PEARSON

Chapter 11 – Interfacing with the Analog World

ELEVENTH EDITION

Digital Systems

Principles and Applications

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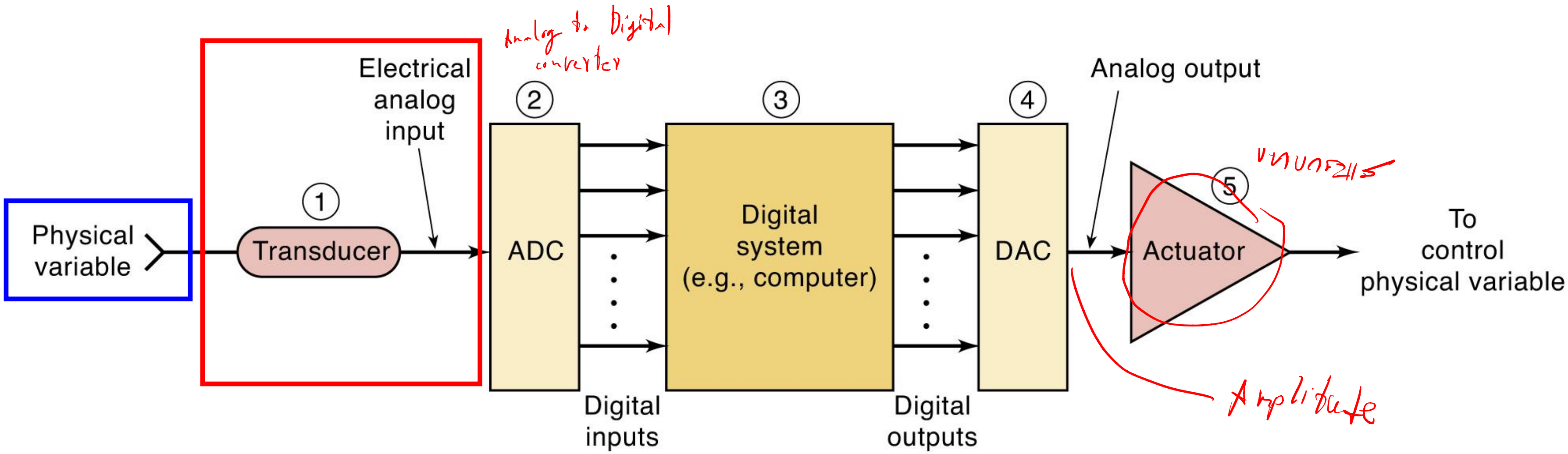
Chapter 11 Objectives

- *Selected areas covered in this chapter*:
  - Theory of operation and circuit limitations of several types of digital-to-analog converters (DACs).
  - Various DAC manufacturer specifications.
  - Test procedures for troubleshooting DAC circuits.
  - Advantages/disadvantages of major analog-to-digital converter (ADC) architectures.
  - Sample-and-hold circuits in conjunction with ADCs.
  - Operation of an analog multiplexing system.
  - Basic concepts of digital signal processing.

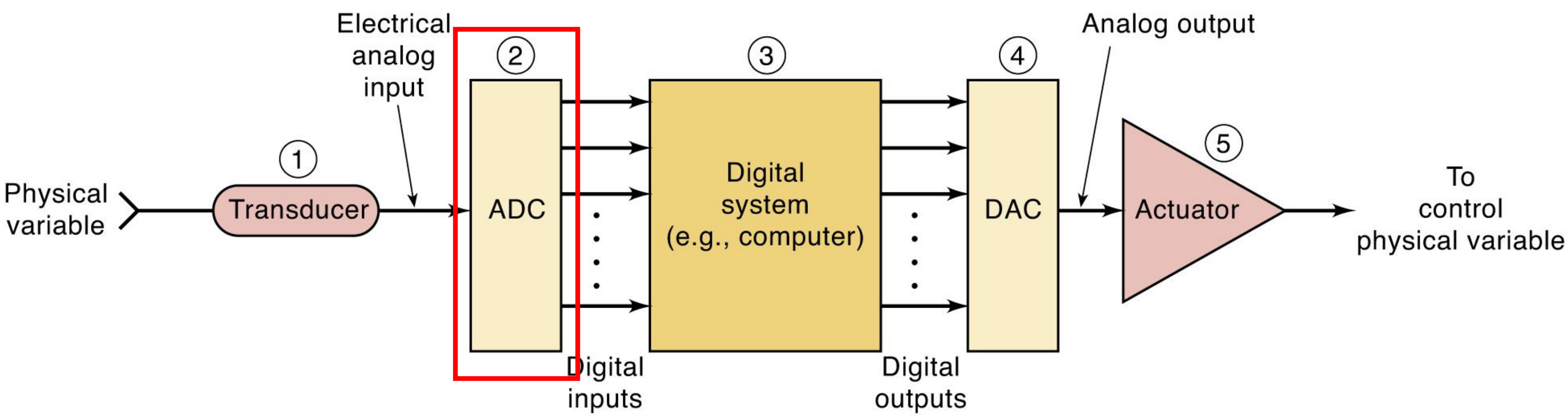
- A review of the difference between digital and analog quantities:
  - **Digital quantities**—values can take on one of two possible values.
    - Actual values can be in a specified range, so exact value is not important.
  - **Analog quantities**—values can take on an infinite number of values, and the exact value is important.

11-1 Interfacing With the Analog World

- Most physical variables are analog, and can take on any value within a continuous range of values.
  - Normally a nonelectrical quantity.
- A **transducer** converts the physical variable to an electrical variable.
  - Thermistors, photo-cells, photodiodes, flow meters, pressure transducers, tachometers, etc.

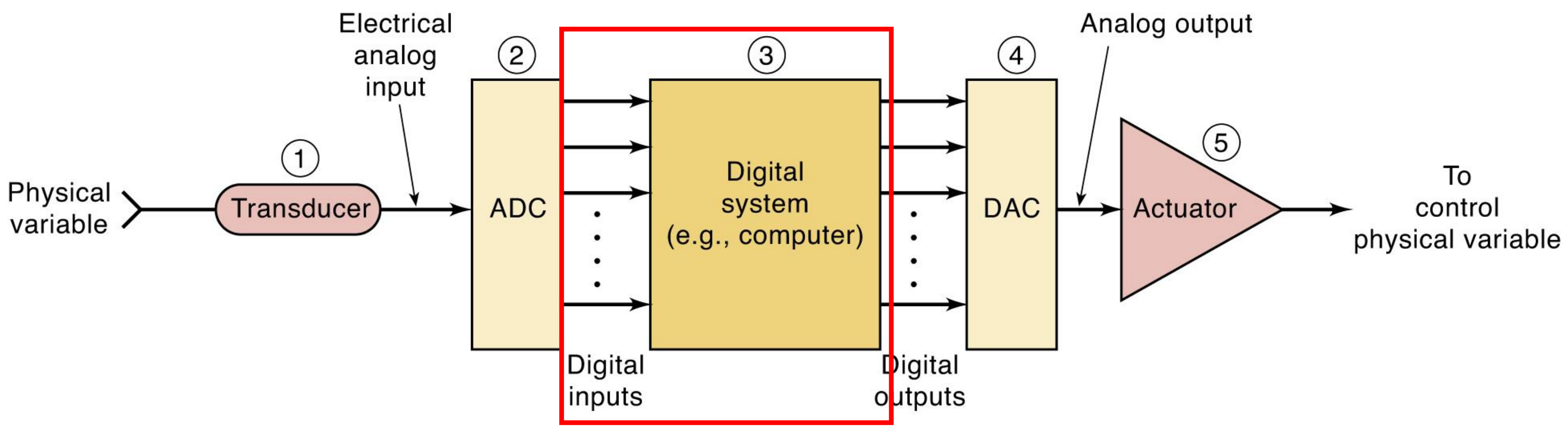


- The transducer's electrical analog output is the analog input to the **analog-to-digital converter**.
- The ADC converts analog input to a digital output
  - Output consists of a number of bits that represent the value of the analog input.
    - The binary output from the ADC is proportional to the analog input voltage.



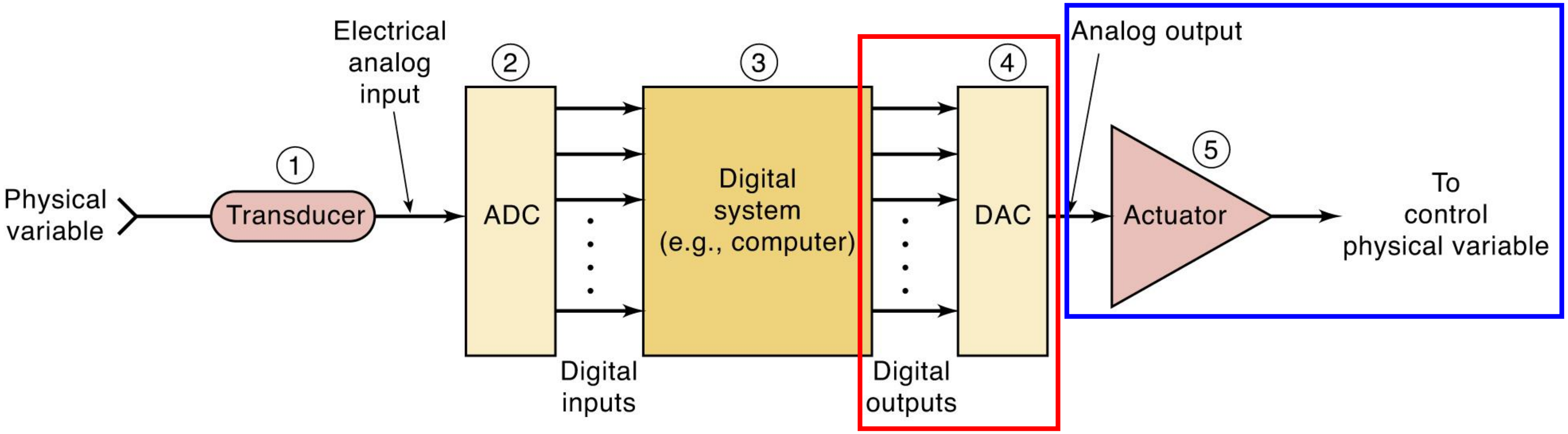
11-1 Interfacing With the Analog World

- The digital representation of the process variable is transmitted from the ADC to the digital computer
  - The digital value is stored & processes according to a program of instructions that it is executing.
- The program might perform calculations or other operations to produce output that will eventually be used to control a physical device.



