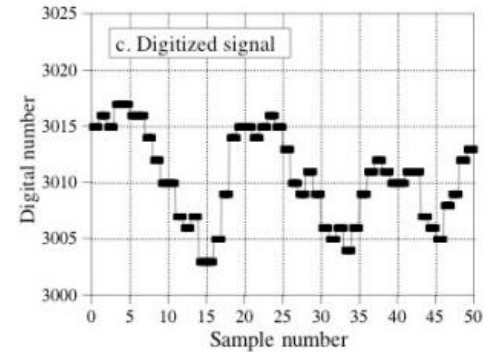
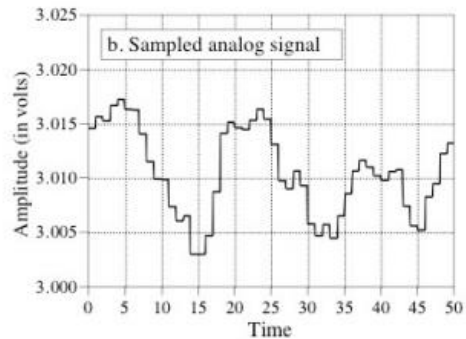
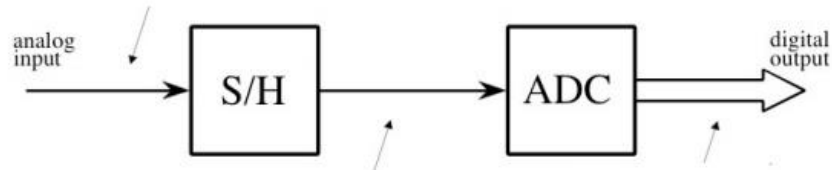
Objective: Representing an analog varying physical quantity by a sequence of discrete numerical values.



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*.

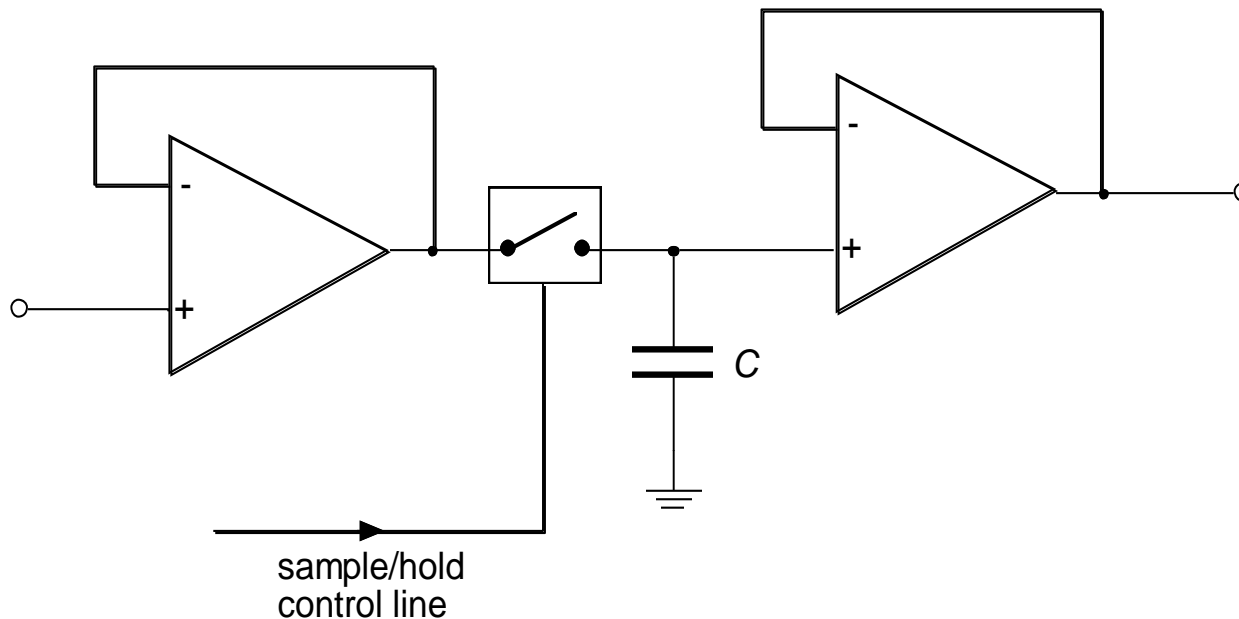


Sample-and-Hold

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

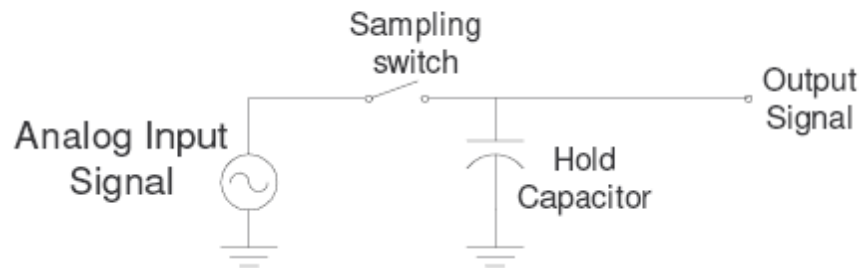
Load placed on the input of the circuit by charging the capacitor during the sample phase.

