Analog-to-Digital and Digital-to-Analog Converters and Circuits

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Lecture References:

- Book:
  - *Microprocessor Architecture, Programming and Applications with 8085 (Chapter-13),* **Author:** Ramesh Gaonkor

- Lecture Materials:
  - *Digital-to-Analog Analog-to-Digital,* Interface Part IV, Microprocessor, Georgia State University, Department of Physics and Astronomy.
  - *Programming the 8051 Microcontroller*, Dr. Konstantinos Tatas , Embedded Real-Time Processor Systems - Frederick University.
  - *Analog to Digital Converters*, Byron Johns, Danny Carpenter, Stephanie Pohl, Harry "Bo" Marr, October 4, 2005.

What is Analog Signals?

Analog signals – directly measurable **quantities** in terms of some other **quantity**.

Examples:

- **Thermometer** – ***mercury*** height rises as ***temperature*** rises.
- **Car Speedometer** – ***Needle*** moves farther right as you ***accelerate***.
- **Stereo** – ***Volume*** increases/decreases as you turn the ***knob***.

What is Digital Signals?

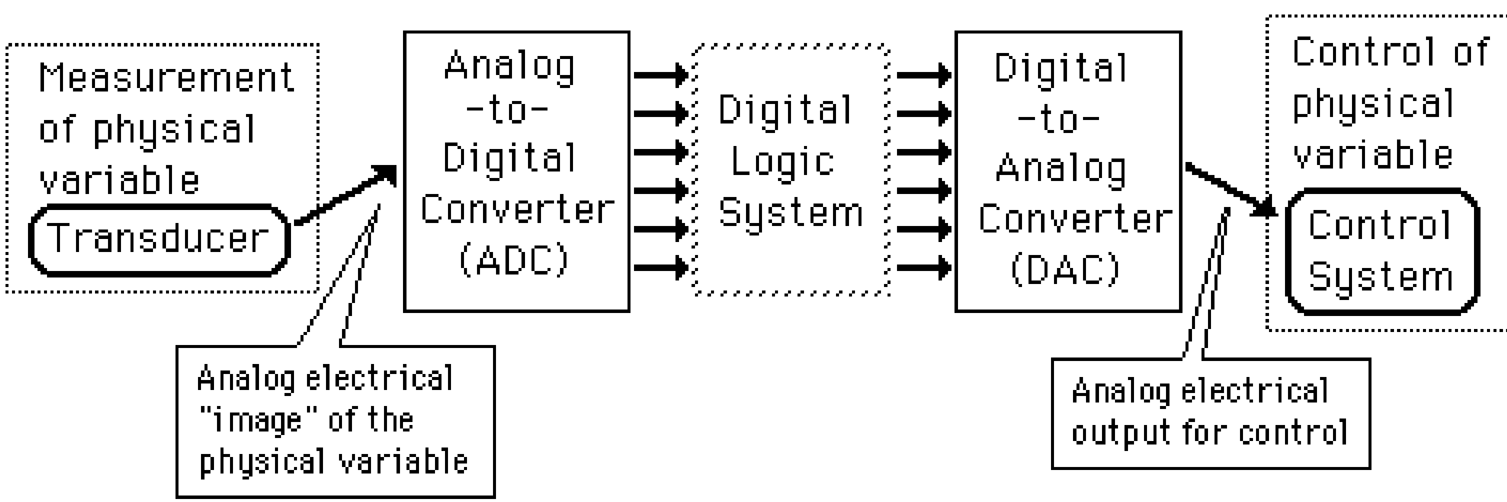
Digital Signals – have only ***two*** states. For digital computers, we refer to binary states, 0 and 1. "1" can be on, "0" can be off.

<u>**Examples:**</u>

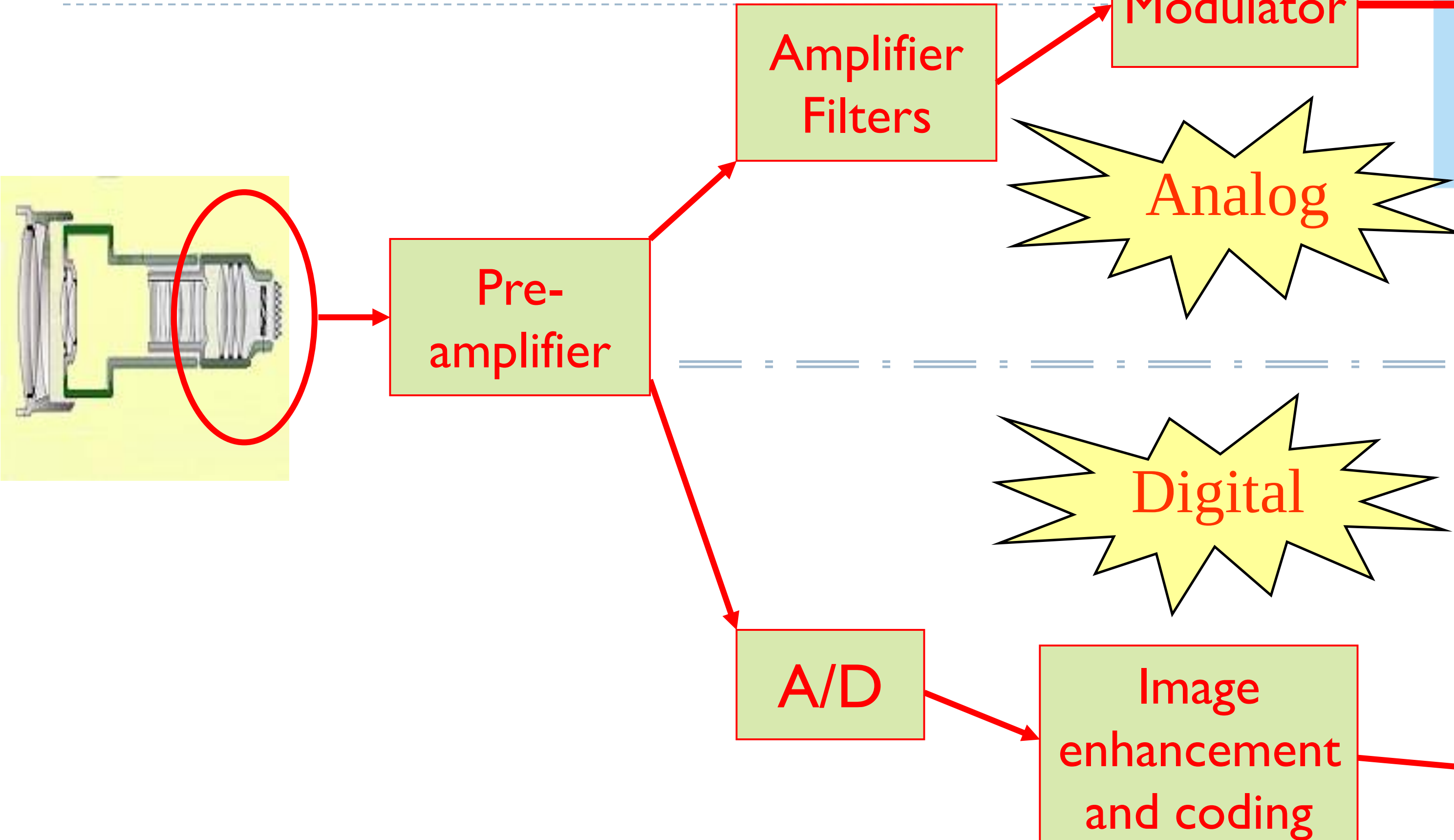
- Light switch can be either on or off
- Door to a room is either open or closed

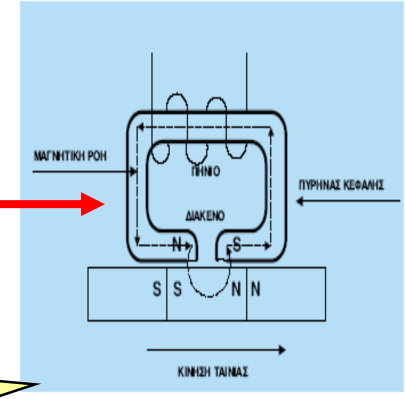
Data Handling System

- Both data about the physical world and control signals sent to interact with the physical world are typically "analog" or continuously varying quantities.
- In order to use the *power of digital systems*, one must convert from **analog to digital** form on the experimental measurement end and convert from **digital to analog** form on the control or output end of a laboratory system.