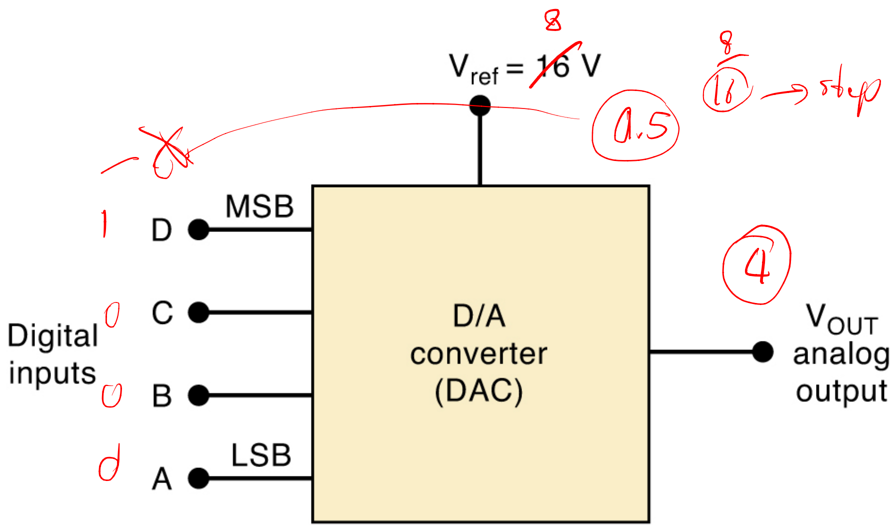
11-1 Interfacing With the Analog World

- Digital output from the computer is connected to a **digital-to-analog converter (DAC**).
  - Converted to a proportional analog voltage/current.
- The analog signal is often connected to some device or circuit that serves as an actuator to control the physical variable.
  - An electrically controlled valve or thermostat, etc.



11-2 Digital to Analog Conversion

- Many A/D conversion methods utilize the D/A conversion process.
  - Converting a value represented in *digital* code to a voltage or current proportional to the digital value.



D	C	B	A	V_{OUT}	
0	0	0	0	0	Volts
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	Volts

DAC output is technically *not* an analog quantity because it can take on only specific values.

11-2 Digital to Analog Conversion

- For each input number, the D/A converter output voltage is a unique value—in general:

$$\text{analog output} = K \times \text{digital input}$$

…where *K* is the proportionality factor and is a constant value for a given DAC connected to a fixed reference voltage.

- The quantity of possible output values can be increased, and the difference between successive values decreased—by increasing the input bits.

Allowing output more & more like an analog quantity that varies continuously over a range of values.

A “pseudo-analog” quantity, which approximates pure analog, referred to as analog for convenience.

11-2 Digital to Analog Conversion

- Each digital input contributes a different amount to the analog output—*weighted* according to their position in the binary number.

D	*C*	*B*	*A*		V_{OUT} (V)
0	0	0	1	→	1
0	0	1	0	→	2
0	1	0	0	→	4
1	0	0	0	→	8

Weights are successively doubled for each bit, beginning with the LSB.

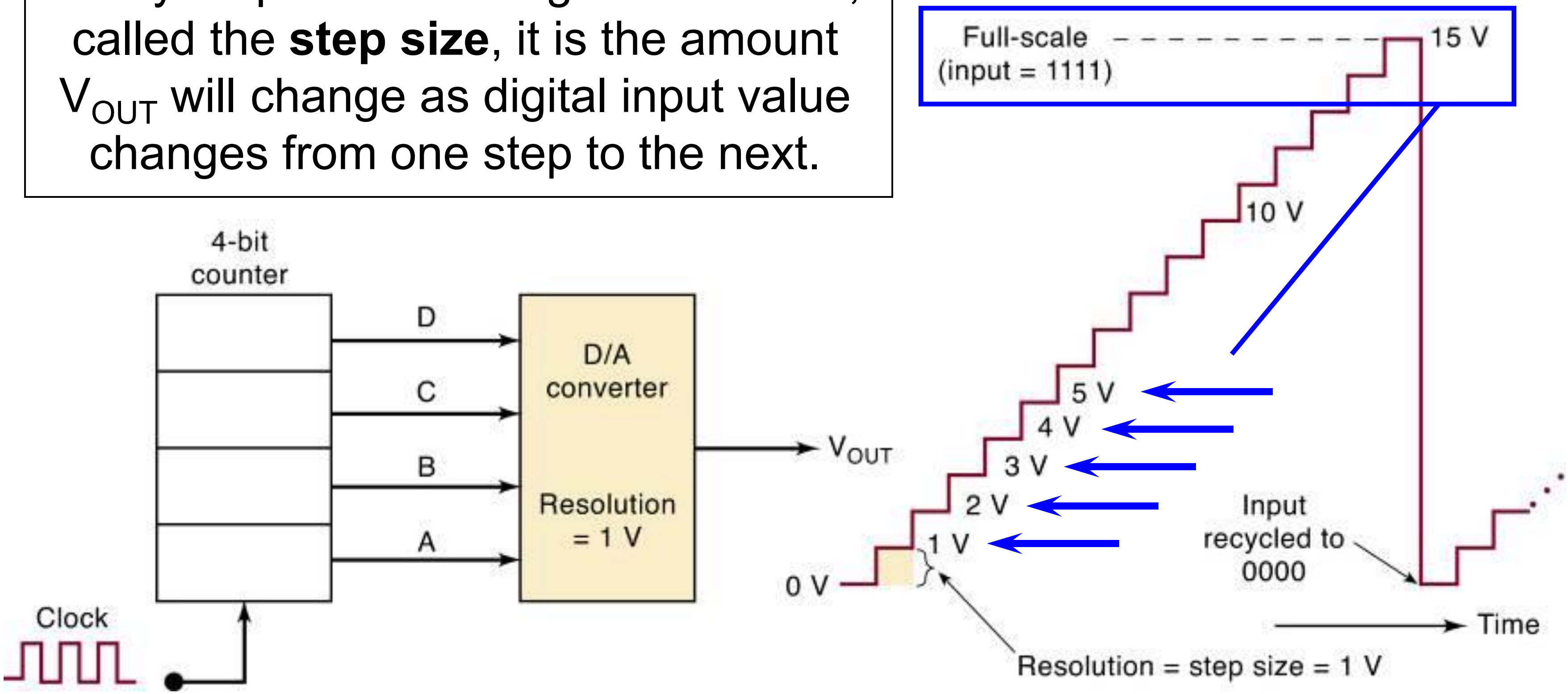
V_{OUT} can be considered to be the weighted sum of the digital inputs.

D	C	B	A	V_{OUT}	
0	0	0	0	0	Volts
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	Volts

11-2 Digital to Analog Conversion

- The **Resolution** of a D/A converter is defined as the smallest change that can occur in analog output as a result of a change in digital input.

Always equal to the weight of the LSB, called the **step size**, it is the amount V_{OUT} will change as digital input value changes from one step to the next.



11-2 Digital to Analog Conversion

- Resolution (step size) is the same as the DAC input/output proportionality factor:

$$\text{analog output} = K \times \text{digital input}$$

…where *K* is the proportionality factor and is a constant value for a given DAC connected to a fixed reference voltage.

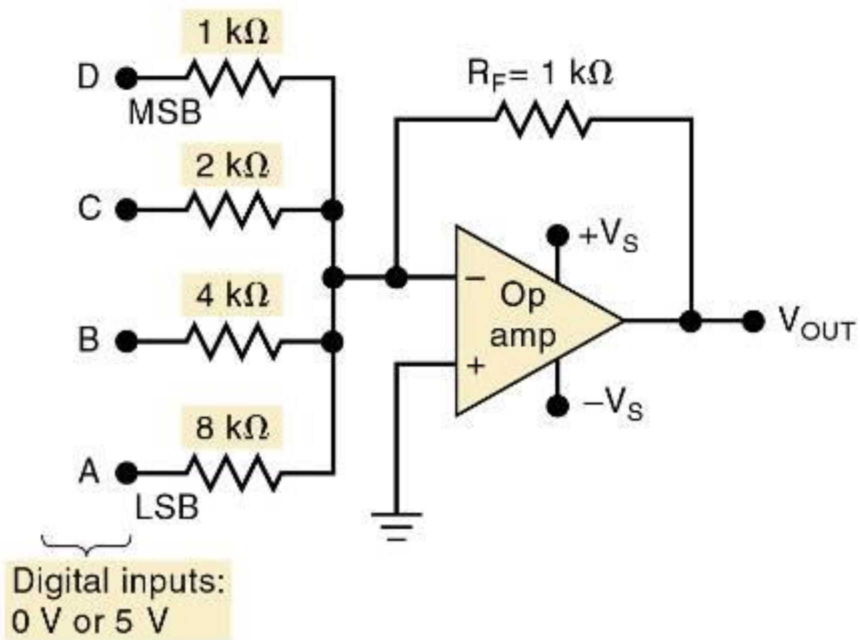
11-2 Digital to Analog Conversion

- Many DACs can also produce negative voltages by making slight changes to the analog circuitry on the output of the DAC.

	Signed 2's Complement	DAC Inputs	DAC V_{out}
Most positive	01111111	11111111	$\sim + V_{ref}$
Zero	00000000	10000000	0 V
Most negative	10000000	00000000	$-V_{ref}$

Other DACs may have the extra circuitry built in and accept 2's complement signed numbers as inputs.

Simple DAC using an op-amp summing amplifier with binary-weighted resistors.