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

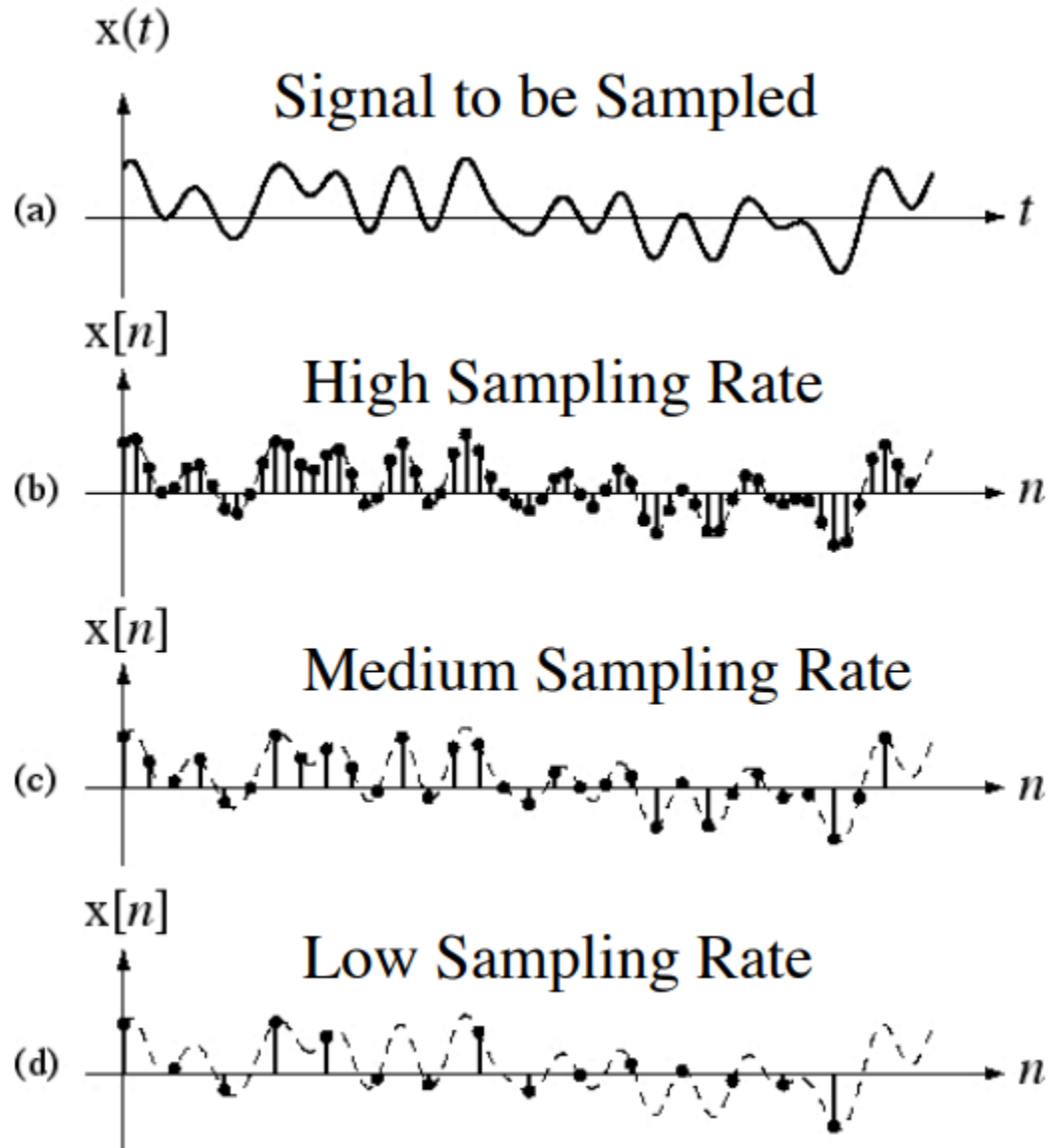


Sample and Hold Circuits

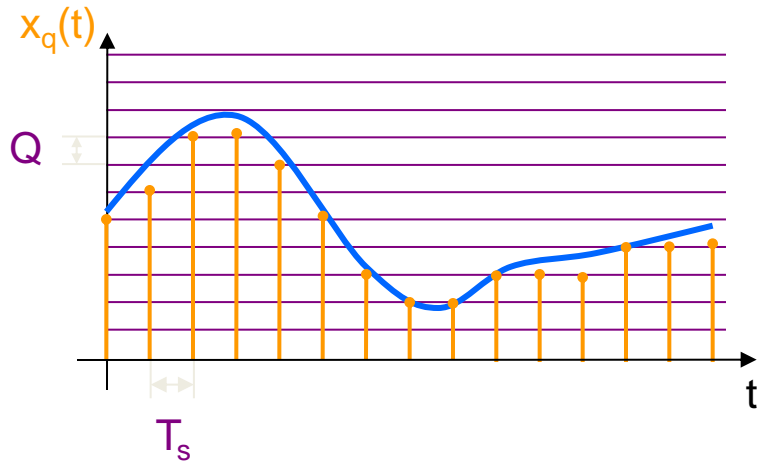
- Sample and hold circuits hold signal constant for conversion
- A sample and a hold device (mostly switch and capacitor)
Demands:
 - Small RC-settling-time (voltage over hold capacitor has to be fast stable at < 1 LSB)
 - Exact switching point
 - Stable voltage over hold capacitor
 - No charge injection by the switch.



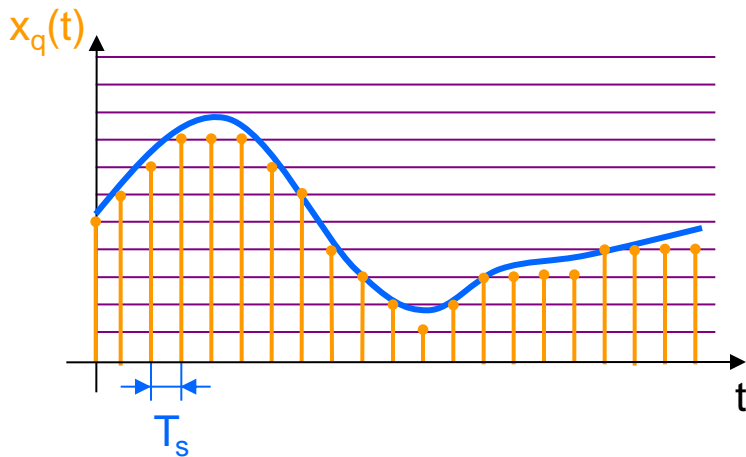
If you can exactly reconstruct the signal from the samples, then you have done a proper sampling and captured the key signal information