Data Converters

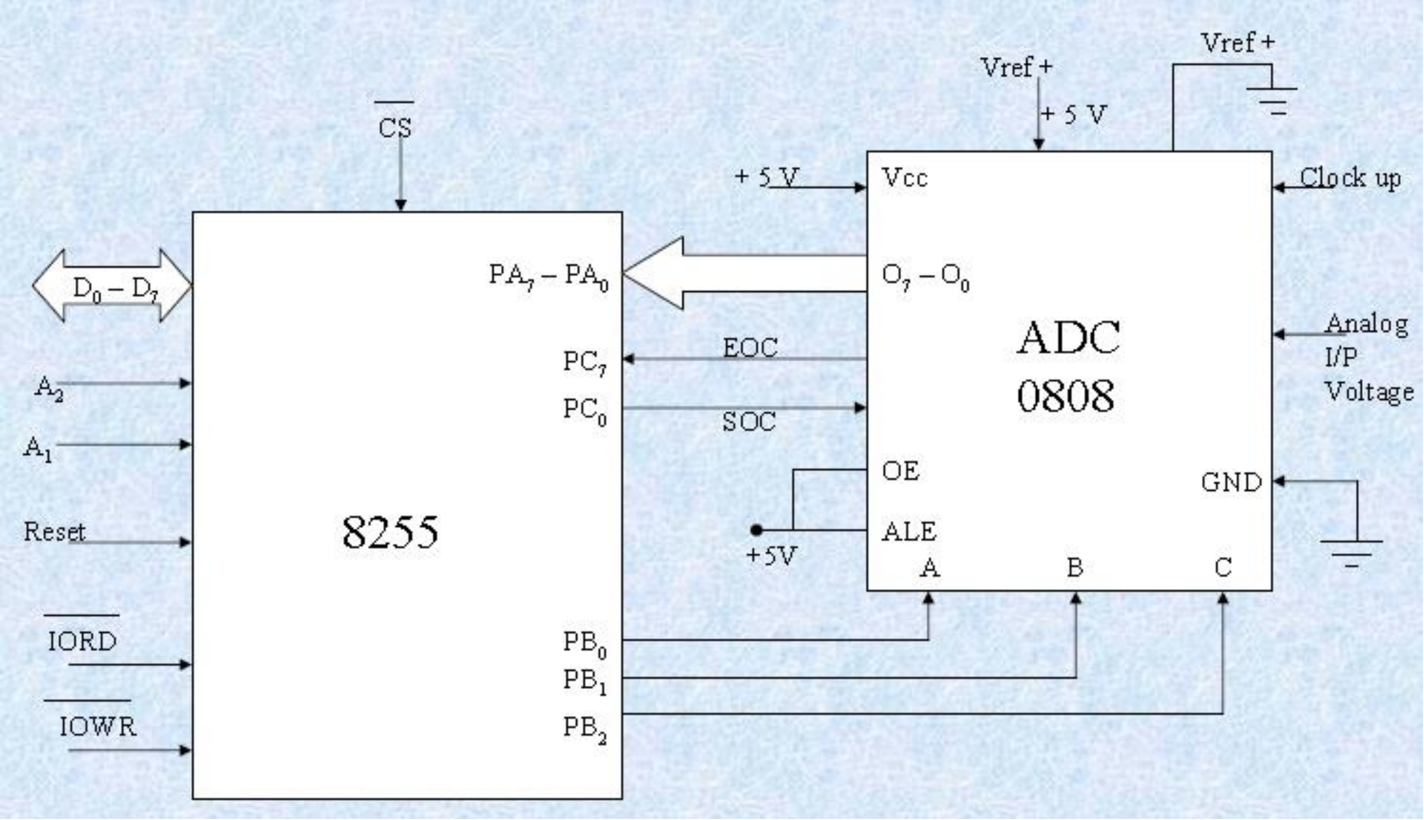




- **Analog to Digital Converters (ADC):** Convert an analog quantity (voltage, current) into a digital code.
- **Digital to Analog Converters (DAC):** Convert a digital code into an analog quantity (voltage, current).

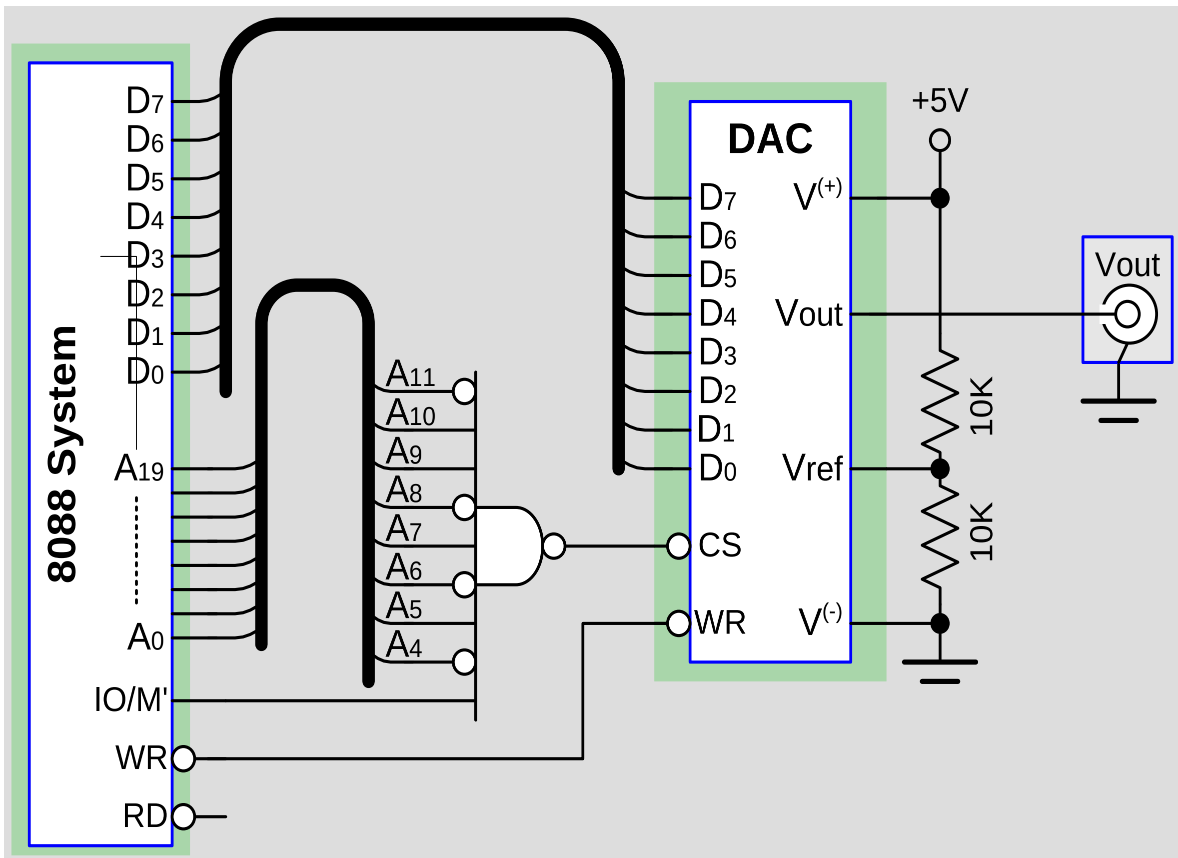
Interfacing with Data Converters

- Microprocessor compatible data converters are attached with the microprocessor through I/O interfaces.