Input code

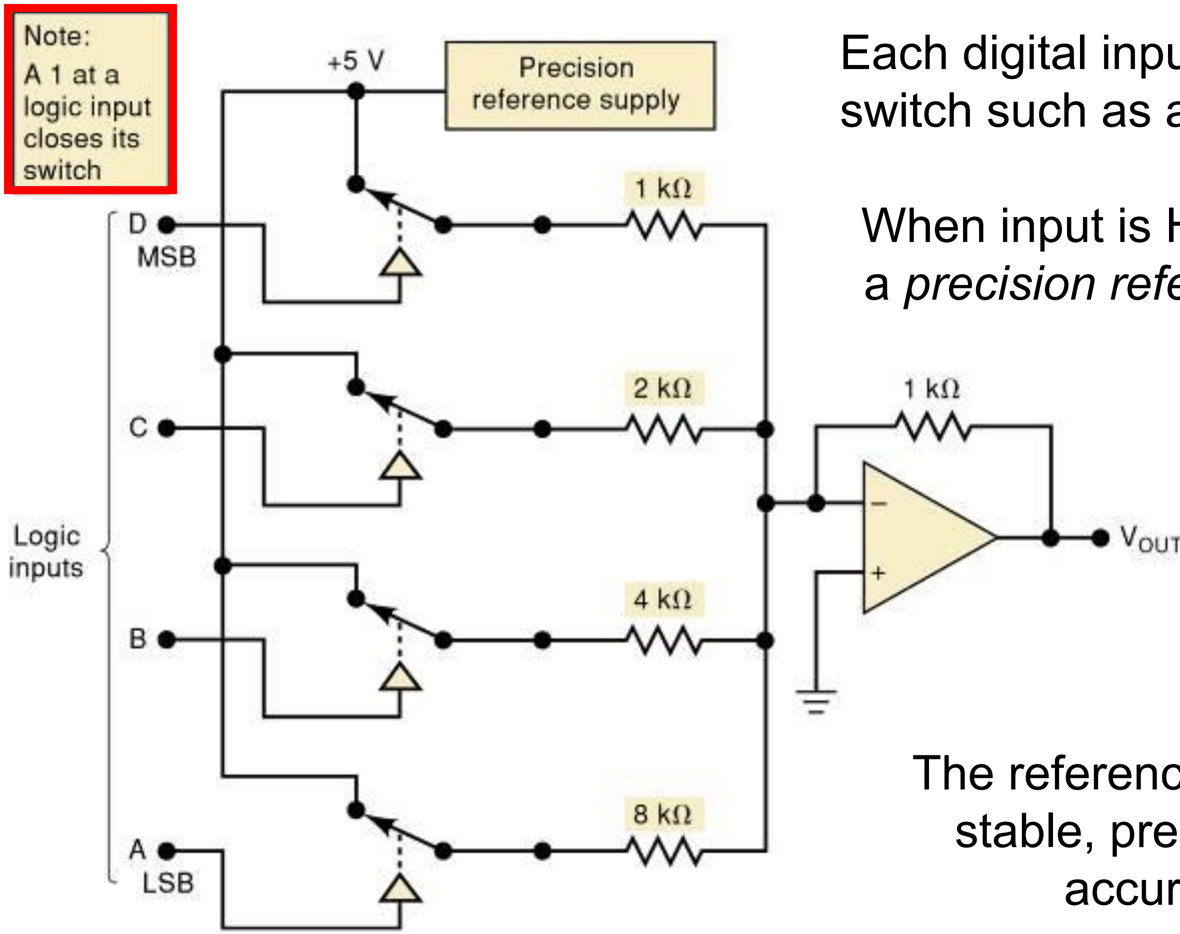
D	C	B	A	V_{OUT} (volts)
0	0	0	0	0
0	0	0	1	–0.625 ← LSB
0	0	1	0	–1.250
0	0	1	1	–1.875
0	1	0	0	–2.500
0	1	0	1	–3.125
0	1	1	0	–3.750
0	1	1	1	–4.375
1	0	0	0	–5.000
1	0	0	1	–5.625
1	0	1	0	–6.250
1	0	1	1	–6.875
1	1	0	0	–7.500
1	1	0	1	–8.125
1	1	1	0	–8.750
1	1	1	1	–9.375 ← Full-scale

Input resistor values are *binarily weighted*. Starting with MSB, resistor values increase by a factor of 2, producing desired weighting in the voltage output.

11-3 DAC Circuitry

- How close the circuit comes to producing the *ideal* values of V_{OUT} depends primarily on two factors.
  - The precision of the input and feedback resistors.
  - The precision of the input voltage levels.
- Resistors can be made very accurate by trimming.
  - Within 0.01 percent of the desired values.
- Digital inputs cannot be taken directly from the outputs of FFs or logic gates because the output logic levels of these vary within given ranges.
  - It is necessary to add circuitry between each digital input and its input resistor to the summing amplifier.

Complete four-bit DAC including precision reference supply.



Each digital input controls a semiconductor switch such as a CMOS transmission gate.

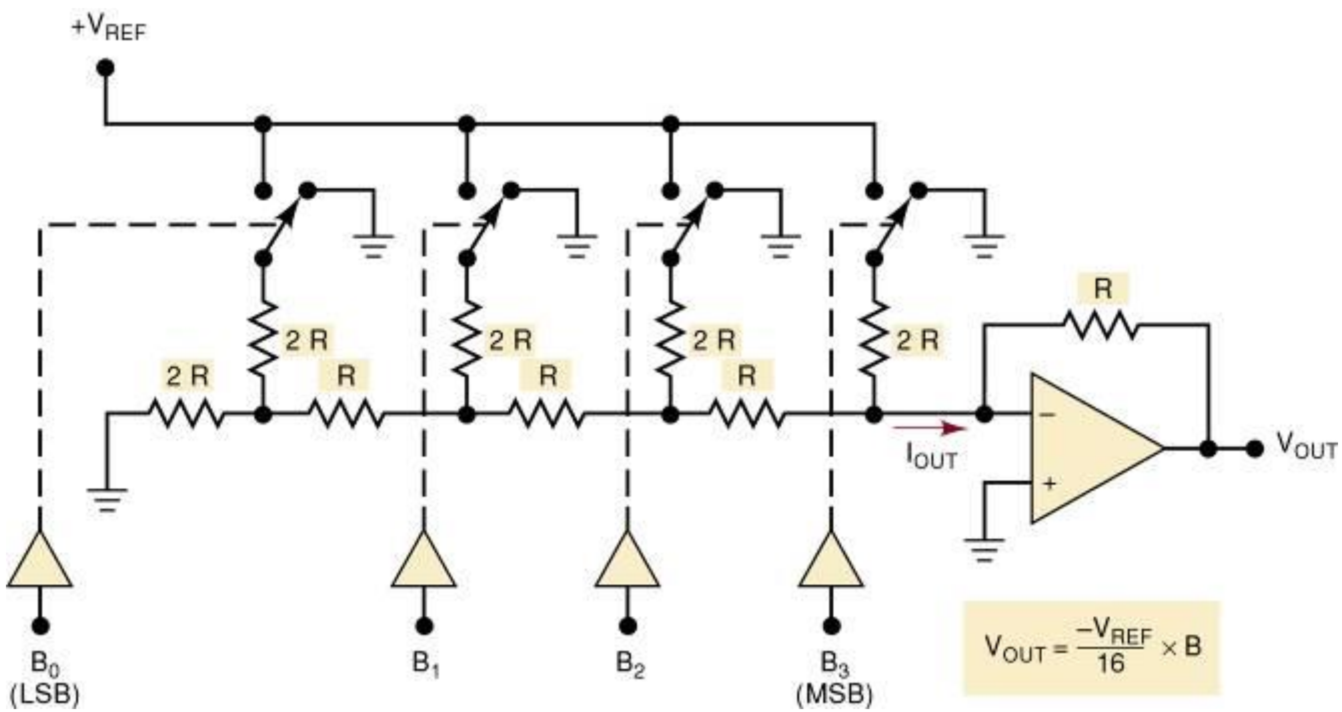
When input is HIGH, the switch connects a *precision reference supply* to the input.

When the input is LOW, the switch is open.

The reference supply produces a very stable, precise voltage needed for accurate analog output.

11-3 DAC Circuitry

- Circuits with binary weighted resistors cause a problem due to the large difference in *R* values between LSB and MSB.
  - The R/2R ladder uses resistances that span only a 2 to 1 range.



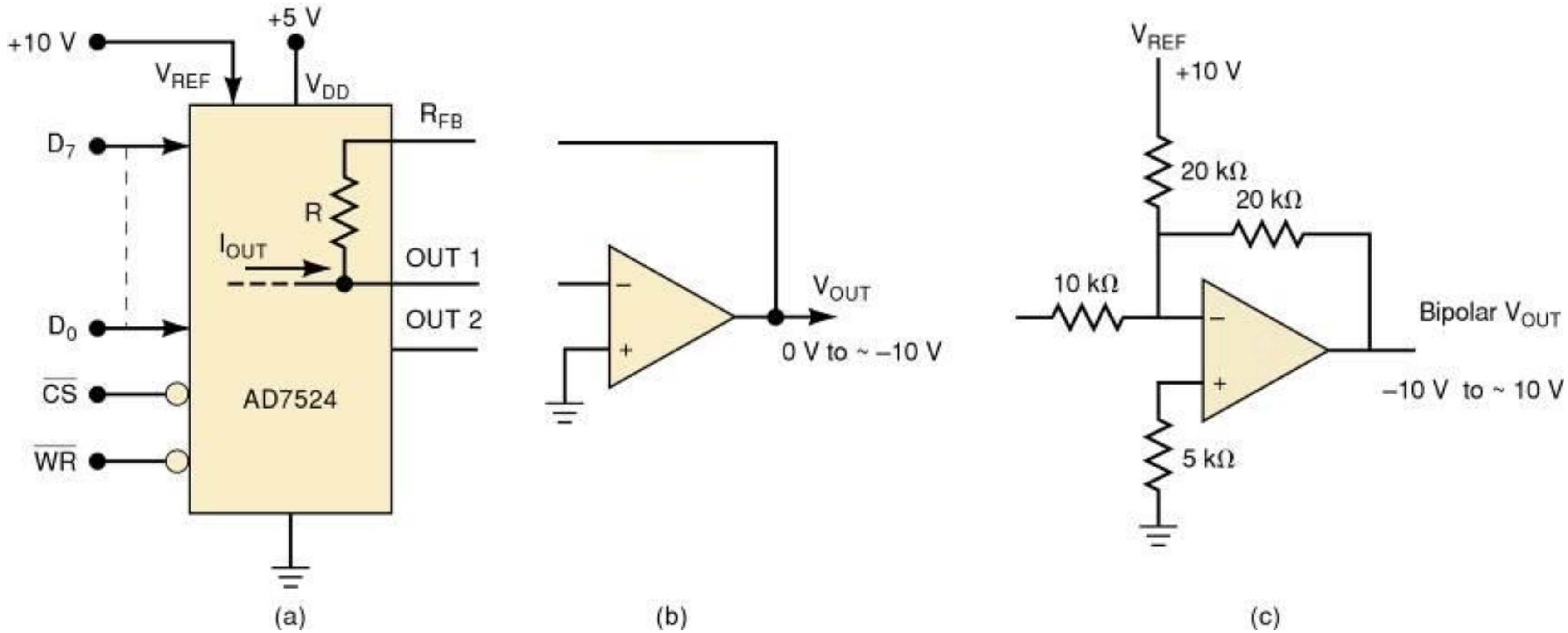
11-4 DAC Specifications

- Many DACs are available as ICs or self contained packages, and key specifications are:
  - Resolution; Accuracy.
  - Offset error; Settling time; Monotonicity.

11-5 An Integrated Circuit DAC

- The AD7524, a CMOS IC is an eight-bit D/A converter that uses an R/*2R* ladder network.
  - This DAC has an eight-bit input that can be latched internally by Chip Select and WRITE inputs.
- When either control input goes HIGH, the digital input data are latched, and the analog output remains at the level corresponding to that latched digital data.

11-5 An Integrated Circuit DAC



(a) AD7524 8-bit DAC with latched inputs.

(b) Op-amp current-to- voltage converter provides 0 to approximately -10 V out

(c) Op-amp circuit to produce bipolar output from -10 V to approximately 10 V.