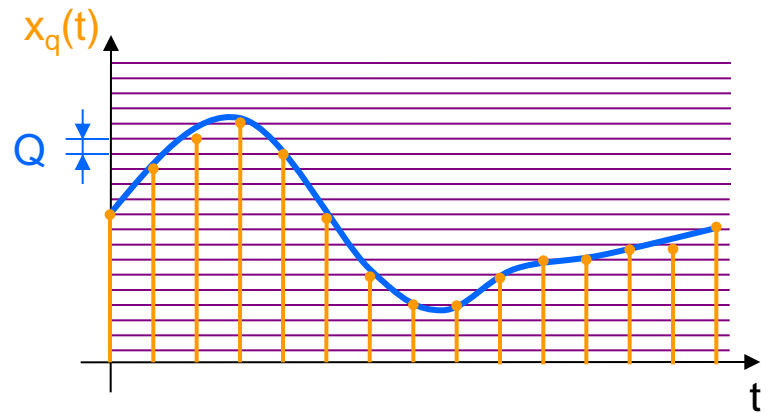
Accuracy



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.

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

$$300 \text{ K} / 2^8 = 1.2 \text{ K per step}$$

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

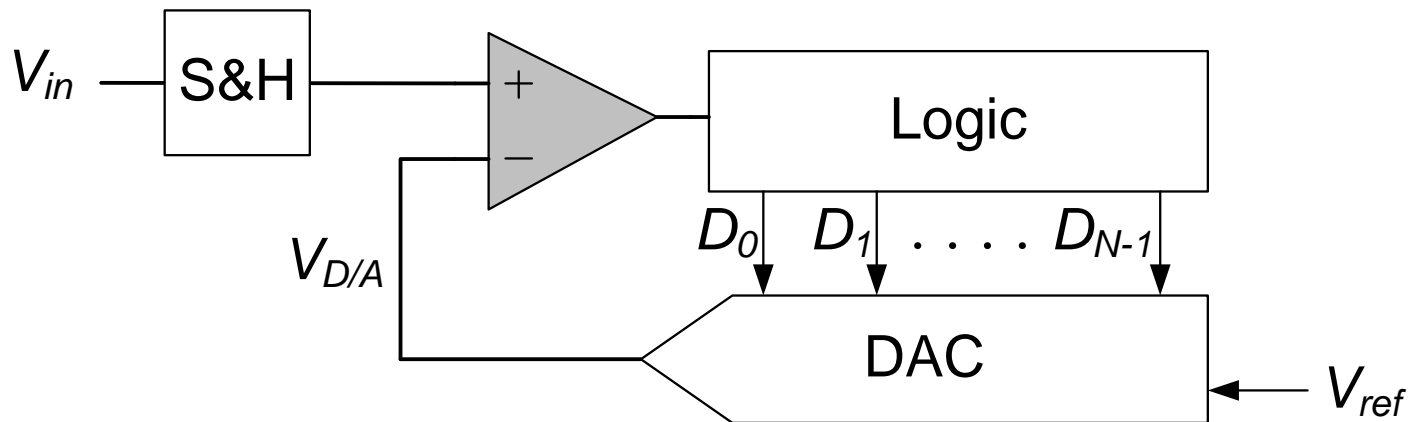
$$2.5 / 2^{10} = 0.00244 \text{ V, or about } 2.4 \text{ mV per step}$$

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

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

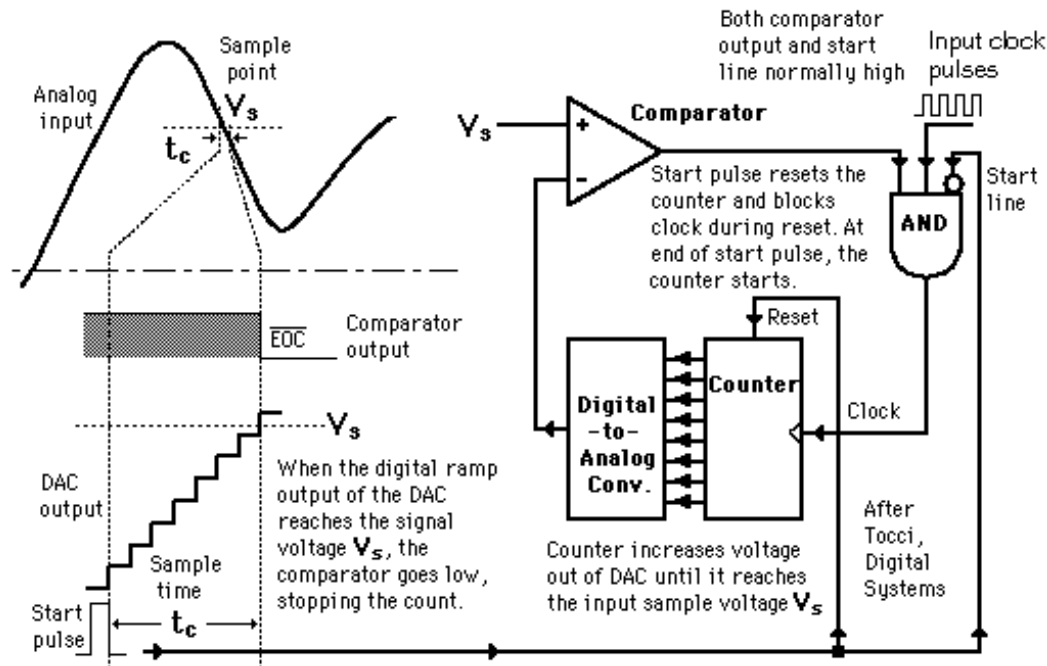
Successive Approximation ADC

- Generate internal analog signal $V_{D/A}$
- Compare $V_{D/A}$ with input signal V_{in}
- Modify $V_{D/A}$ by $D_0D_1D_2\dots D_{N-1}$ 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.

