

Lecture THREE

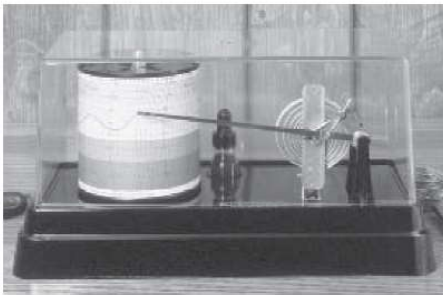
Digital-to-Analog

Analog-to-Digital

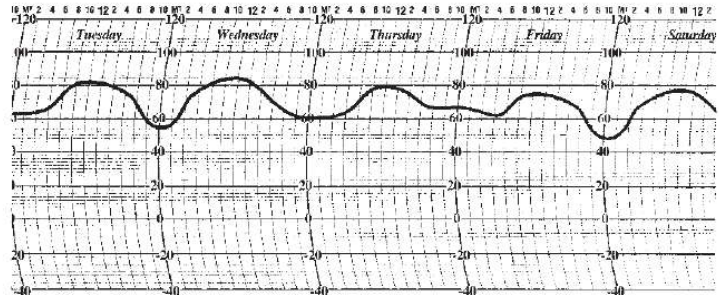
REAL-TIME SYSTEMS

Analog

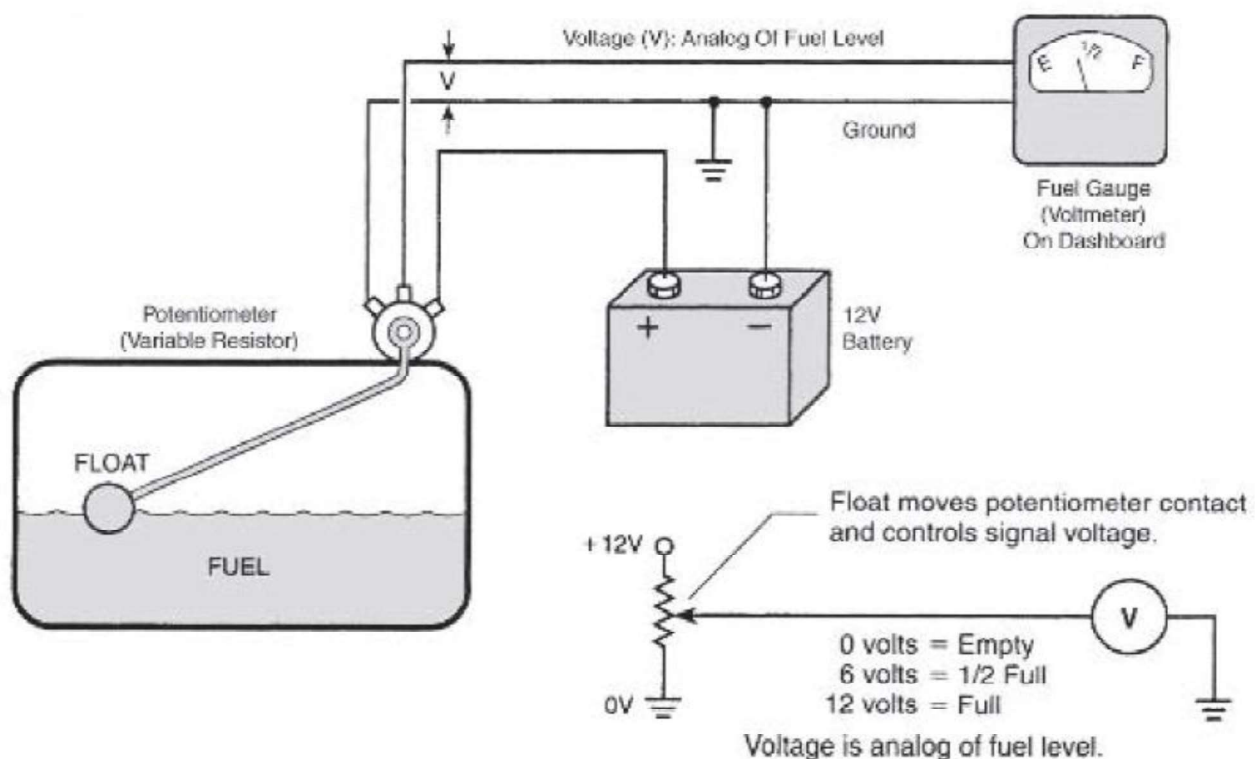
Analog quantities vary continuously, and analog systems represent the analog information using electrical signals that vary smoothly and continuously over a range.