11-6 DAC Applications

- Used when a digital circuit output must provide an analog voltage or current.
  - **Control**—use a digital computer output to adjust motor speed or furnace temperature.
  - **Automatic testing**—computer generated signals to test analog circuitry.
  - **Signal reconstruction**—restoring an analog signal after it has been converted to digital.
  - **Digital amplitude control**—used to reduce the amplitude of an analog signal.
  - **Serial DACs**—with a built-in serial in/parallel out shift register—many have more than one DAC on the same chip.

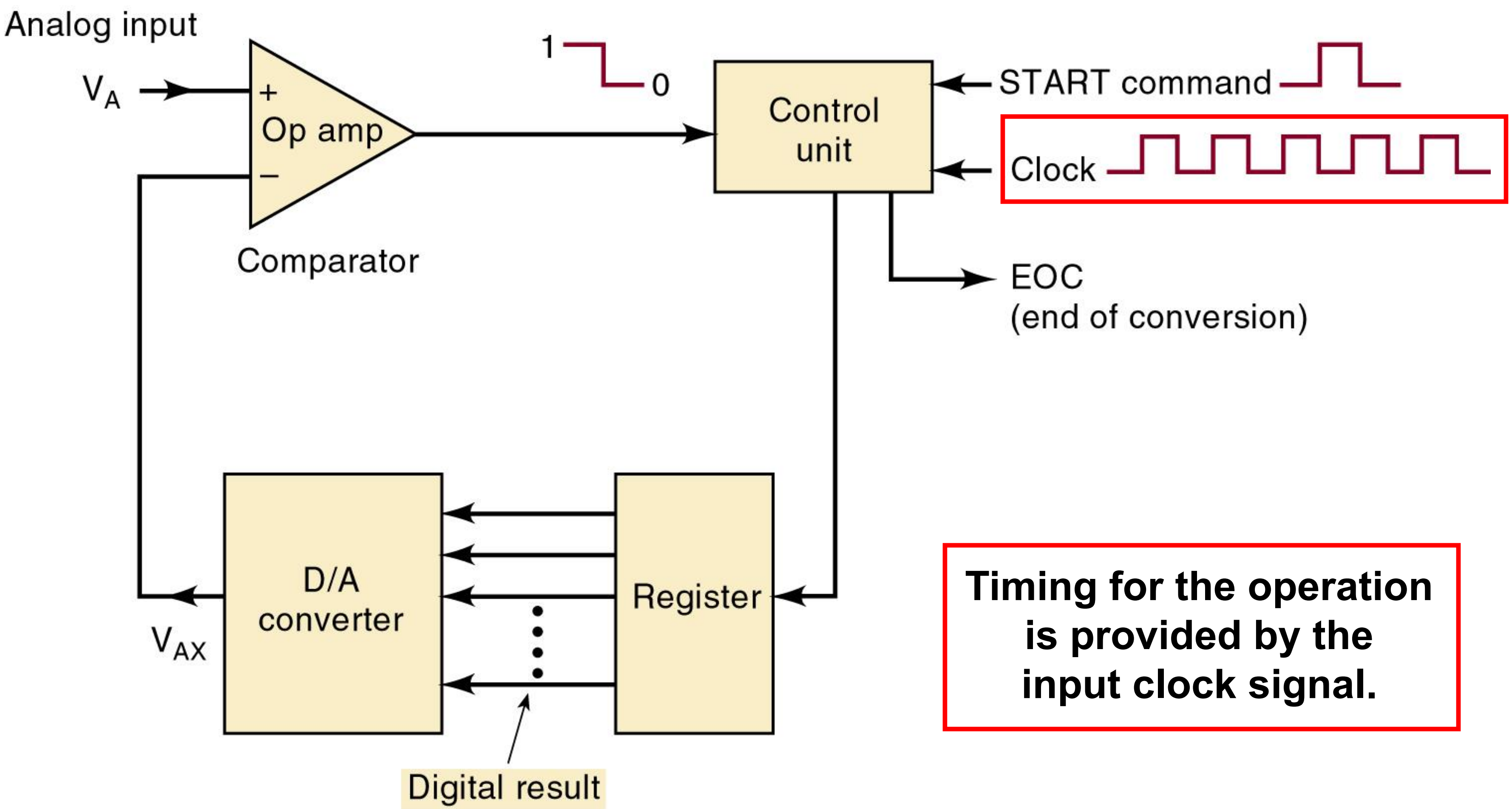
11-7 Troubleshooting DACs

- DACs are both digital and analog.
  - Logic probes & pulsers can be used on digital inputs.
  - A meter or an oscilloscope must be used on the analog output.
- Two ways to test DAC operation:
  - *Static accuracy test*—binary input is set to a fixed value while analog output is checked with a very accurate meter.
  - *Staircase test*—binary input is incremented and output is checked for problems on the “steps”.

11-8 Analog to digital Conversion

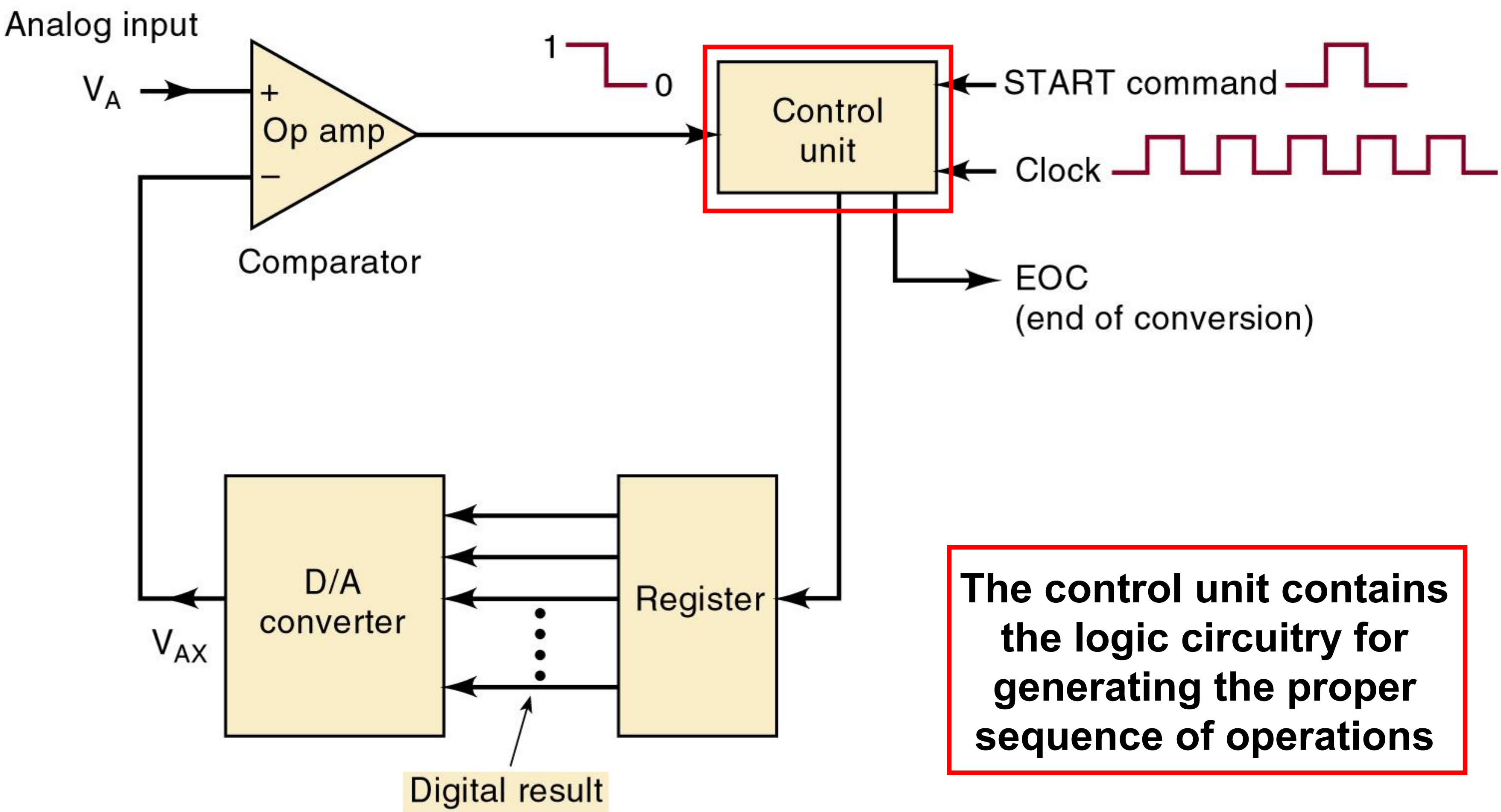
- An analog-to-digital converter takes an analog input voltage and, after a certain amount of time, produces a digital output code that represents the analog input.
  - Several important types of ADCs utilize a DAC as part of their circuitry.
- The Op amp comparator ADC
  - Variations differ in how the control section continually modifies numbers in the register

General diagram of one class of ADCs.



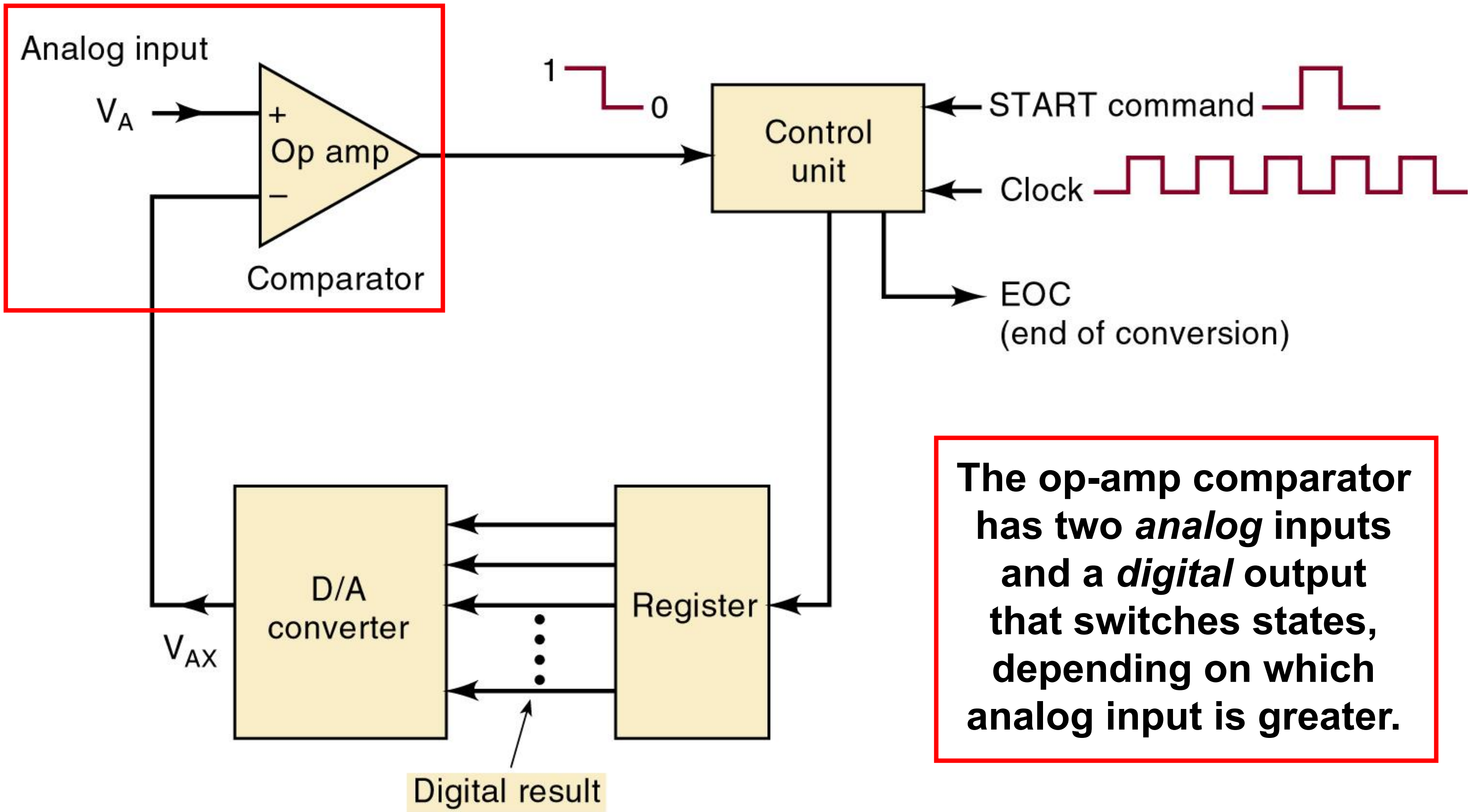
Timing for the operation is provided by the input clock signal.