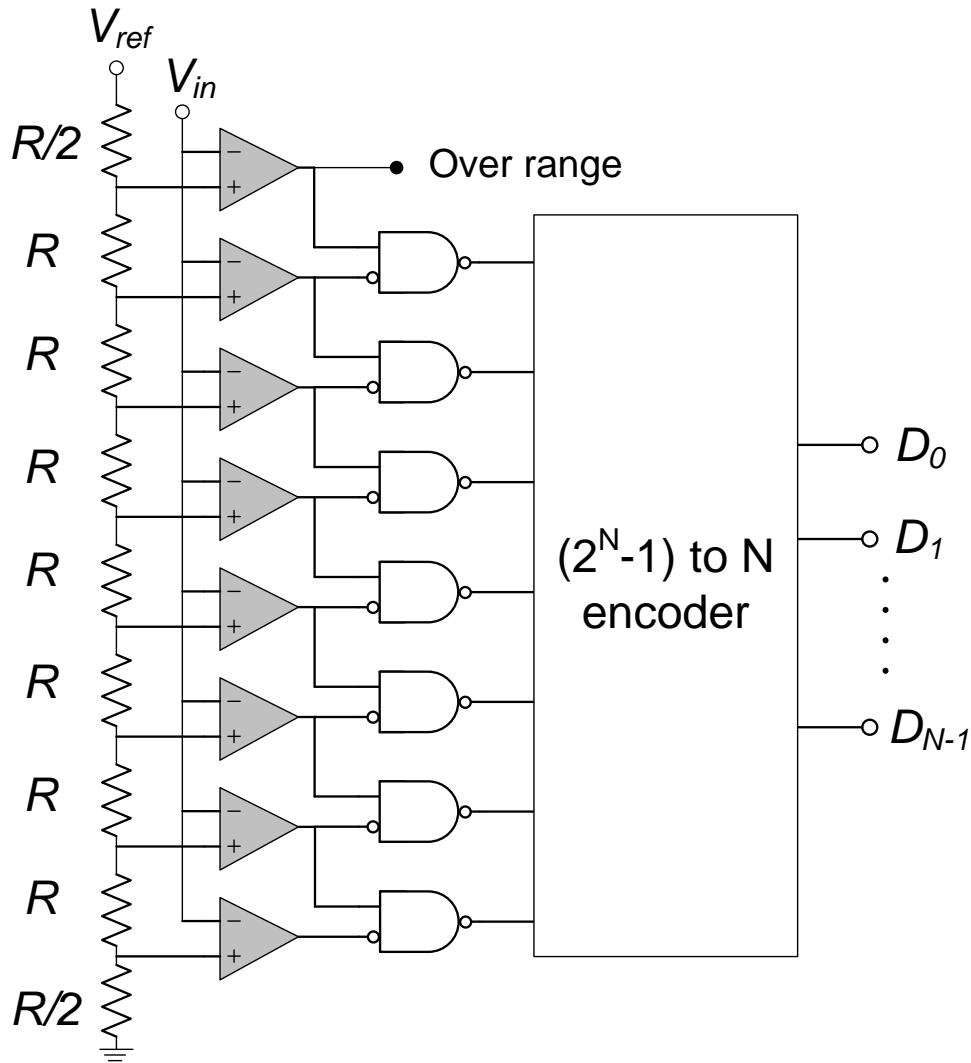


Calculate the maximum conversion time of a 8-bit staircase ramp ADC.

The maximum number of count is $n_c = 2^8 = 256$. The maximum conversion time is:

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

Flash ADC

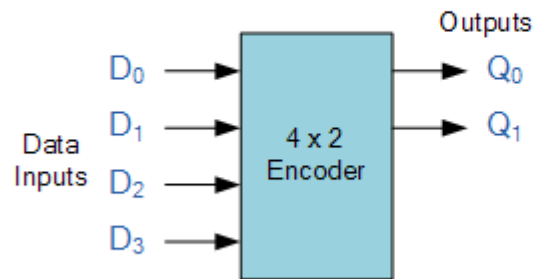


- V_{in} connected with 2^N comparators in parallel
- Comparators connected to resistor string