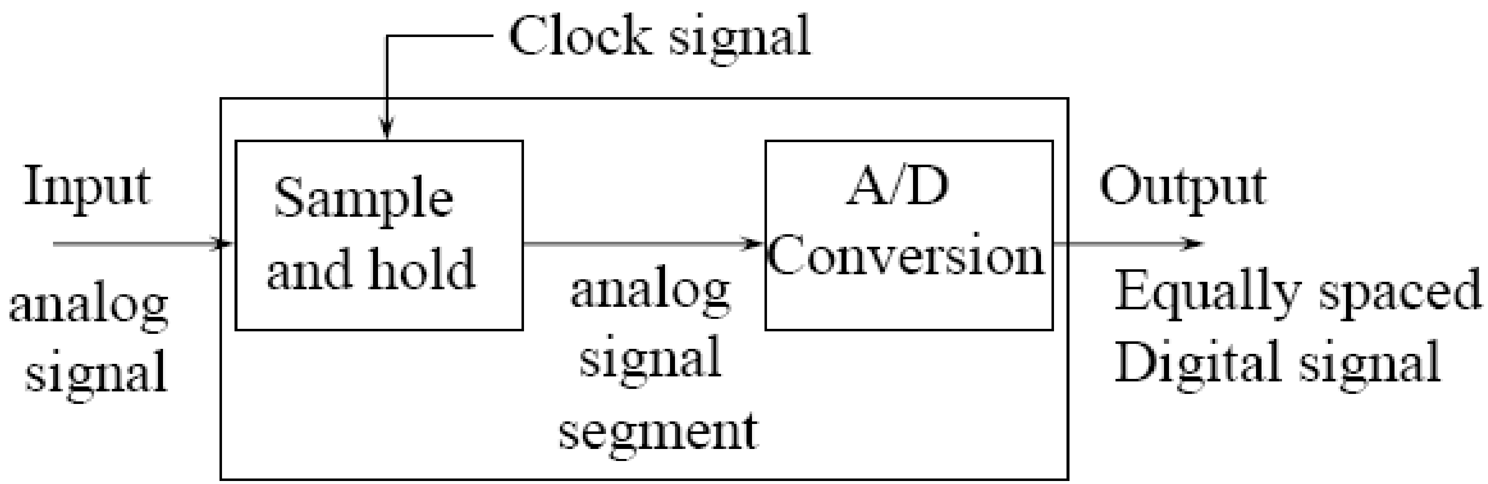
Interfacing with Data Converters

- Microprocessor compatible data converters are attached on the microprocessor's bus as standard I/O devices.



What does an A/D converter DO?

- Converts analog signals into binary words

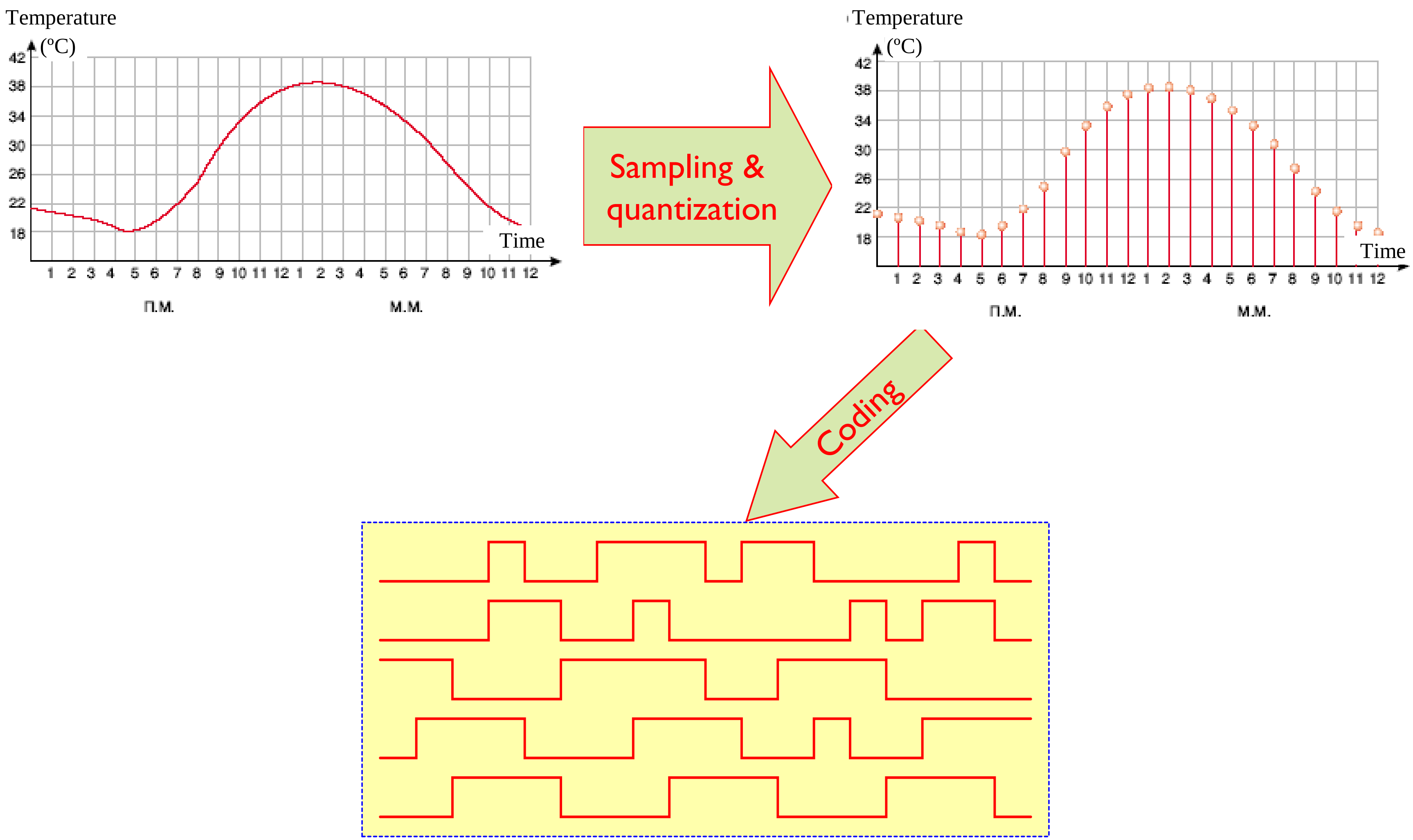


Analog-to-Digital (A/D) Conversion

- 2-step process required:

  - **Quantizing** - breaking down analog value is a set of finite states.
  - **Encoding** - assigning a digital word or number to each state and matching it to the input signal.