General diagram of one class of ADCs.



The control unit contains the logic circuitry for generating the proper sequence of operations

General diagram of one class of ADCs.



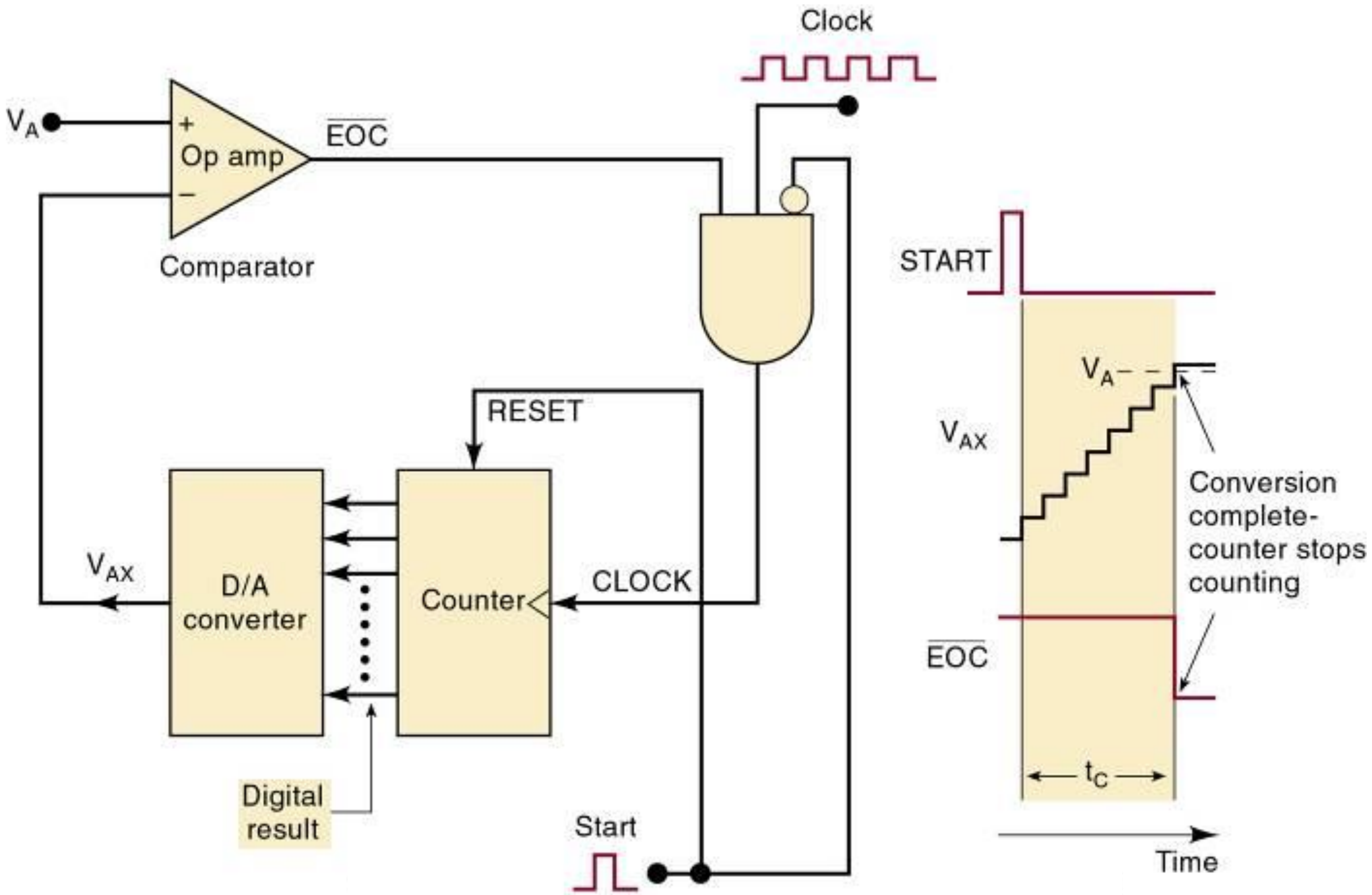
The op-amp comparator has two *analog* inputs and a *digital* output that switches states, depending on which analog input is greater.

- Basic operation of ADC types:
  - The START command pulse initiates the operation.
  - At a rate determined by the clock, the control unit continually modifies the binary number in the register.
  - The binary number in the register is converted to an analog voltage (V_{AX}), by the DAC.
  - The comparator compares V_{AX} with analog input V_A.
    - While $V_{AX} < V_A$,comparator output stays HIGH.
    - When V_{AX} exceeds V_A by at least an amount equal to V_T (threshold voltage), comparator out-put goes LOW and stops modifying the register number.
  - The control logic activates the end-of-conversion signal, *EOC*, when the conversion is complete.

11-8 Analog to digital Conversion

- One of the simplest versions of the general ADC uses a binary counter as the register and allows the clock to increment the counter one step at a time until $V_{AX} \geq V_A$.
  - Called a **digital-ramp ADC** because the waveform at V_{AX} is a step-by-step ramp.

Digital-ramp ADC

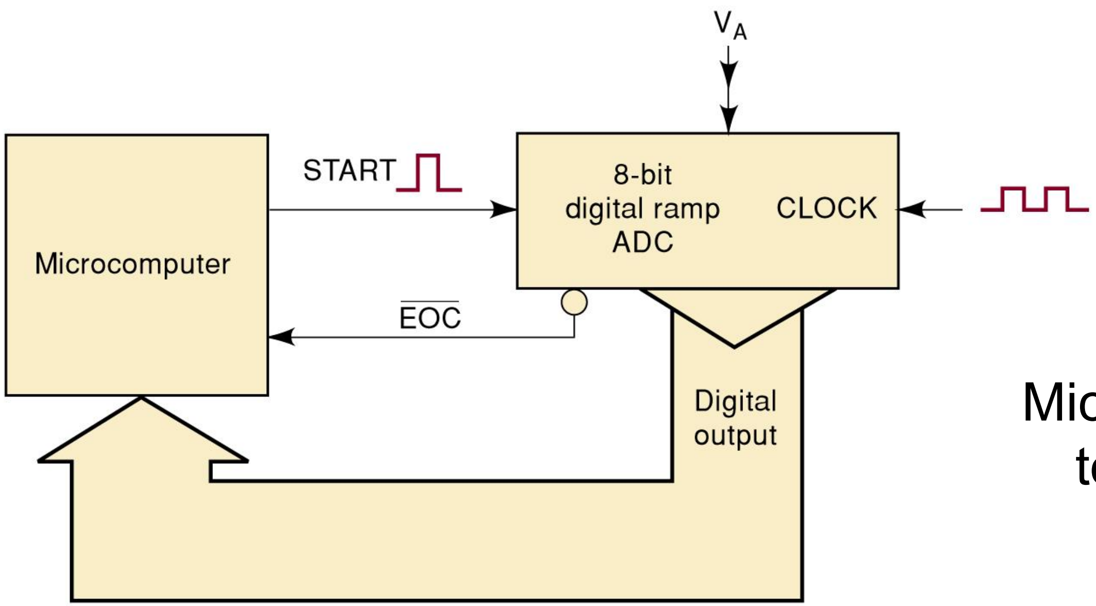


11-9 Digital Ramp ADC

- A/D resolution and accuracy.
  - Measurement error is unavoidable.
  - Reducing the step size can reduce but not eliminate potential error—called **quantization error**.