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

Binary Encoder

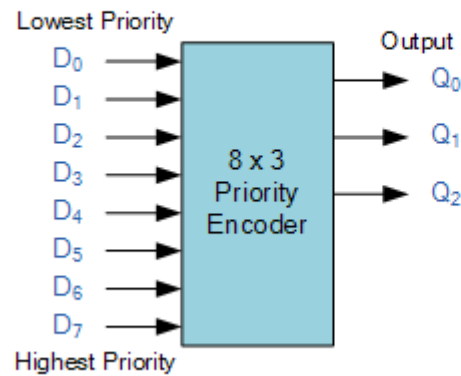
4-to-2 Bit Binary Encoder



| 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 |

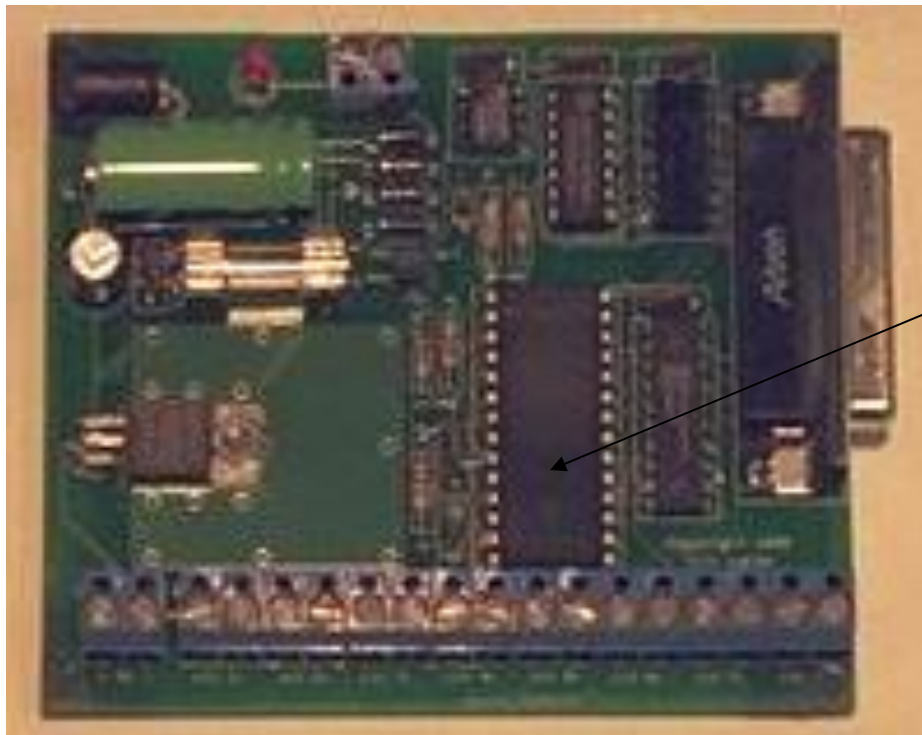
Priority Encoder

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 |

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 $\pm \frac{1}{2}$ 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

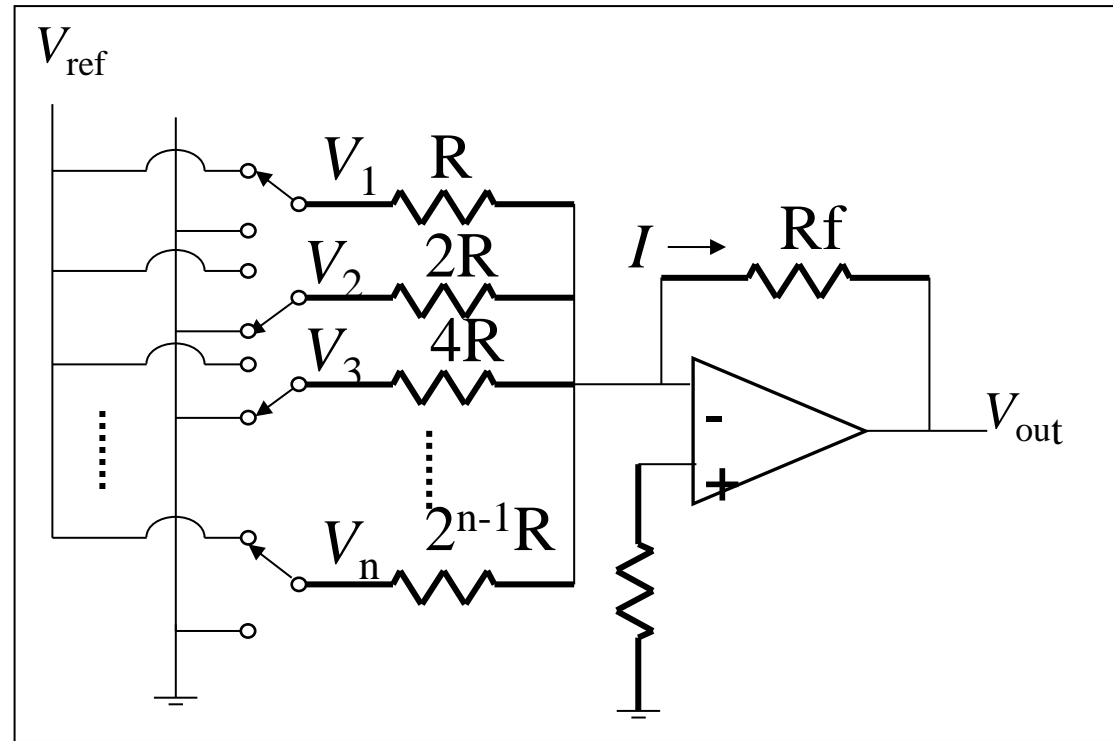
V_1 is most significant bit

V_n is least significant bit

MSB

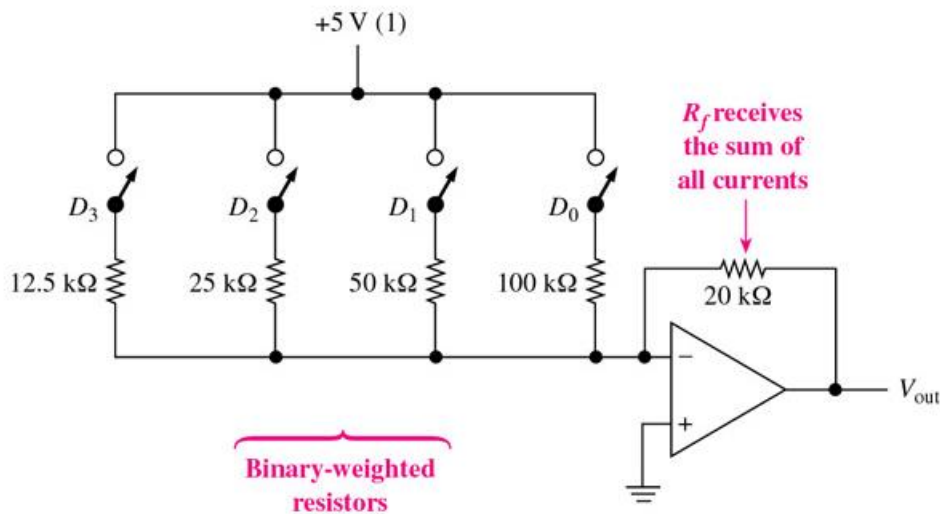
$$V_{\text{out}} = -IR_f = -R_f \left(\frac{V_1}{R} + \frac{V_2}{2R} + \frac{V_3}{4R} + \dots + \frac{V_n}{2^{n-1}R} \right)$$

LSB



Binary-Weighted Digital-to-Analog Converters

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



| Digital | | | | Analogue |
|---------|-------|-------|-------|----------------|
| 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