Analog-to-Digital (A/D) Conversion



Step-1: Quantizing

- **Example:**
  - You have 0-10V signals. Separate them into a set of discrete states with 1.25V increments. (**How did we get 1.25V?**)

Output States	Discrete Voltage Ranges (V)
0	0.00-1.25
1	1.25-2.50
2	2.50-3.75
3	3.75-5.00
4	5.00-6.25
5	6.25-7.50
6	7.50-8.75
7	8.75-10.0

Step-1: Quantizing

- The number of possible states that the converter can output is:

$$N=2^n$$

where, n is the number of bits in the A/D converter

- **Example:** For a 3 bit A/D converter, $N=2^3=8$.

- **Analog quantization size:**

$$Q=(Vmax-Vmin)/N = (10V - 0V)/8 = 1.25V$$

Step-2: Encoding

- Assign the digital value (binary number) to each state for the computer to read.

Output States	Output Binary Equivalent
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

Accuracy of A/D Conversion

- There are two ways to best improve accuracy of A/D conversion:

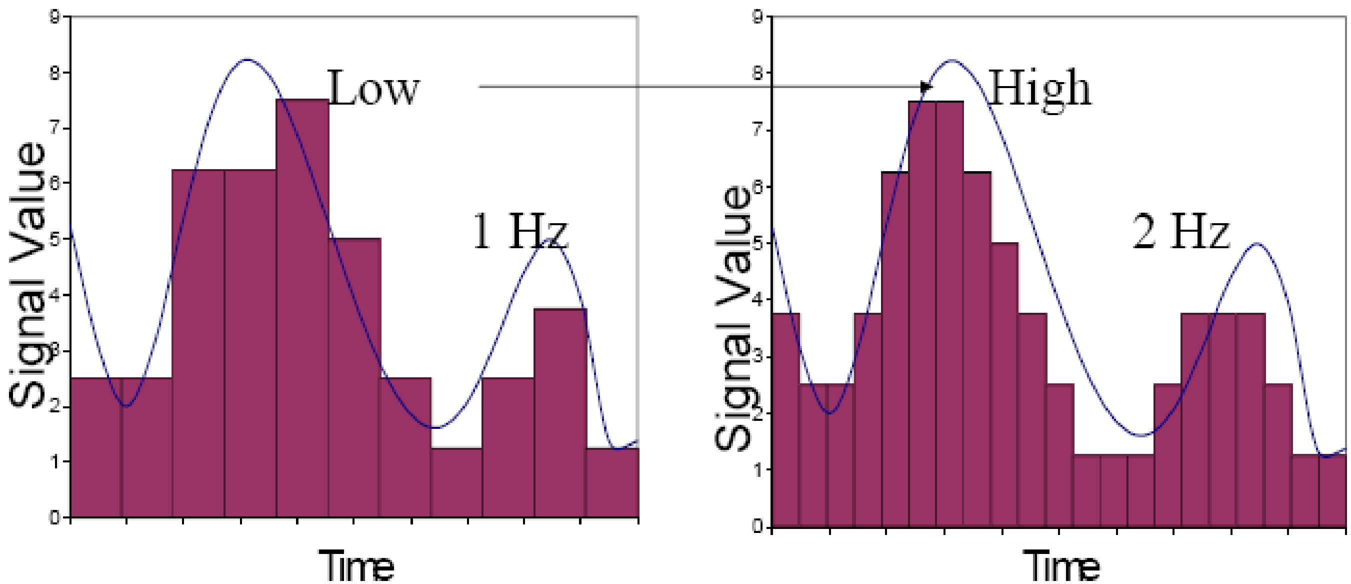
1. Increasing the ***resolution*** which improves the accuracy in measuring the amplitude of the analog signal.
   - **Resolution** (number of discrete values the converter can produce) = Analog Quantization size (Q)

     (Q) = V_{range} / 2^n, where V_{range} is the range of analog voltages which can be represented
   - limited by ***signal-to-noise ratio*** (should be around 6dB)
   - In the previous example: Q = 1.25V, this is a high resolution. A lower resolution would be if we used a 2-bit converter, then the resolution would be 10/2^2 = 2.50V.

Accuracy of A/D Conversion

2. Increasing the ***sampling rate*** which increases the maximum frequency that can be measured.

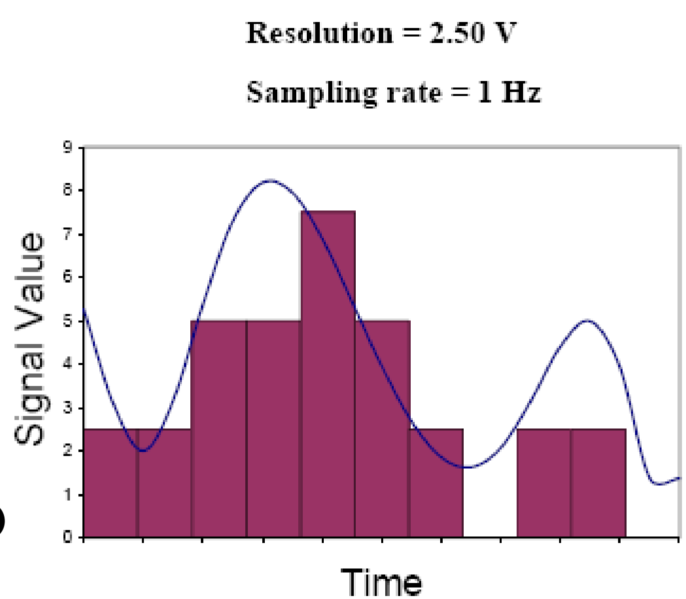
- Frequency at which ADC evaluates analog signal. As we see in the second picture, evaluating the signal more often more accurately depicts the ADC signal.

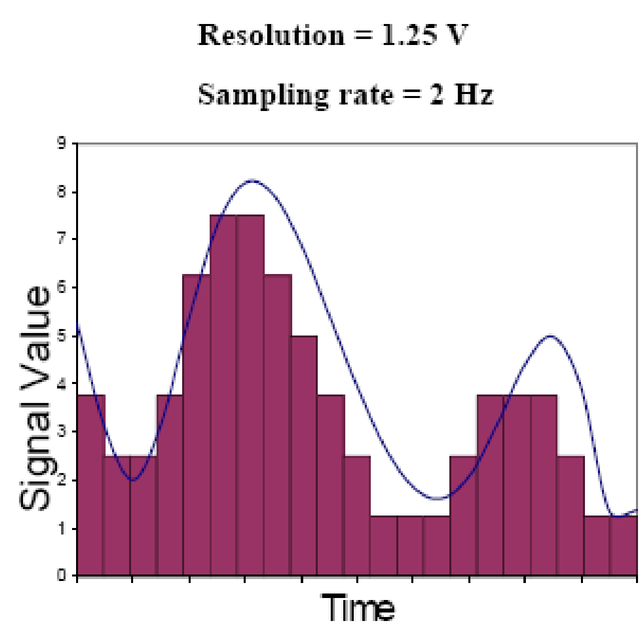


Aliasing Problem

- Aliasing occurs when the input signal is changing much faster than the sample rate.
  - For example, a 2 kHz sine wave being sampled at 1.5 kHz would be reconstructed as a 500 Hz (the aliased signal) sine wave.
  - **<u>Nyquist Rule:</u>** Use a sampling frequency at least twice as high as the maximum frequency in the signal to avoid aliasing.

<u>Better Accuracy:</u> Therefore, increasing both the ***sampling rate*** and the ***resolution*** you can obtain better accuracy in your AD signals.