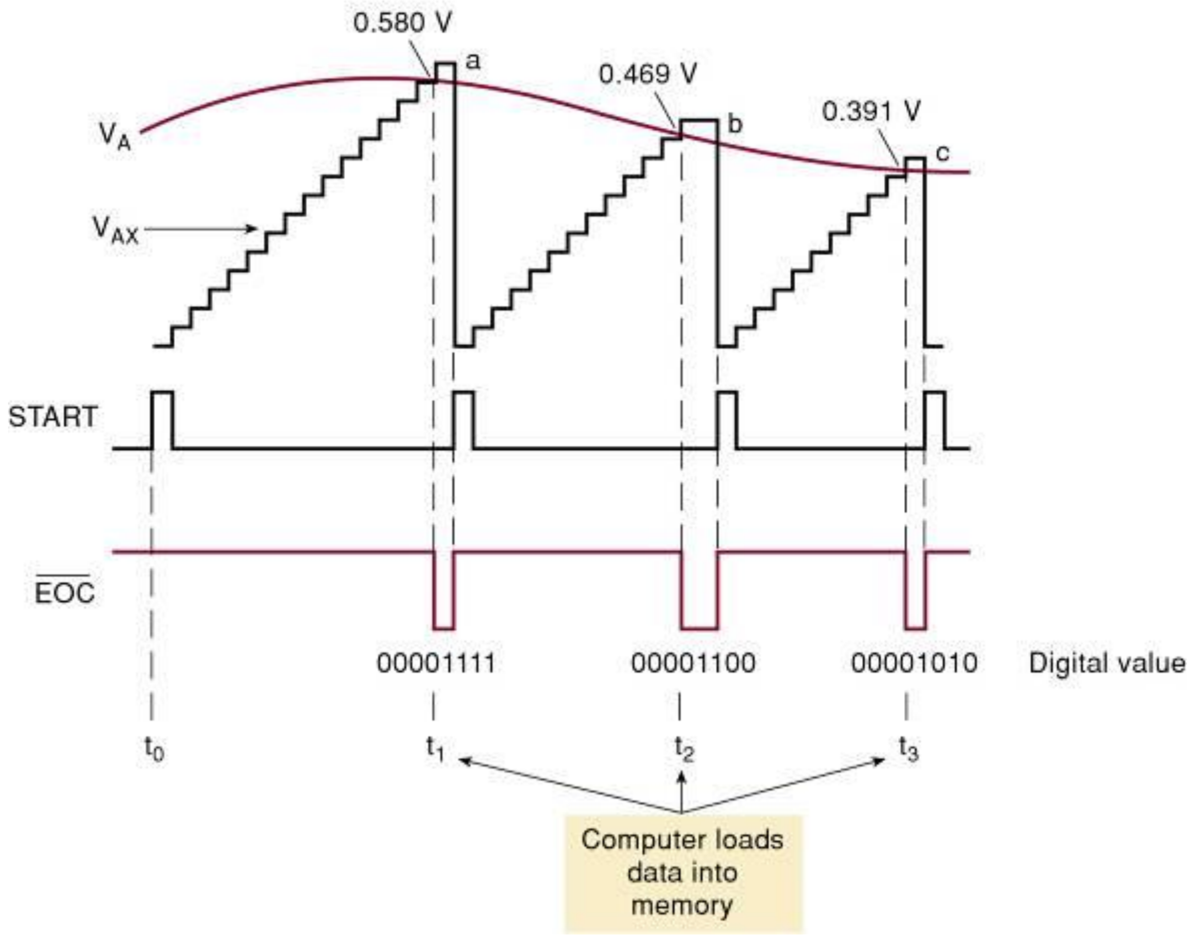
11-9 Digital Ramp ADC

- The process by which the computer acquires digitized analog data is called *data acquisition*.
- Acquiring a single data point's value is referred to as **sampling** the analog signal.
  - That data point is often called a *sample*.

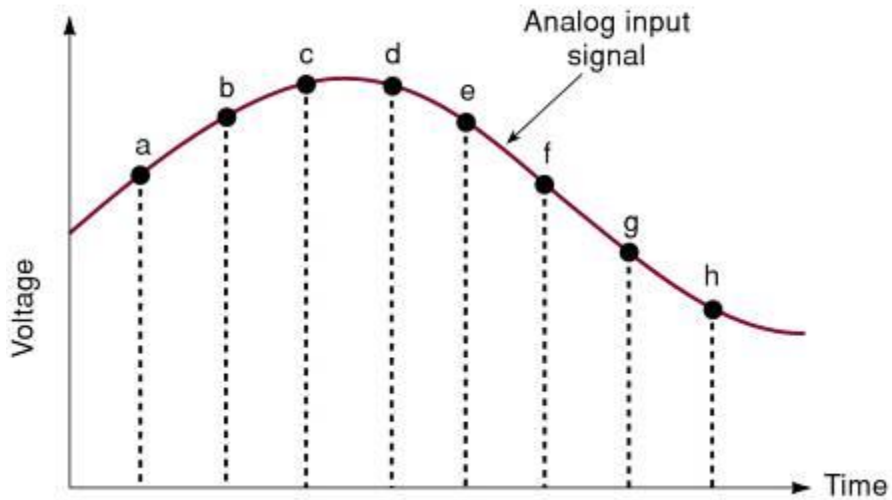


Microcomputer connected to a digital-ramp ADC for data acquisition.

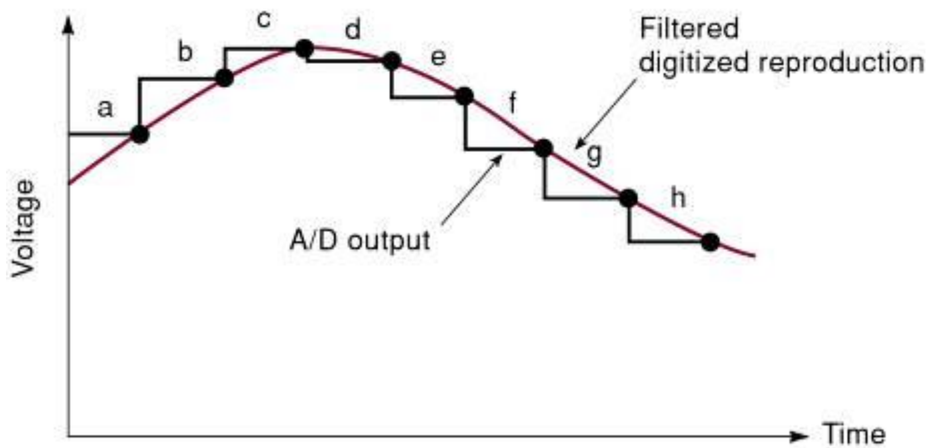
The waveforms illustrate how the computer acquires digital version of the analog signal (V_A).



11-10 Data Acquisition



Digitizing an analog signal.



Reconstructing the signal from the digital data.

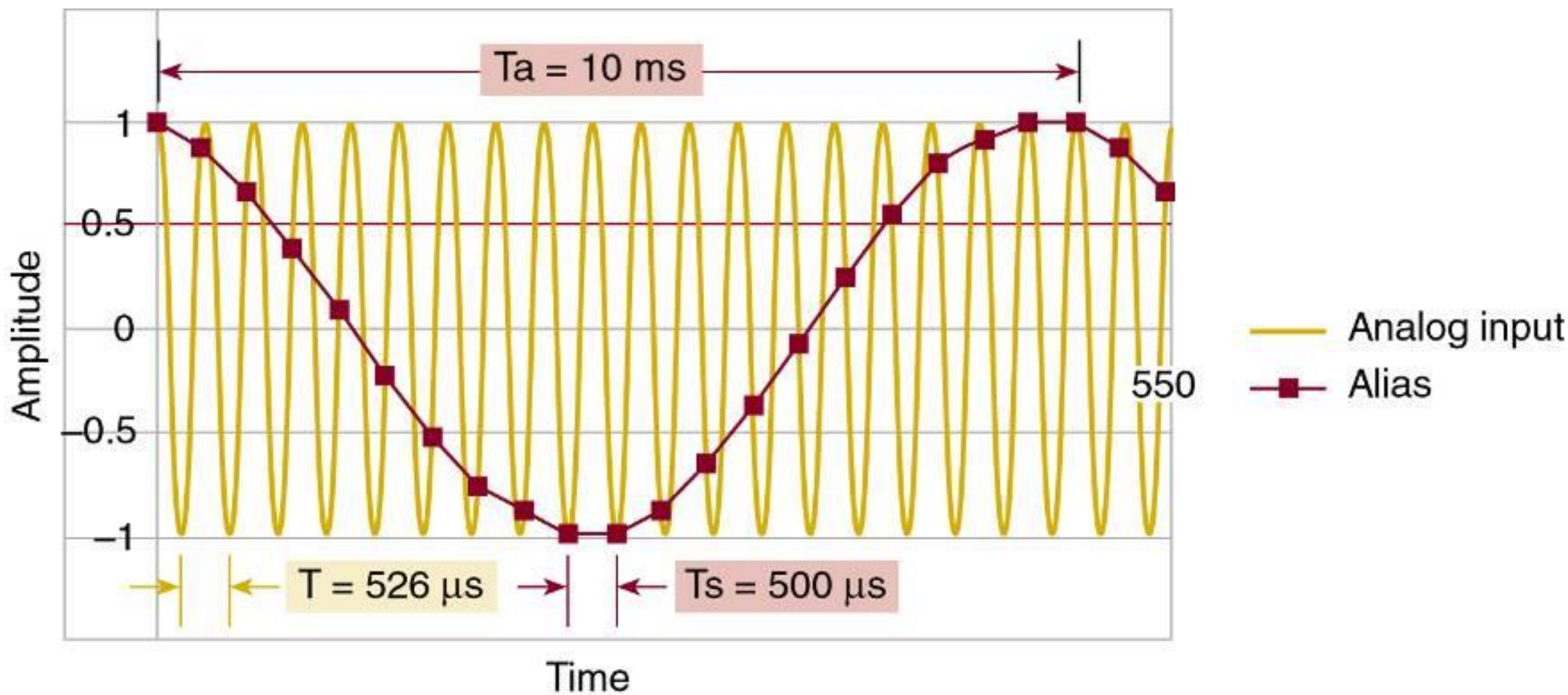
11-10 Data Acquisition

- The goal in signal reconstruction is to make the reconstruction nearly identical to the original analog signal.
- To avoid loss of information, the incoming signal must be sampled at a rate *greater than two times* the frequency component in the incoming signal.
  - Proven by a man named Harry Nyquist.
- The frequency at which samples are taken is referred to as the **sampling frequency** (F_S).

11-10 Data Acquisition

- Consider sampling a 10-kHz frequency, at 20,000 samples/sec.
  - If, for example a 12-kHz tone were present in the input signal, a phenomenon called *aliasing* would occur.
  - A signal **alias** is produced by sampling at *less* than the minimum rate—in this case, *24,000 samples/sec.*
    - The alias frequency is always the difference between any integer multiple of the sampling frequency and the incoming frequency being digitized.