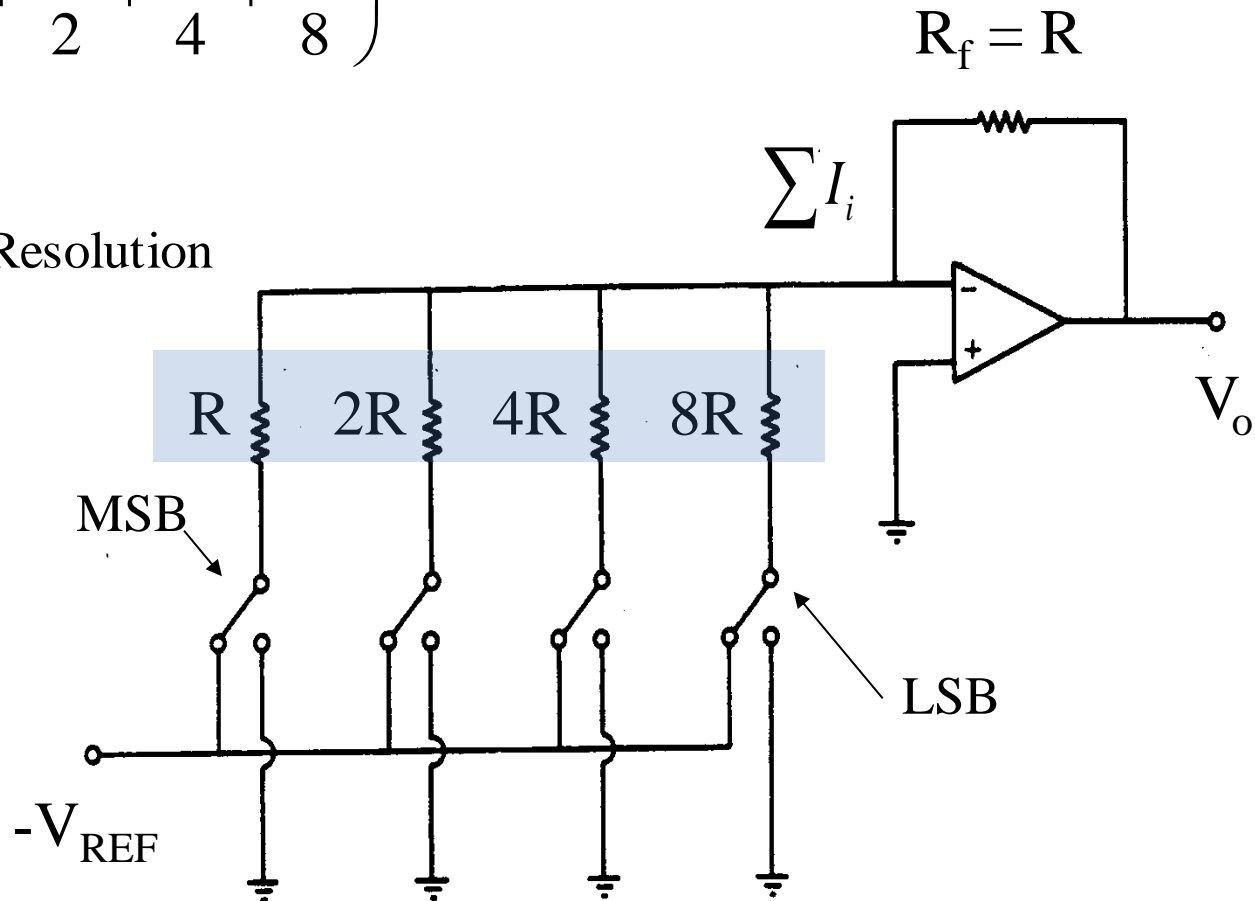
Binary Weighted Resistor

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

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

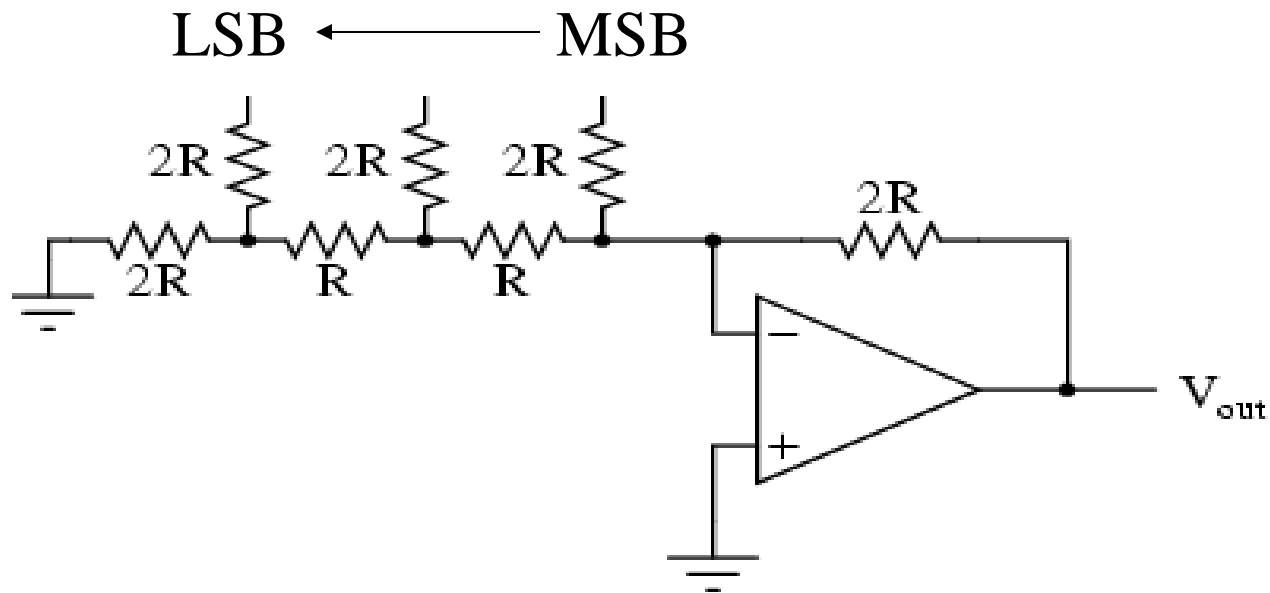
$$V_{OUT} = V_{REF} \sum \frac{B_i}{2^{n-i-1}}$$