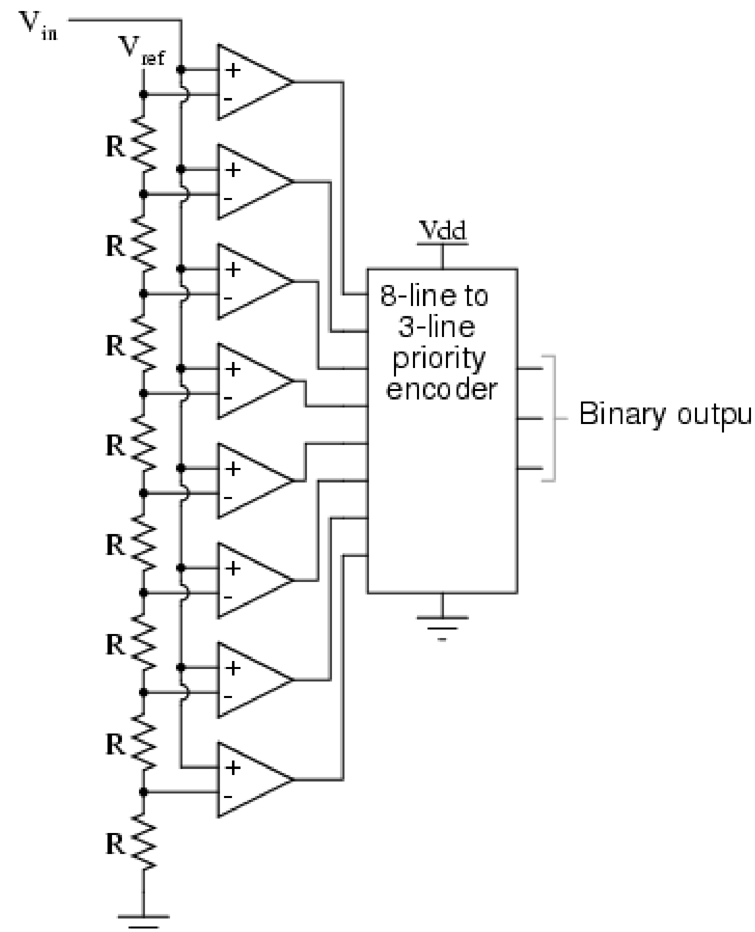


Analog-to-Digital (A/D) Converter Types

- A/D Converters
  - Flash ADC
  - Delta-Sigma ADC
  - Successive Approximation ADC

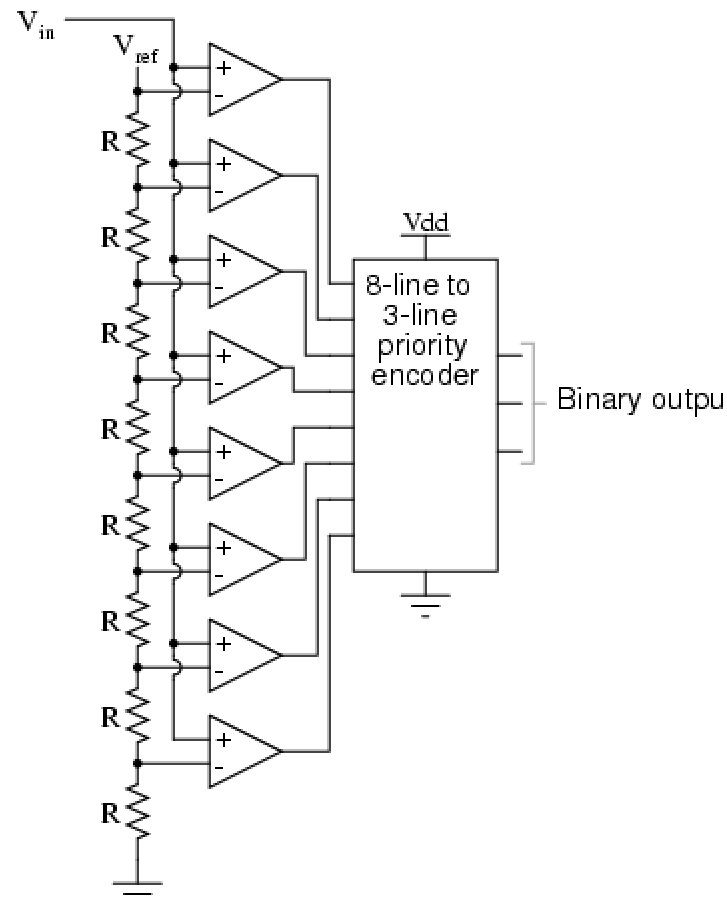
A/D Converters: **Flash ADC**

- Consists of a series of **comparators**, each one comparing the input signal to a **unique reference voltage**.
- The comparator outputs connect to the inputs of a **priority encoder** circuit, which produces a binary output
- As the ***analog input voltage exceeds*** the reference voltage at each comparator, the comparator outputs will sequentially saturate to a ***high*** state.
- The priority encoder generates a binary number based on the highest-order active input, ignoring all other active inputs.



A/D Converters: **Flash ADC**

- It is the fastest type of ADC available, but requires a comparator for each value of output. (8 for 3-bit, 64 for 6-bit, 256 for 8-bit, etc.)
- Such ADCs are available in IC format up to 8-bit and 10-bit flash ADCs (1024 comparators) are planned.
- The encoder logic executes a truth table to convert the ladder of inputs to the binary number output.



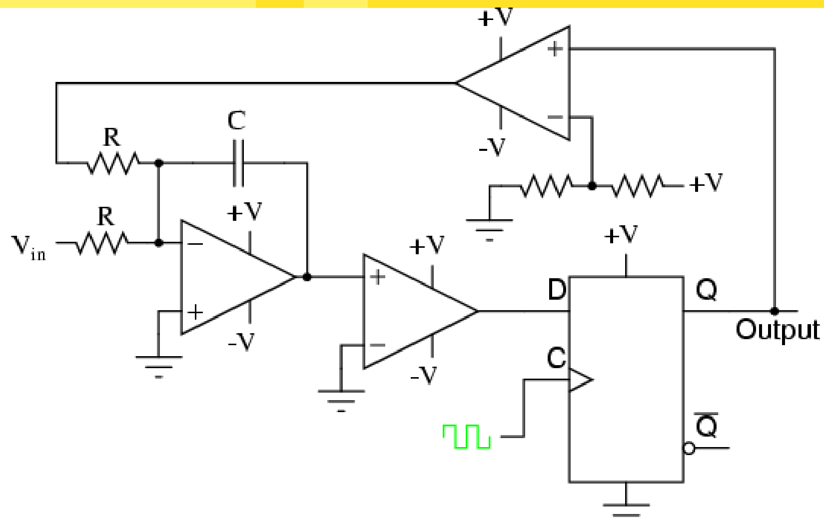
A/D Converters: **Flash ADC**

- **Advantages**
  - Simplest in terms of operational theory
  - Most efficient in terms of speed, very fast

- **Disadvantages**
  - Lower resolution
  - Expensive
  - Limited only in terms of comparator and gate propagation delays
  - For each additional output bit, the number of comparators is doubled
    - i.e. for 8 bits, 256 comparators needed