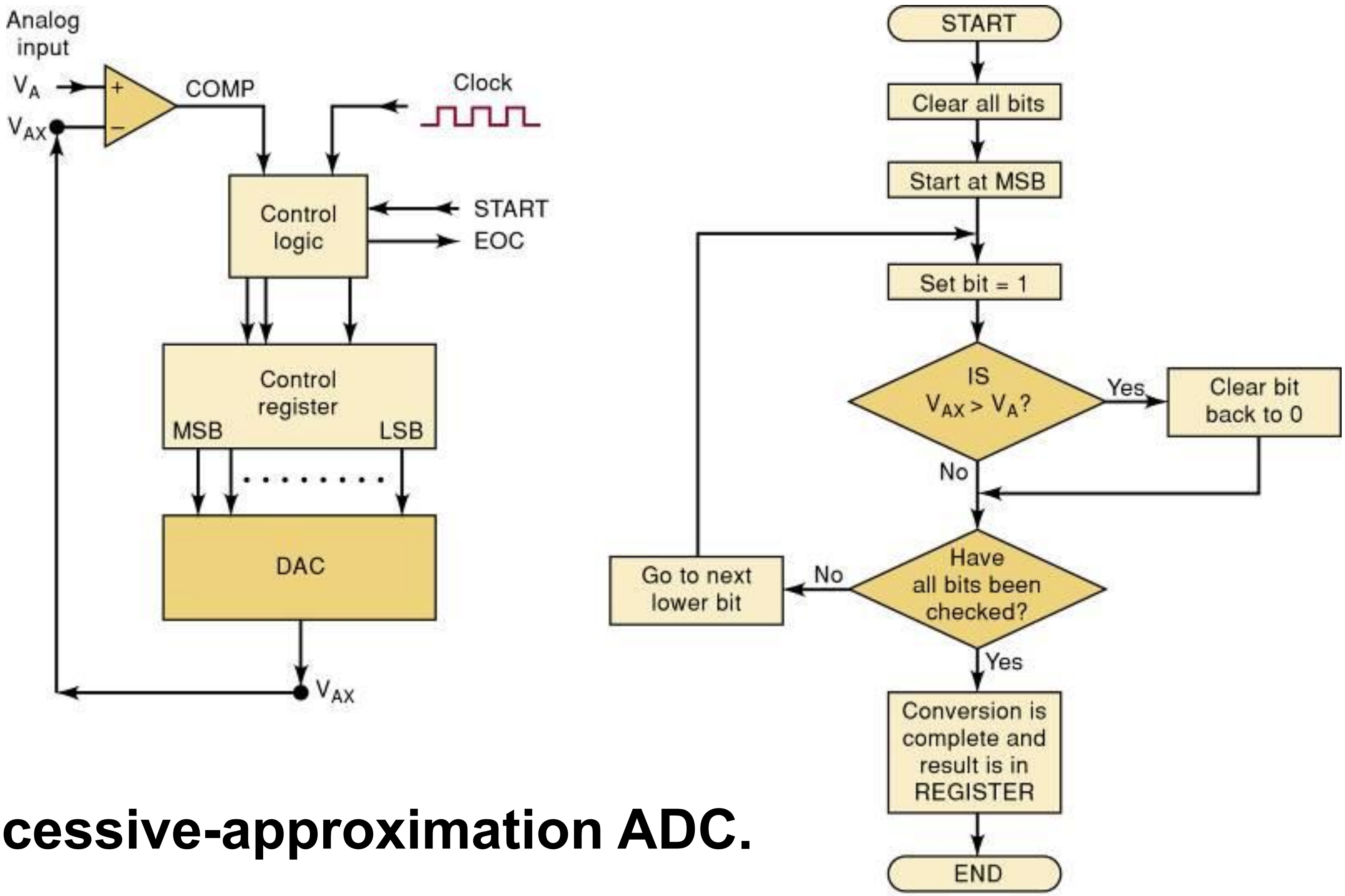
An alias signal due to *undersampling*.



11-11 Successive Approximation ADC

- The **successive-approximation converter** is one of the most widely used types of ADC.
  - It has more complex circuitry than the digital-ramp ADC but a much shorter conversion time.
    - A fixed value of conversion time not dependent on the value of the analog input.

11-11 Successive Approximation ADC



Successive-approximation ADC.

11-11 Successive Approximation ADC

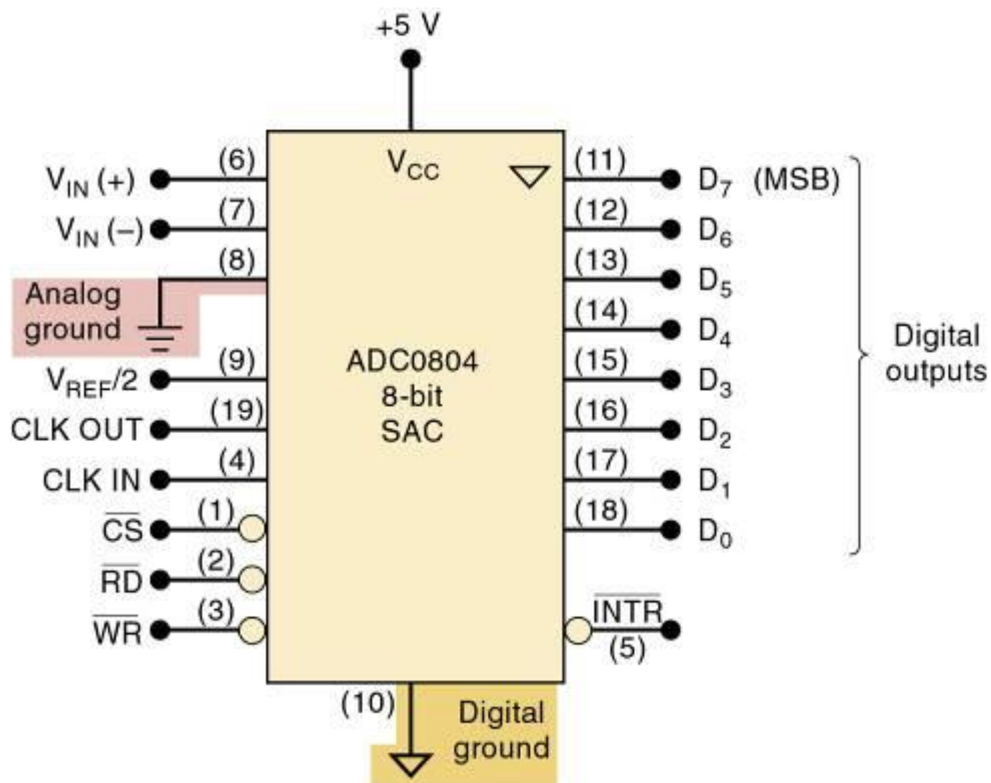
- ADCs are available with a wide range of operating characteristics and features.
  - The ADC0804 is a 20-pin CMOS IC that performs A/D conversion using successive approximation.

It has two analog inputs, to allow **differential inputs**.

It converts differential analog input voltage to an eight-bit tristate buffered digital output.

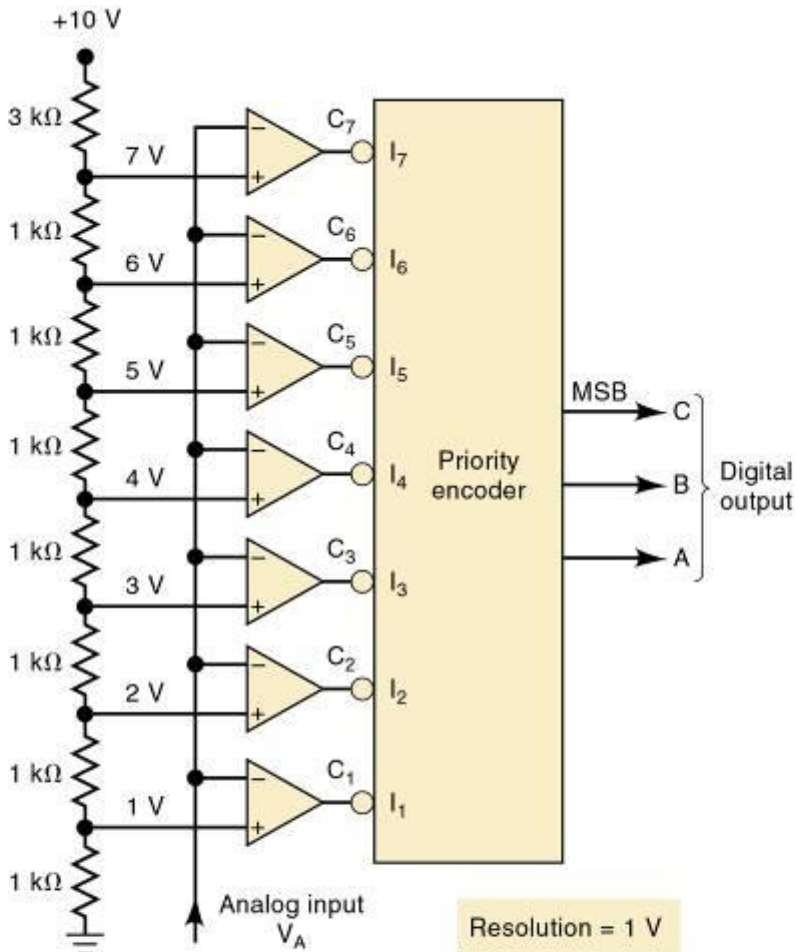
Internal clock generator circuit that produces a frequency based on values of externally connected components.

Separate ground connections for digital and analog voltages.



11-12 Flash ADCs

- The **flash converter** is the highest-speed ADC.
  - Requires much more circuitry than the other types.



IC flash converters are commonly available in two- to eight-bit units, and nine- and ten-bit units.

Analog in	Comparator outputs							Digital outputs		
V_A	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C	B	A
0–1 V	1	1	1	1	1	1	1	0	0	0
1–2 V	0	1	1	1	1	1	1	0	0	1
2–3 V	0	0	1	1	1	1	1	0	1	0
3–4 V	0	0	0	1	1	1	1	0	1	1
4–5 V	0	0	0	0	1	1	1	1	0	0
5–6 V	0	0	0	0	0	1	1	1	0	1
6–7 V	0	0	0	0	0	0	1	1	1	0
> 7 V	0	0	0	0	0	0	0	1	1	1

11-12 Flash ADCs

- Flash converters use no clock signal because no timing or sequencing is required.
  - The conversion takes place continuously.
- When analog input value changes, comparator outputs change—causing encoder output change.
  - Conversion time depends only on the propagation delays of the comparators and encoder logic.
- Flash converters can be very expensive and tend to have relatively low resolutions and high power consumption.

11-13 Other A/D Conversion Methods

- There are many other methods of A/D conversion.
  - The **dual-slope converter** has one of the slowest conversion times (typically 10 to 100 ms).
    - Relatively low cost—no precision components.
  - The **voltage-to-frequency ADC** is simpler than other ADCs because it does not use a DAC.
    - A *linear voltage-controlled oscillator (VCO)* produces an output frequency proportional to input voltage.
  - A **sigma/delta modulation** converter is an over-sampling device.
    - It effectively samples the analog information more often than the minimum sample rate.
  - A **pipelined ADC** has two or more subranging stages.
    - Each with an *n*-bit ADC along with an *n*-bit DAC.