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



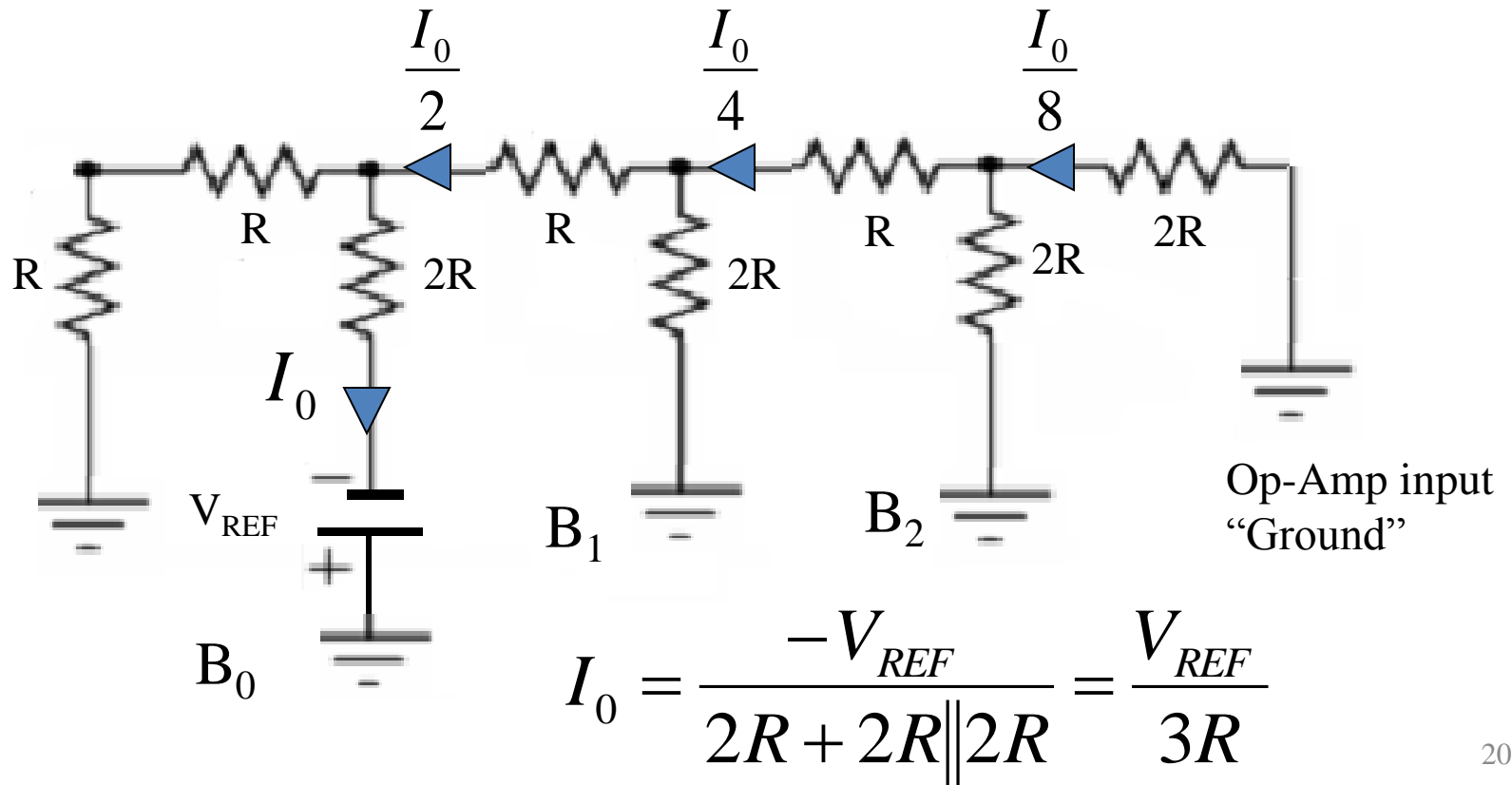
R - $2R$ Ladder

- 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



$R-2R$ Ladder

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



R - $2R$ Ladder: An Example

Find the output voltage of the Op-Amp for the following DAC

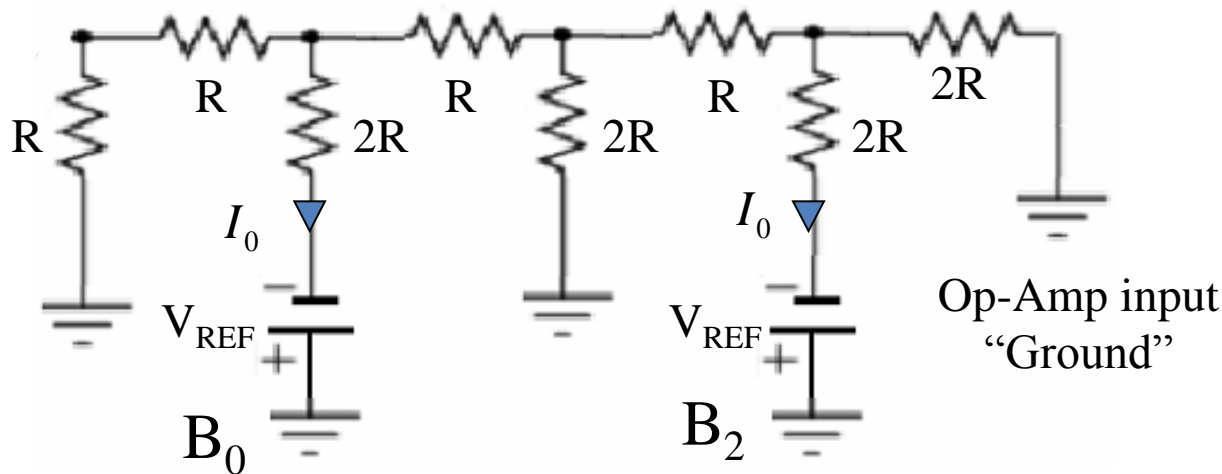
- Given Values

- Input = $(101)_2$
- $V_{REF} = 10\text{ V}$
- $R = 2\ \Omega$
- $R_f = 2R$

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

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