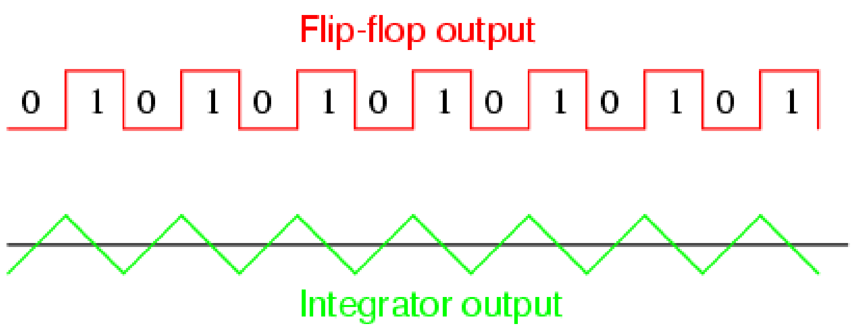
A/D Converters: **Delta-Sigma ADC**

- It involves changing an analog signal into time or frequency and comparing these parameters with the known values.
- Over sampled input signal goes to the integrator
- Output of integration is compared to GND
- Iterates to produce a serial bit stream
- Output is serial bit stream with # of 1's proportional to V_{in}

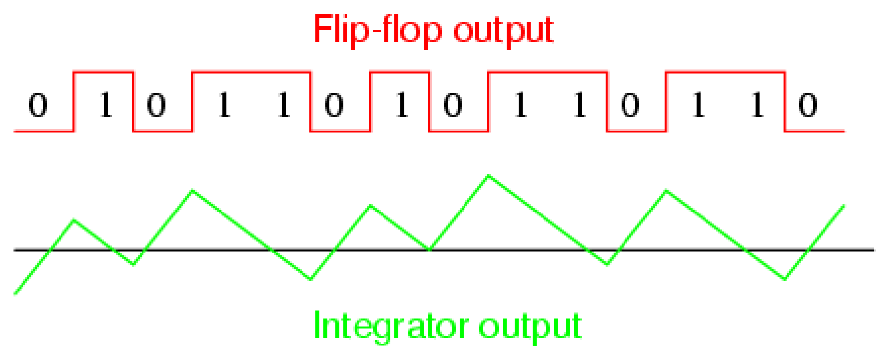


A/D Converters: **Delta-Sigma ADC**

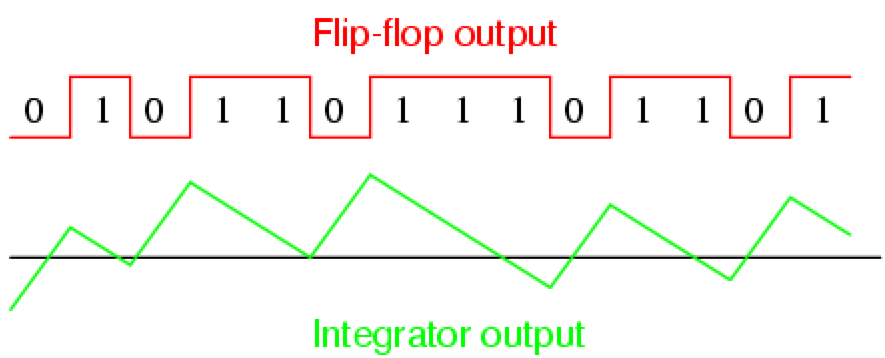
ΔΣ converter operation with
0 volt analog input



ΔΣ converter operation with
medium negative analog input



ΔΣ converter operation with
large negative analog input



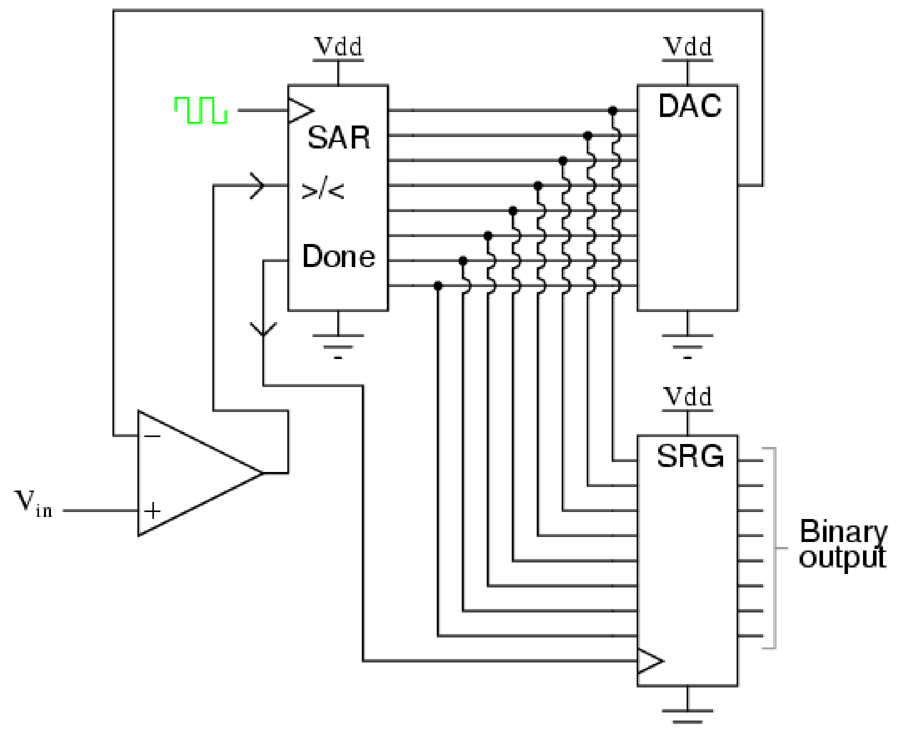
A/D Converters: **Delta-Sigma ADC**

- **Advantages**
  - High resolution
  - No precision external components needed
  - Accuracy is high

- **Disadvantages**
  - Slow due to oversampling

A/D Converters: **Successive Approximation ADC**

- A Successive Approximation Register (SAR) is added to the circuit.
- Instead of counting up in binary sequence, this register counts by trying all values of bits starting with the MSB and finishing at the LSB.
- The register monitors the comparators output to see if the binary count is greater or less than the analog signal input and adjusts the bits accordingly.
- **Applications**: Data Loggers and Instrumentation.



A/D Converters: **Successive Approximation ADC**

- **Example:**
  - 10 bit resolution or 0.0009765625V of V_{ref}
  - V_{in}= 0.6 volts
  - V_{ref}=1volts
  - Find the digital value for V_{in}

Bit	Voltage
9	.5
8	.25
7	.125
6	.0625
5	.03125
4	.015625
3	.0078125
2	.00390625
1	.001952125
0	.0009765625

- **Step 1:** MSB (Bit 9)
  - Divide V_{ref} by 2 to get V
  - Compare $V=V_{ref}/2$ with V_{in}
  - If V_{in} is greater than V, turn MSB on (1)
  - If V_{in} is less than V, turn MSB off (0)
  - V_{in} =0.6V and V=1/2=0.5
  - Since V_{in}>V, MSB = 1 (on) →

1									

A/D Converters: **Successive Approximation ADC**

- **<u>Step 2:</u>** MSB-1 (Bit 8)
  - Compare V_{in}=0.6V to $V = V_{ref}/2 + V_{ref}/4$= 0.5+0.25 =0.75V
  - Since 0.6<0.75, MSB-1 is turned off (0).

1	0								

- **<u>Step 3:</u>** MSB-2 (Bit 7)
  - Go back to the last voltage that caused it to be turned on (MSB, Bit 9) and add it to $V_{ref}/8$, and compare with V_{in}
  - Compare V_{in} with $(0.5+V_{ref}/8)$=0.625
  - Since 0.6<0.625, MSB-2 is turned off (0).