a. Recording thermometer
Photo courtesy of Taylor Precision Products

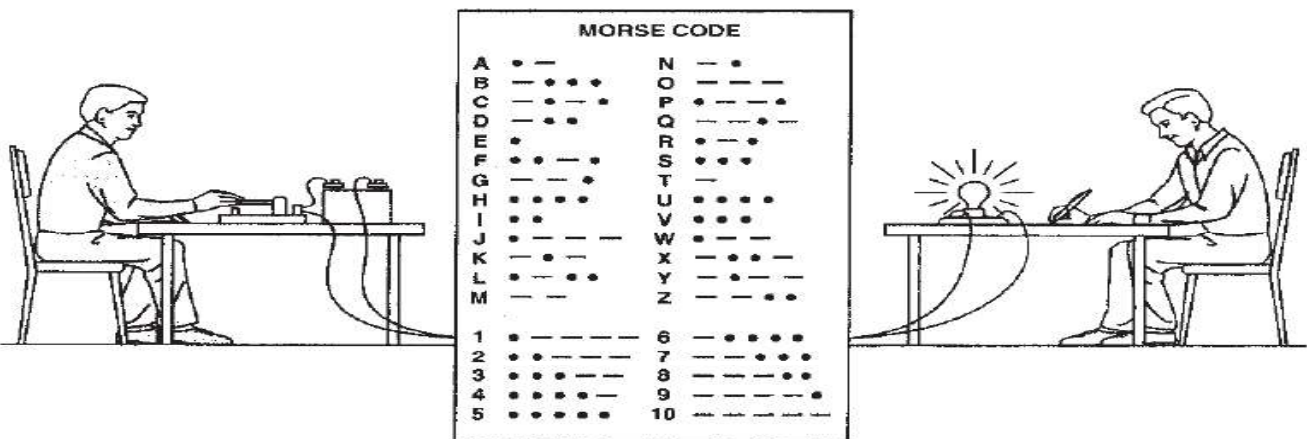
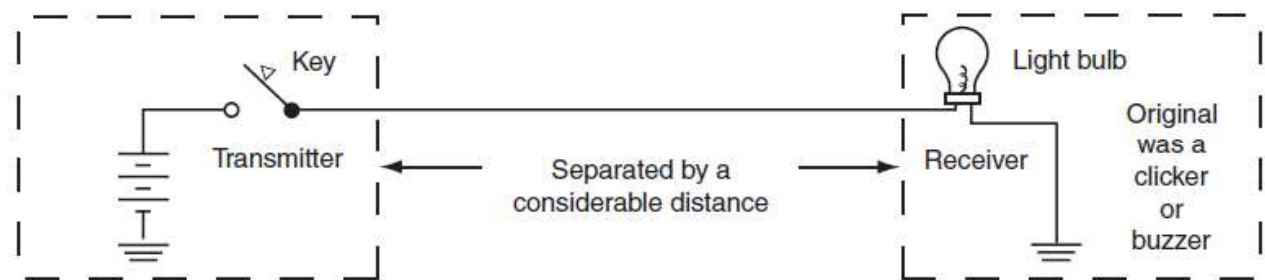


b. Plot of daily temperature variations
Courtesy of Master Publishing, Inc.

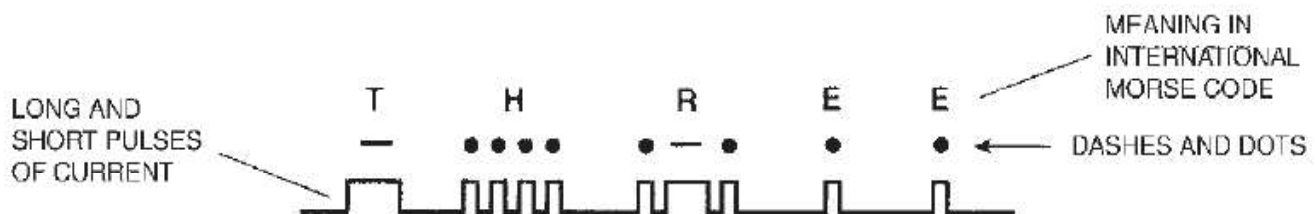


Digital

Digital quantities vary in discrete levels. In most cases, the discrete levels are just two values—ON and OFF. Digital systems carry information using combinations of ON-OFF electrical signals that are usually in the form of codes that represent the information.