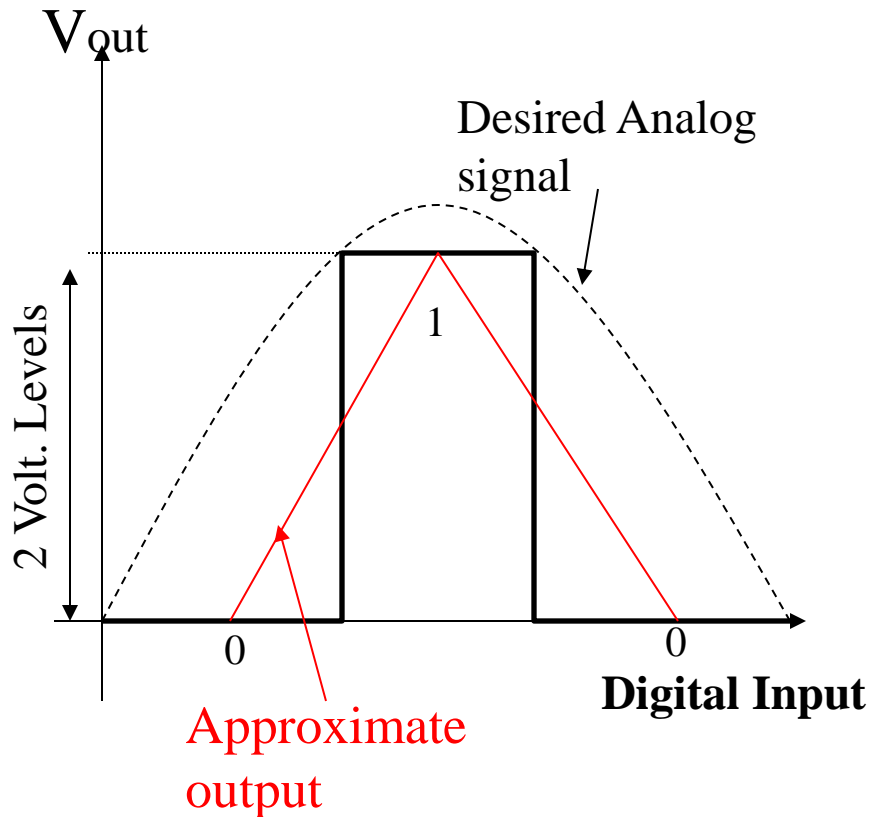
$$V_{OUT} = -I_{op-amp} R_f = 4.17\text{ V}$$



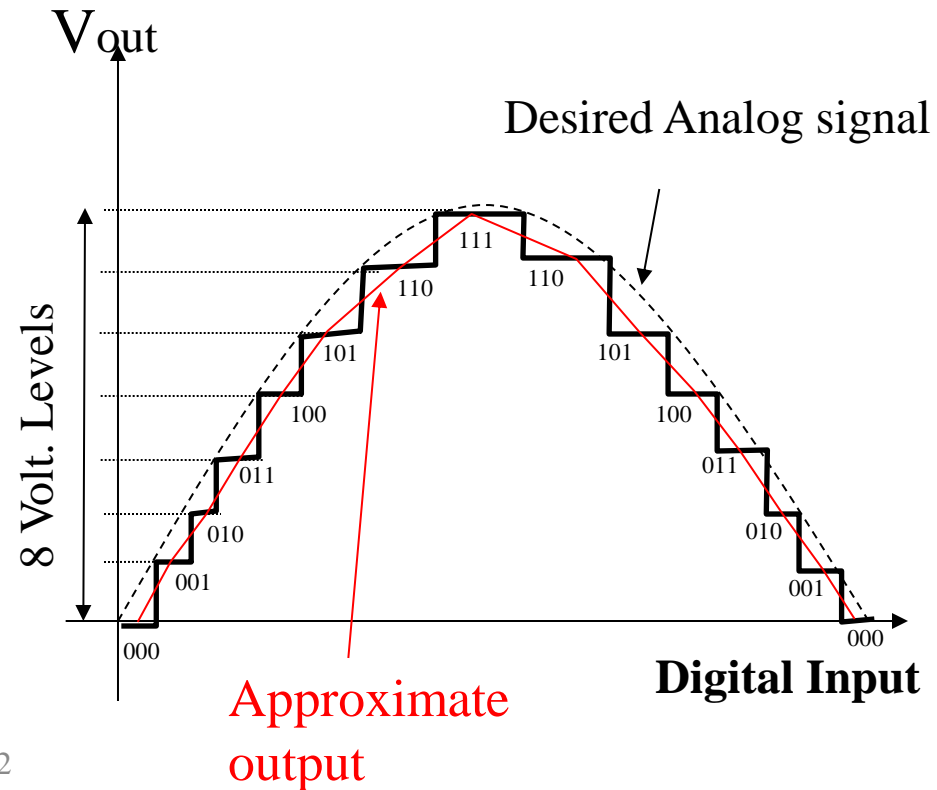
Resolution

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

Poor Resolution(1 bit)



Better Resolution(3 bit)



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

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

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.

$$\text{Output voltage range} = 7.5 - 4.5 = 3.0\text{V}$$

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.