1	0	0							

- **<u>Step 4:</u>** MSB (Bit 6)
  - Go to the last bit that caused it to be turned on (In this case MSB, Bit 9) and add it to $V_{ref}/16$, and compare it to V_{in}
  - Compare V_{in} to $V= 0.5 + V_{ref}/16$= 0.5625
  - Since 0.6>0.5625, MSB-3 turned on (1)

MSB	MSB-1	MSB-2	MSB-3	…					
1	0	0	1						

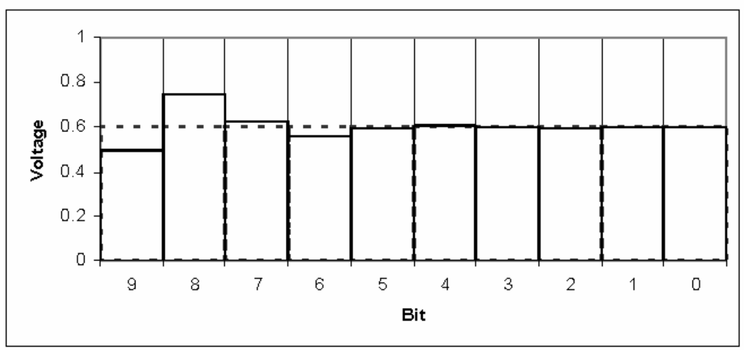
A/D Converters: **Successive Approximation ADC**

- This process continues for all the remaining bits.

•Digital Results:

MSB	MSB-1	MSB-2	MSB-3	…					LSB
1	0	0	1	1	0	0	1	1	0

•Results: $\frac{1}{2}+\frac{1}{16}+\frac{1}{32}+\frac{1}{256}+\frac{1}{512}=.599609375\text{ V}$



A/D Converters: **Successive Approximation ADC**

- **Advantages**
  - Capable of high speed and reliable.
  - Medium accuracy compared to other ADC types
  - Good tradeoff between speed and cost
  - Capable of outputting the binary number in serial (one bit at a time) format.

- **Disadvantages**
  - Higher resolution successive approximation ADC's will be slower.
  - Less accurate than the other converters.

A/D Converters Types Comparision

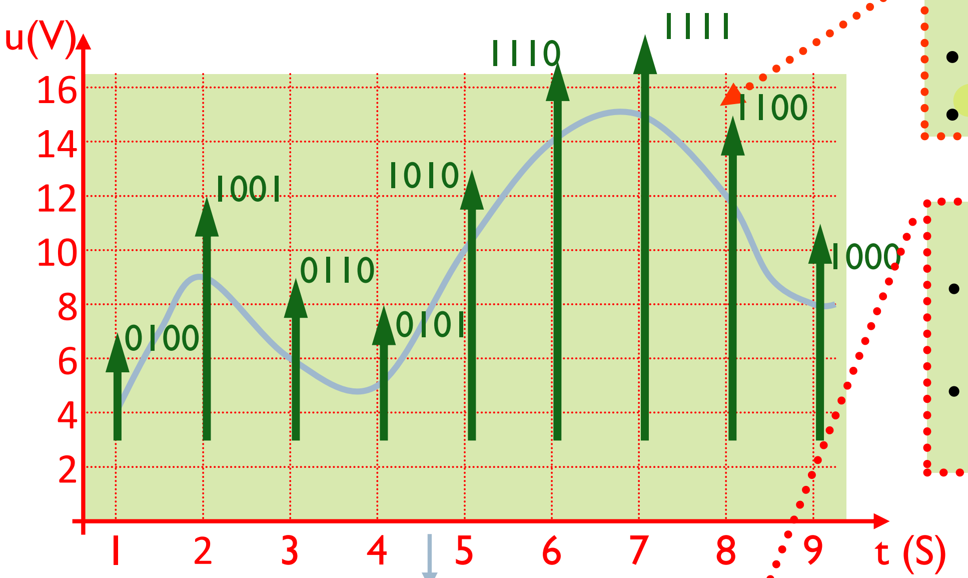
Type	Speed (relative)	Cost (relative)
Flash	Very Fast	High
Delta-Sigma	Slow	Low
Successive Approximation	Medium – Fast	Low

What does a D/A converter DO?

- The analog signal at the output of a D/A converter is linearly proportional to the binary code at the input of the converter.
  - If the binary code at the input is **0001** and the output voltage is **5mV**.
  - If the binary code at the input becomes **1001**, the output voltage will become **45mV**.
- If a D/A converter has 4 digital inputs then the analog signal at the output can have one out of 16 values.
- If a D/A converter has N digital inputs then the analog signal at the output can have one out of 2^N values.

D3	D2	D1	D0	Vout (mV)
0	0	0	0	0
0	0	0	1	5
0	0	1	0	10
0	0	1	1	15
0	1	0	0	20
0	1	0	1	25
0	1	1	0	30
0	1	1	1	35
1	0	0	0	40
1	0	0	1	45
1	0	1	0	50
1	0	1	1	55
1	1	0	0	60
1	1	0	1	65
1	1	1	0	70
1	1	1	1	75

What does a D/A converter DO?



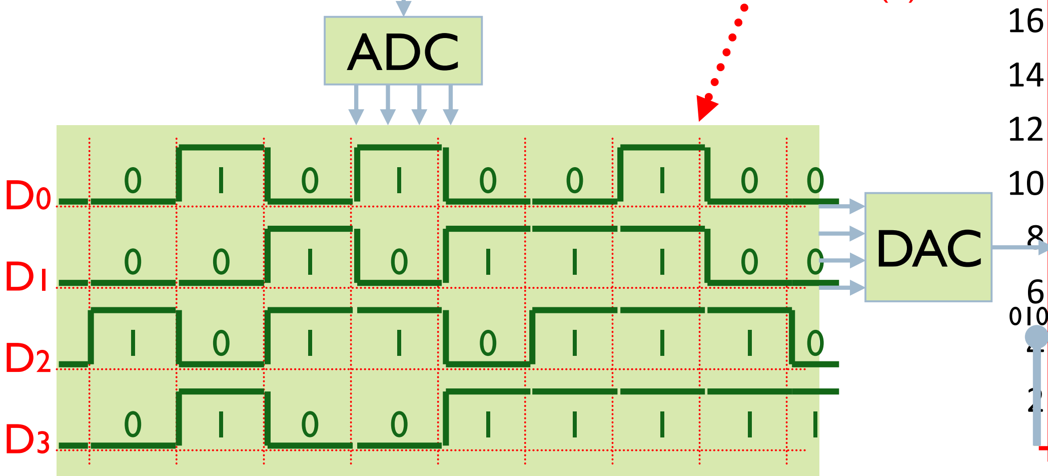
Analog Signal

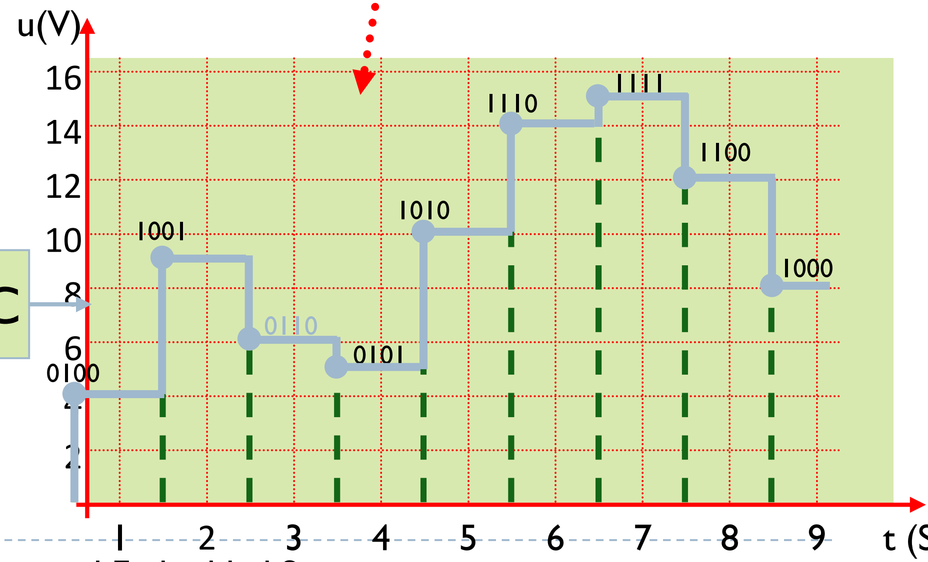
- can take infinity values
- can change at any time