b. International Morse code



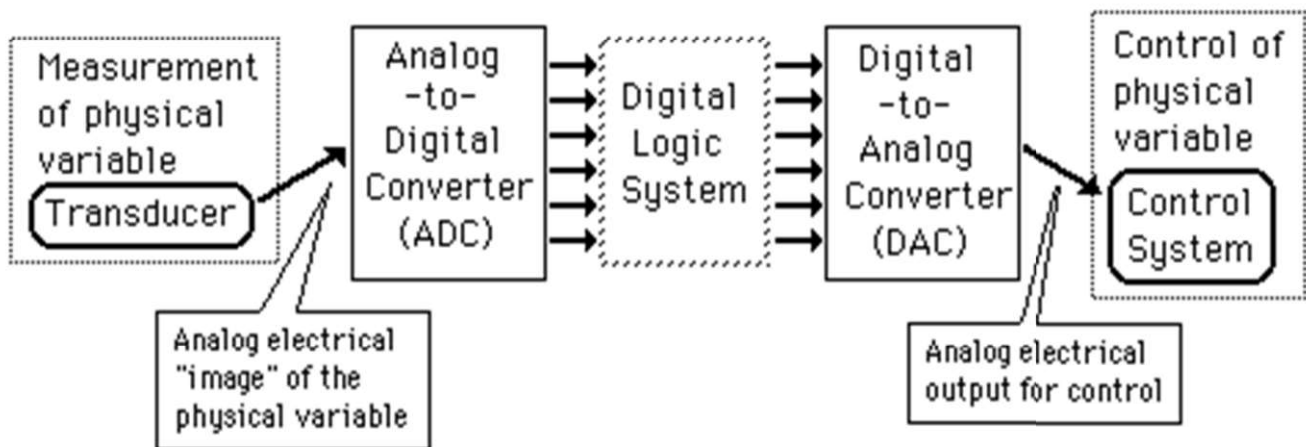
c. Digital information

Figure 1-3: The telegraph is a digital system that sends information as patterns of switched signals

Data Handling Systems

- 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 electronics, 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 Collection and Control



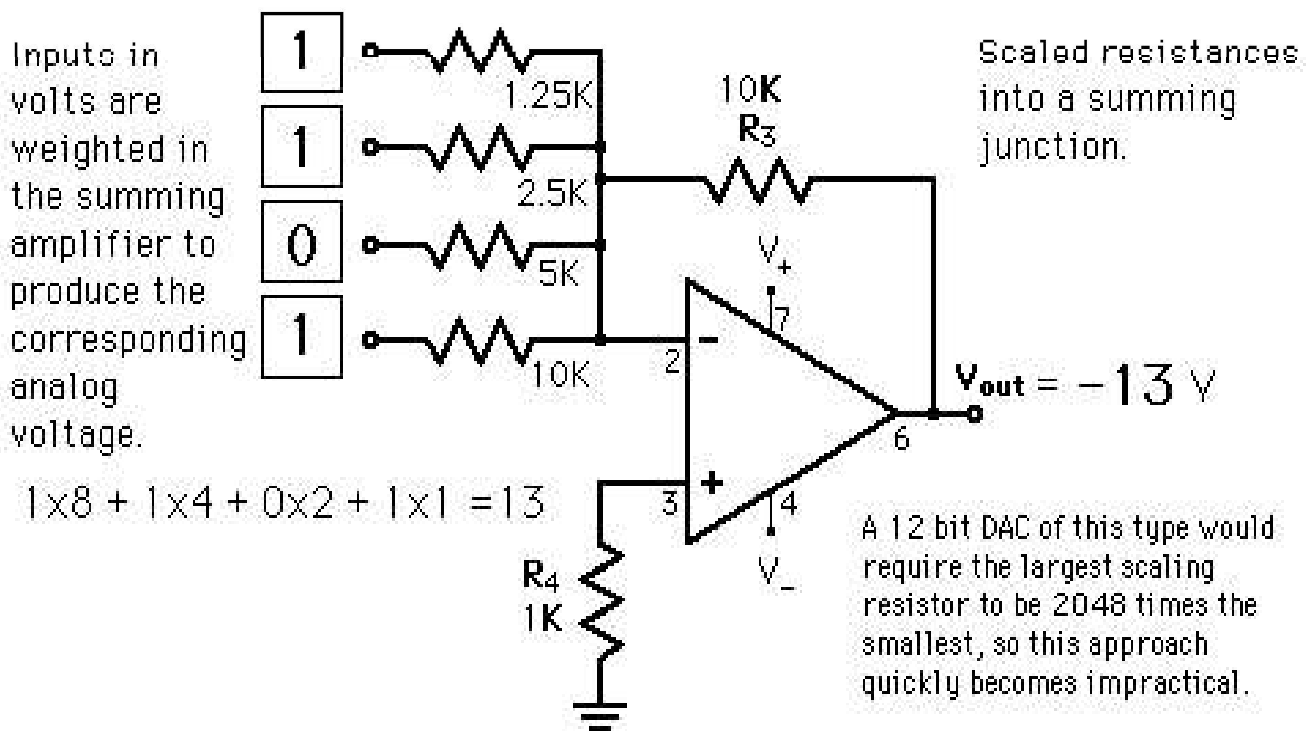
Digital-to-Analog Conversion

- When data is in binary form, the 0's and 1's may be of several forms such as the TTL form where the logic zero may be a value up to 0.8 volts and the 1 may be a voltage from 2 to 5 volts.
- The data can be converted to clean digital form using gates which are designed to be on or off depending on the value of the incoming signal.

- Data in clean binary digital form can be converted to an analog form by using a summing amplifier.
- For example, a simple 4-bit D/A converter can be made with a four-input summing amplifier.
- 2 Basic Approaches
 - Weighted Summing Amplifier
 - R-2R Network Approach

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 is overcome in the R-2R network DAC.

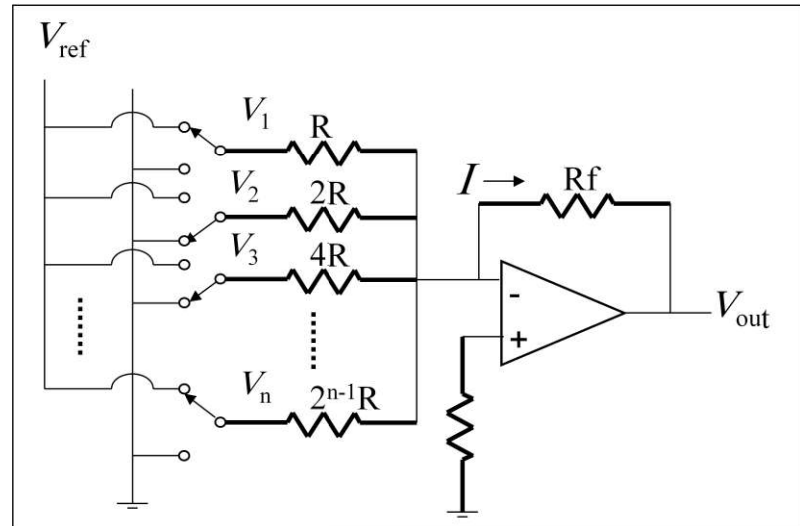


Binary Weighted Resistor

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



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

If $R_f = R/2$

$$V_{out} = -IR_f = - \left(\frac{V_1}{2} + \frac{V_2}{4} + \frac{V_3}{8} + \dots + \frac{V_n}{2^n} \right)$$

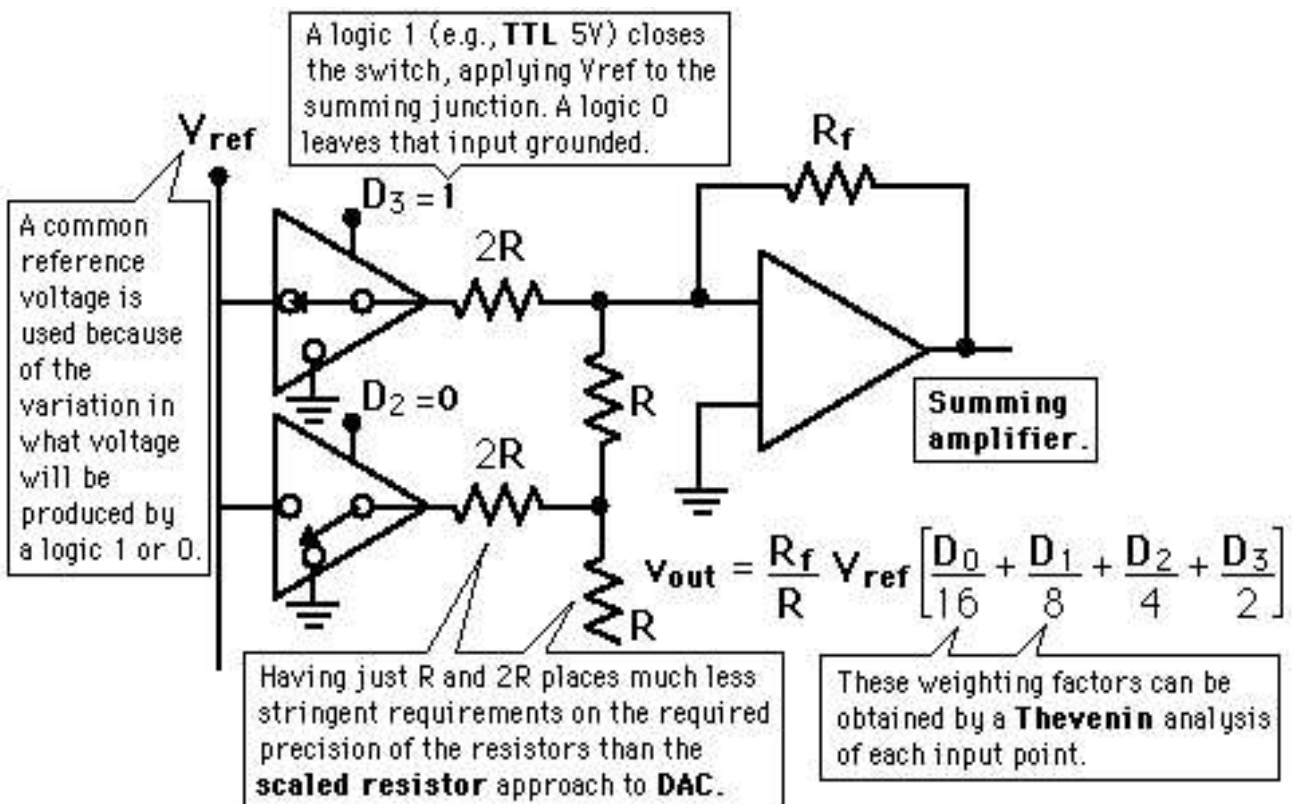
For example, a 4-Bit converter yields

$$V_{out} = -V_{ref} \left(b_3 \frac{1}{2} + b_2 \frac{1}{4} + b_1 \frac{1}{8} + b_0 \frac{1}{16} \right)$$

Where b_3 corresponds to Bit-3, b_2 to Bit-2, etc.