Digital Signal

- can take one of 2 values (0 or 1)
- can change only at distinct times

Reconstruction of an analog signal from a digital one (Can take only predefined values)



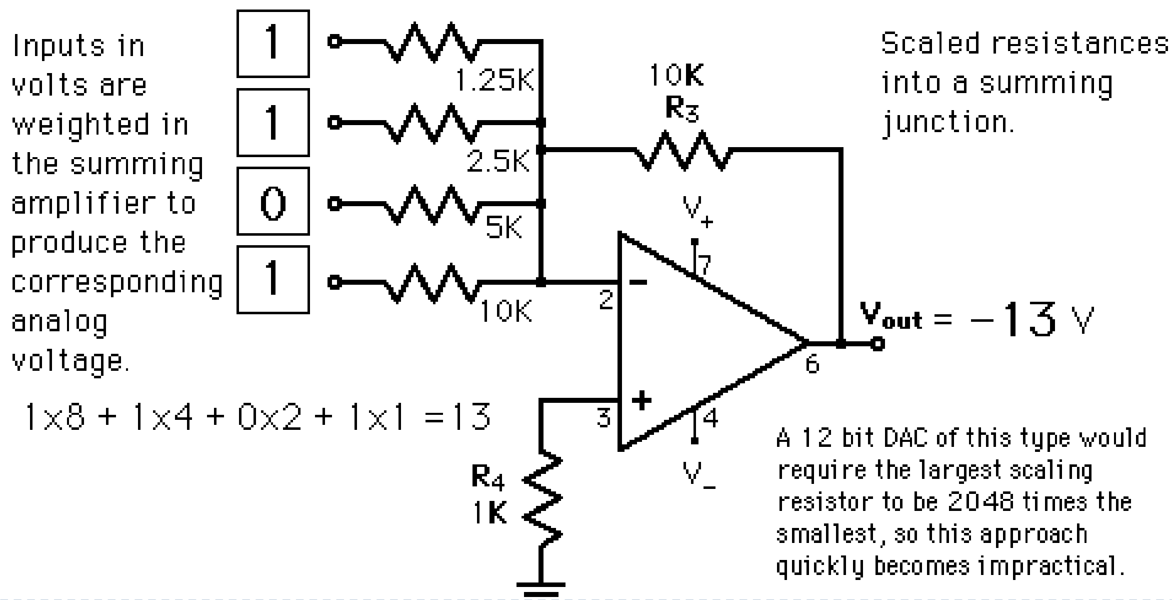


Digital-to-Analog (D/A) Converter Types

- D/A Converters
  - Weighted Summing Amplifier
  - R-2R Network Approach

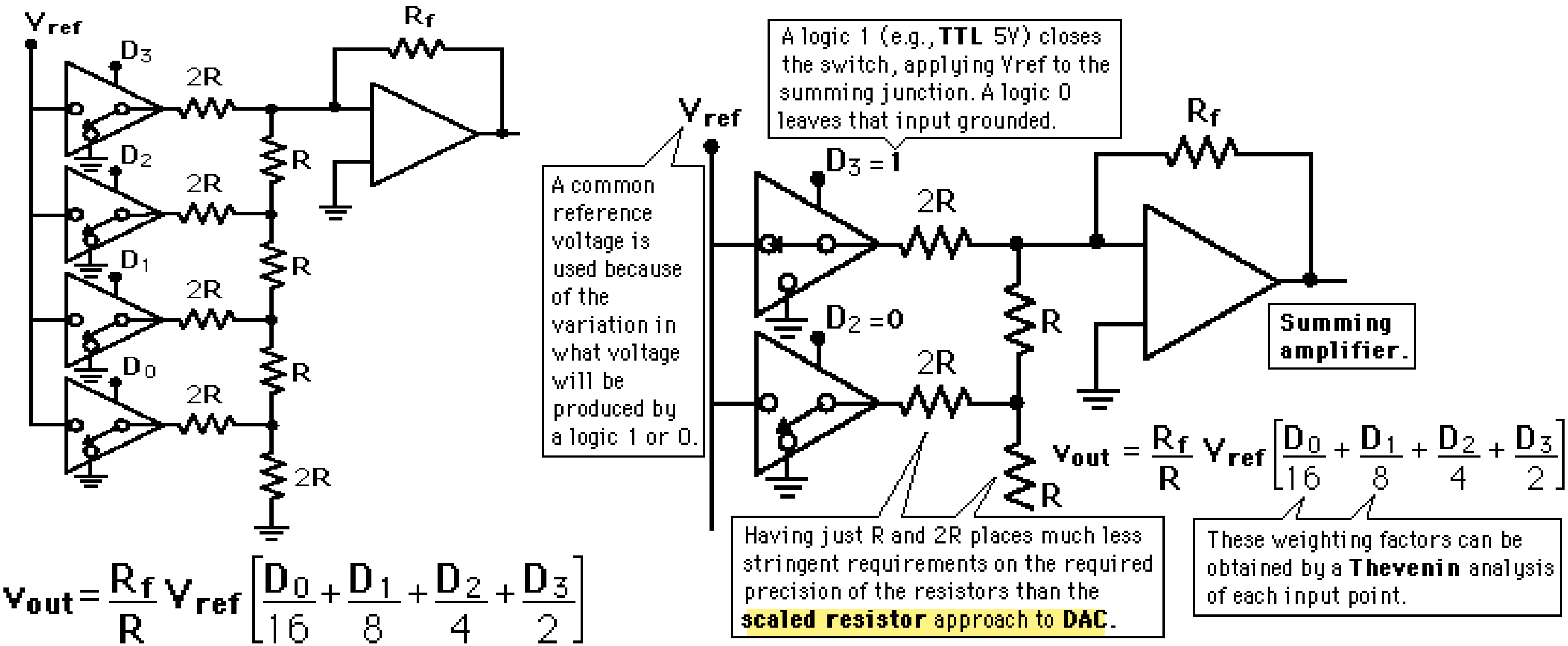
D/A Converters: **Weighted Sum DAC**

- One way to achieve D/A conversion is to use a **summing amplifier**.
- This approach is not satisfactory for a large number of bits because it requires too much precision in the summing resistors.
  - This problem can be overcome in the R-2R network DAC.



D/A Converters: **R-2R Ladder DAC**

- The summing amplifier with the R-2R ladder of resistances produces the output where the D's take the value 0 or 1.
- This is illustrated for 4 bits, but can be extended to any number with just the resistance values R and 2R.



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