LADDER NETWORK CONVERSION

Digital-to-analog conversion can be achieved using a number of different methods. One popular scheme uses a network of resistors, called a *ladder network*. A ladder network accepts inputs of binary values at, typically, 0 V or V_{ref} and provides an output voltage proportional to the binary input value. Figure 17.12a shows a ladder network with four input voltages, representing 4 bits of digital data and a dc voltage output. The output voltage is proportional to the digital input value as given by the relation



- The summing amplifier with the R-2R ladder of resistances shown produces the output where the D's take the value 0 or 1.
- The digital inputs could be TTL voltages which close the switches on a logical 1 and leave it grounded for a logical 0.
- This is illustrated for 4 bits, but can be extended to any number with just the resistance values R and 2R.

For a 4-Bit R-2R Ladder

$$V_{\text{out}} = -V_{\text{ref}} \left(b_3 \frac{1}{2} + b_2 \frac{1}{4} + b_1 \frac{1}{8} + b_0 \frac{1}{16} \right)$$

For general n-Bit R-2R Ladder or Binary Weighted Resistor DAC

$$V_{\text{out}} = -V_{\text{ref}} \sum_{i=1}^n b_{n-i} \frac{1}{2^i}$$

- **Advantages**
 - Only two resistor values (R and 2R)
 - Does not require high precision resistors
- **Disadvantage**
 - Lower conversion speed than binary weighted DAC

Resolution

- Smallest analog increment corresponding to 1 LSB change
- An N-bit resolution can resolve 2^N distinct analog levels
- Common DAC has a 8-16 bit resolution

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

where $N = \text{number of bits}$

Analog to Digital Conversion [ADC]

ADC Basic Principle

- The basic principle of operation is to use the comparator principle to determine whether or not to turn on a particular bit of the binary number output.
- It is typical for an ADC to use a digital-to-analog converter (DAC) to determine one of the inputs to the comparator.

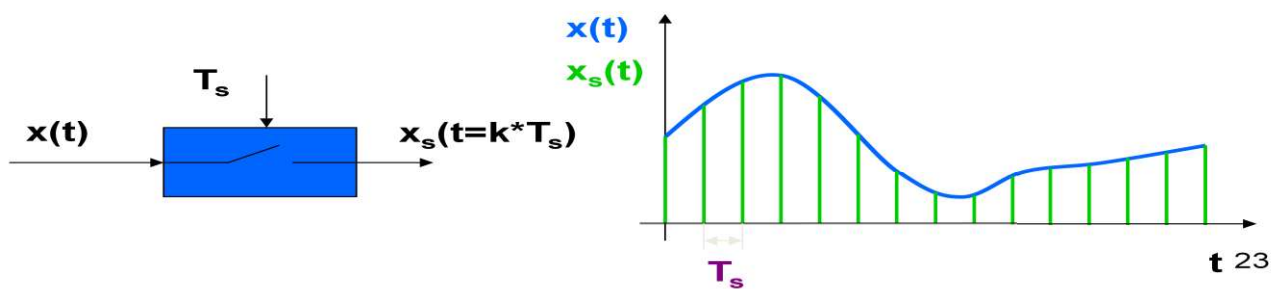
Conversion process

3 steps:

- Sampling
- Quantification
- Coding

Conversion process: Sampling

- Digital system works with discrete states
- The signal is only defined at determined times
- The sampling times are proportional to the sampling period (T_s)



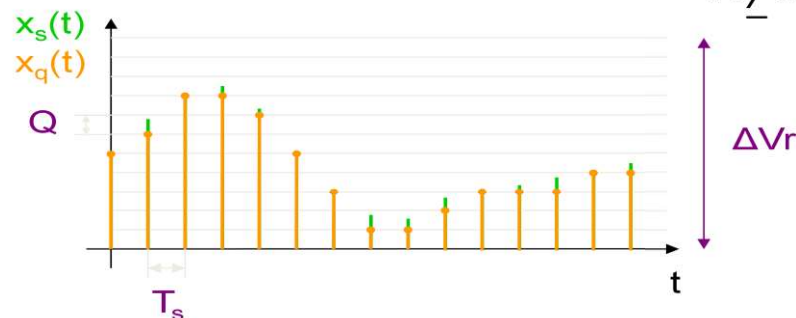
Conversion process: Quantification

The signal can only take determined values
Belonging to a range of conversion (ΔV_r)

- Based on number of bit combinations that the converter can output
- Number of possible states:
 $N=2^n$ where n is number of bits
- Resolution: $Q = \Delta V_r / N$

$$n \geq \ln \frac{V_{\max}}{V_{\min}}$$

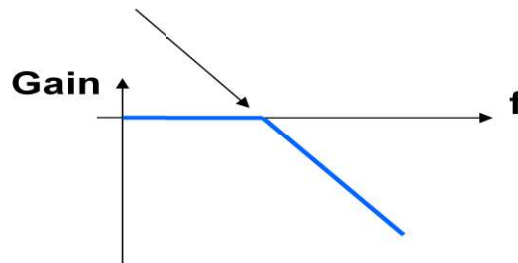
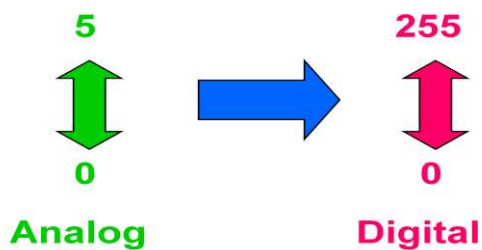
$$n \geq \ln \frac{V_{\max}}{V_{\text{noise}}}$$



Example

- 8 bits converter: $n=8$
- Range of conversion: $\Delta V_r=5V$
- Sampling time: $T_s=1ms$

- Number of possible states: $N=2^8=256$
- Resolution: $Q=\Delta V_r/N=19.5 \text{ mV}$
- Analog Filter: $f_{\text{filter}} \approx f_s/5 = 200 \text{ Hz}$



Selection of DAC

For the selection of an IC DAC, there are several parameters that can determine the suitability of a particular device.

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.

Solution: 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.

Solution:

Output voltage range = $7.5 - 4.5 = 3.0V$

Accuracy

The accuracy is usually expressed by the error in output voltage compared with the expected output voltage. The higher the accuracy, the lower will be the error. Due to the incremental nature of the digital input word, an error can be tolerated but it should not exceed $\pm\frac{1}{2}LSB$ or $\frac{1}{2}$ resolution.

Example. The error at full-scale for an 8-bit DAC with 10V maximum output is 50mV. Calculate the error and compare it with the resolution.

Solution: Error = $\frac{0.05}{10} \times 100\% = 0.5\%$

Resolution = $\frac{1}{256} \times 100\% = 0.391\%$; $\frac{1}{2}$ Resolution = 0.195%

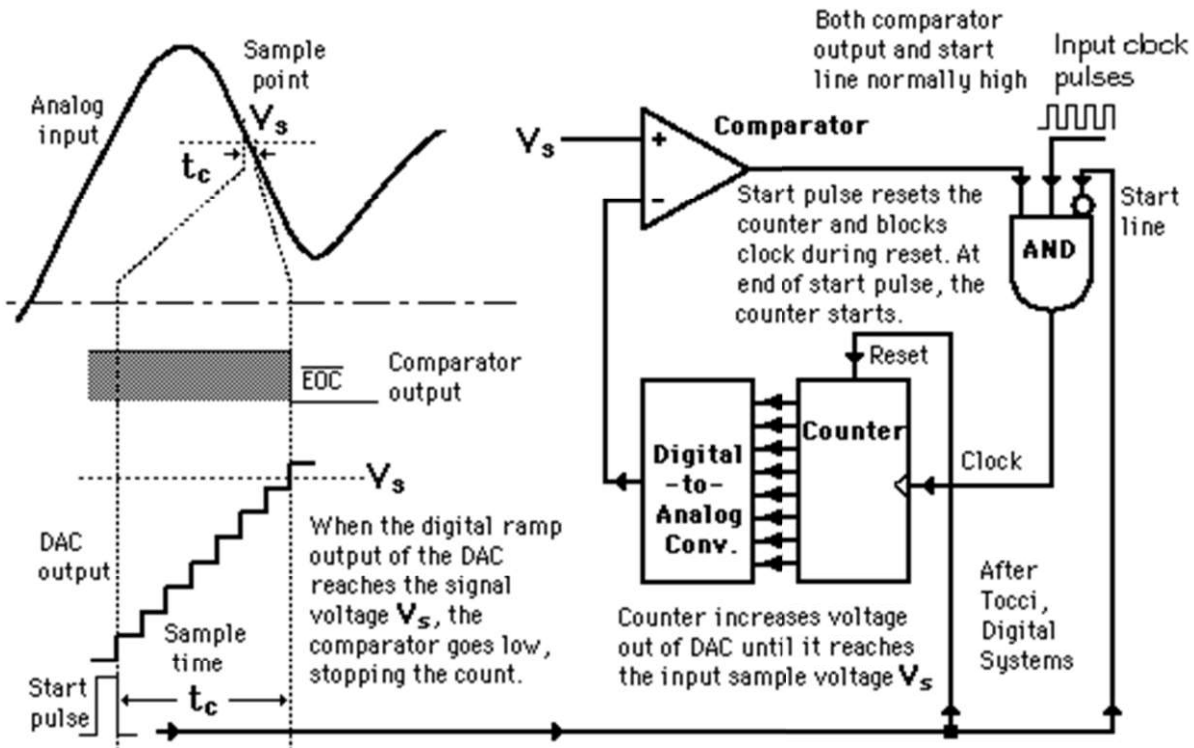
ADC Various Approaches

- 3 Basic Types
- Digital-Ramp ADC
- Successive Approximation ADC
- Flash ADC

Digital-Ramp ADC

- Conversion from analog to digital form inherently involves comparator action where the value of the analog voltage at some point in time is compared with some standard.
- A common way to do that is to apply the analog voltage to one terminal of a comparator and trigger a binary counter which drives a DAC.

Digital-Ramp ADC



Digital-Ramp ADC

- The output of the DAC is applied to the other terminal of the comparator.
- Since the output of the DAC is increasing with the counter, it will trigger the comparator at some point when its voltage exceeds the analog input.
- The transition of the comparator stops the binary counter, which at that point holds the digital value corresponding to the analog voltage.

Successive approximation ADC

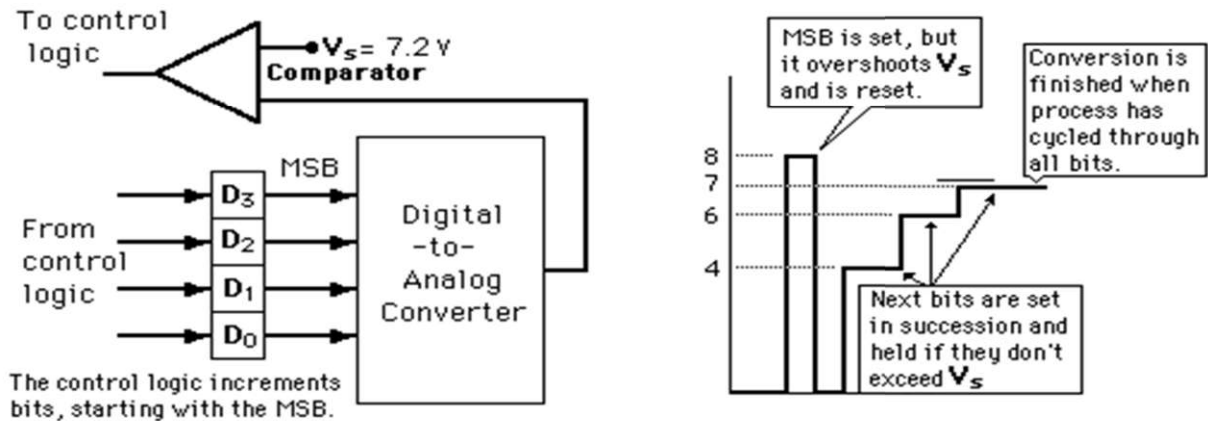
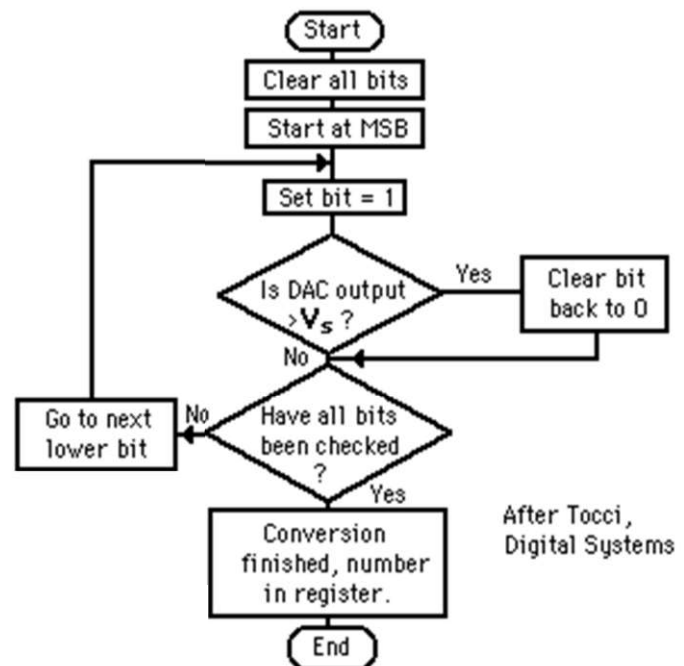


Illustration of 4-bit SAC with 1 volt step size

Successive approximation ADC

- Much faster than the digital ramp ADC because it uses digital logic to converge on the value closest to the input voltage.
- A comparator and a DAC are used in the process.



After Tocci,
Digital Systems

Successive Approximation

Advantages

- Capable of high speed
- Medium accuracy compared to other ADC types
- Good tradeoff between speed and cost

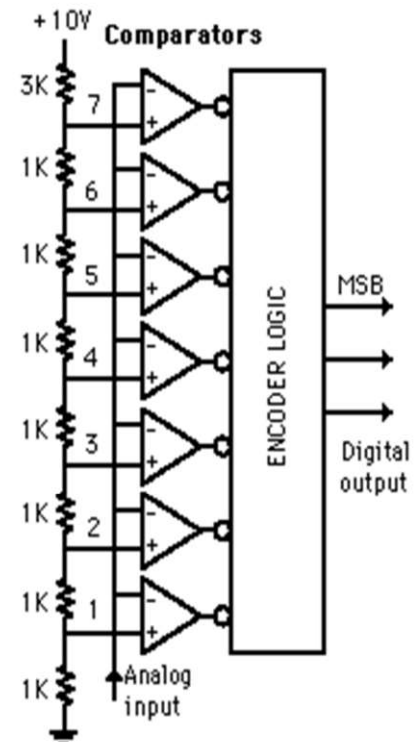
Disadvantages

- Higher resolution successive approximation ADCs will be slower
- Speed limited ~5Mps

Flash ADC

- It is the fastest type of ADC available, but requires a comparator for each value of output.
(63 for 6-bit, 255 for 8-bit, etc.)
- Such ADCs are available in IC form up to 8-bit and 10-bit flash ADCs (1023 comparators) are planned.
- The encoder logic executes a truth table to convert the ladder of inputs to the binary number output.

Illustrated is a 3-bit flash ADC with resolution 1 volt



Flash ADC

- The resistor net and comparators provide an input to the combinational logic circuit, so the conversion time is just the propagation delay through the network - it is not limited by the clock rate or some convergence sequence.

Flash ADC

Advantages

- Very fast

Disadvantages

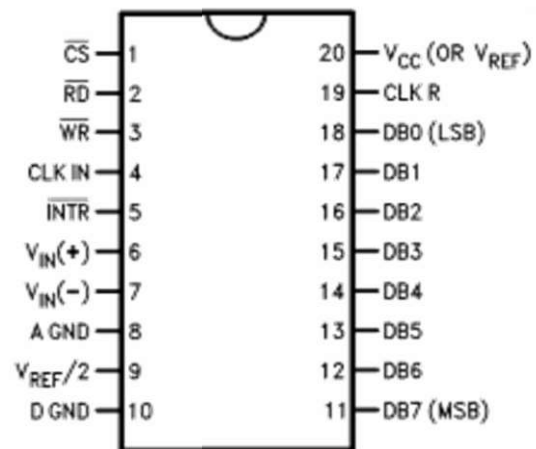
- Needs many parts (255 comparators for 8-bit ADC)
- Lower resolution
- Expensive
- Large power consumption

ADC080x, 8-Bit μ P Compatible A/D Converters

- CMOS 8-bit successive approximation A/D converters that use a differential potentiometer ladder—similar to the 256R products.
- These converters are designed to allow operation with the NSC800 and INS8080A derivative control bus with TRI-STATE output latches directly driving the data bus.
- These A/Ds appear like memory locations or I/O ports to the microprocessor and no interfacing logic is needed.
- Differential analog voltage inputs allow increasing the common-mode rejection and offsetting the analog zero input voltage value.
- In addition, the voltage reference input can be adjusted to allow encoding any smaller analog voltage span to the full 8 bits of resolution.

ADC080x Features

- Compatible with 8080 μ P derivatives—no interfacing logic needed - access time - 135 ns
- Easy interface to all microprocessors, or operates “stand alone”
- Differential analog voltage inputs
- Logic inputs and outputs meet both MOS and TTL voltage level specifications
- Works with 2.5V (LM336) voltage reference
- On-chip clock generator
- 0V to 5V analog input voltage range with single 5V supply
- No zero adjust required



DS005671-30

Question 1. Calculate the maximum conversion time of (a) a 8-bit staircase ramp ADC and (b) a successive approximation ADC, if the clock rate is 2MHz.

Solution:

(a) For a 8-bit staircase ramp ADC, the maximum number of count is

$$n_c = 2^8 = 256$$

Therefore, the maximum conversion time is

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

(b) For a 8-bit successive approximation ADC, the conversion time is constant and equal to

$$T_c = \frac{n}{f} = \frac{8}{2 \times 10^6} = 4 \times 10^{-6} s = 4 \mu s$$

It can be noted that the conversion speed of successive approximation ADC is much faster than the staircase ramp type.

Question 2.

Find out the percentage resolution of a DAC of n bits, and hence determine the value for $n = 12$.

Solution:

$$\text{Percentage resolution} = \frac{1}{2^n} \times 100\%$$

For $n = 12$,

$$\text{Percentage resolution} = \frac{1}{2^{12}} \times 100\% = 0.0244\% = 244 \text{ppm (part per million)}$$