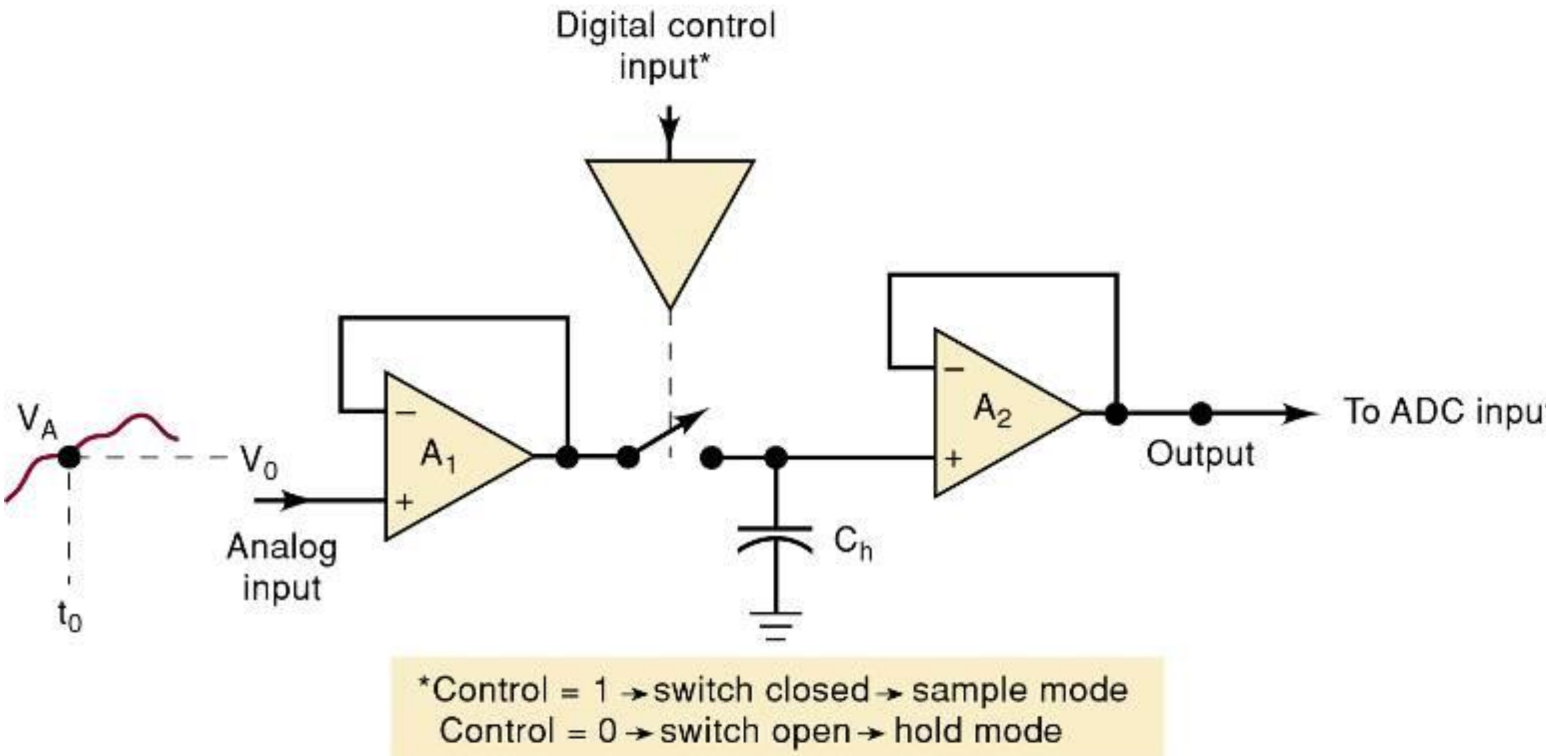
11-14 Typical ADC Architecture for Applications

- Most ADC applications fall into one of four areas:
  - Precision industrial measurement.
  - Voice/audio.
  - Data acquisition.
  - High speed.

11-15 Sample and Hold Circuits

- Analog voltage connected directly to an ADC input conversion can be adversely affected if analog voltage is changing during the conversion time.
- Stability of conversion can be improved by using a **sample-and-hold** (**S/H**) **circuit**.
  - To hold the analog voltage constant while the A/D conversion is taking place.
- In a computer-controlled data acquisition system the sample-and-hold switch would be controlled by a digital signal from the computer.
  - The amount of time the switch would have to remain closed is called the **acquisition time**

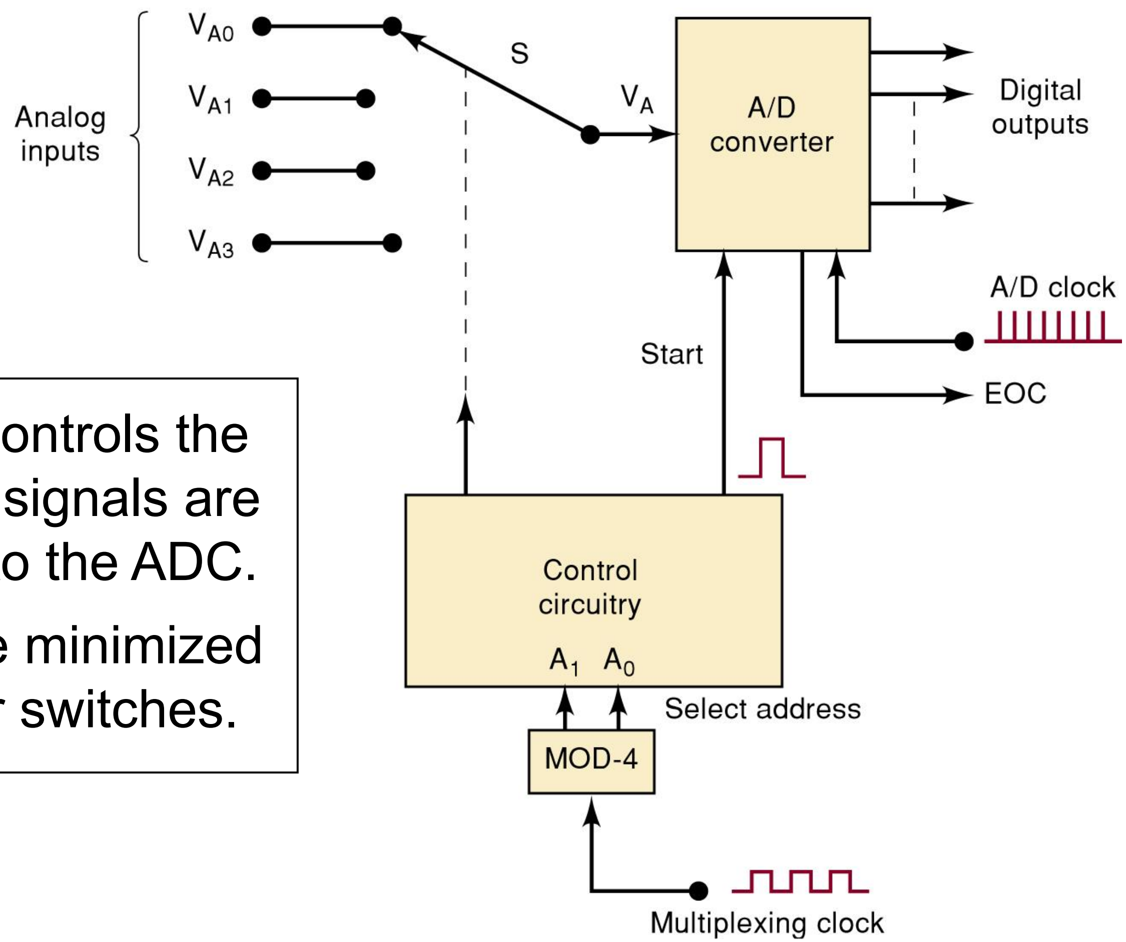
Simplified diagram of a sample-and-hold circuit.



11-16 Multiplexing

- When analog inputs from several sources are to be converted, a multiplexing technique can be used so that one ADC may be time-shared.

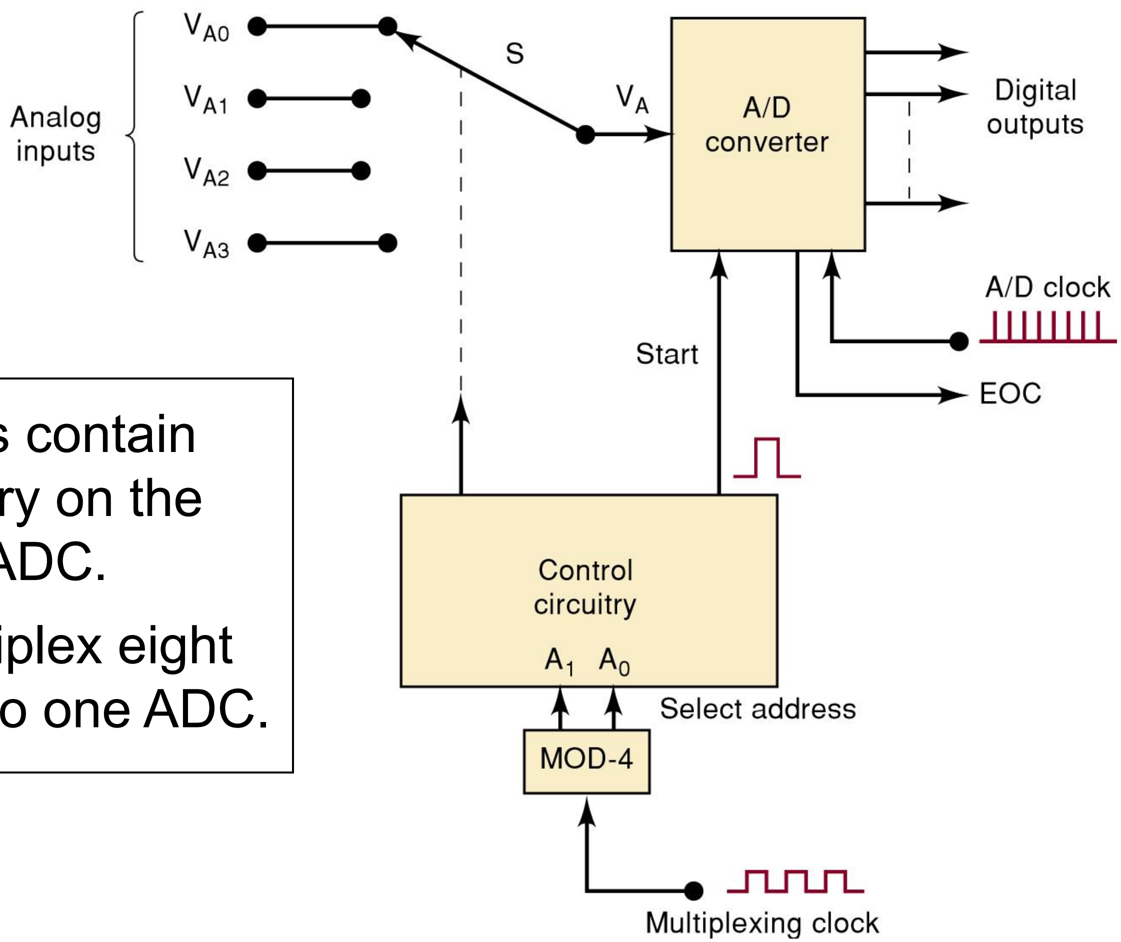
Conversion of four analog inputs by multiplexing through one ADC.



The multiplexing clock controls the rate at which the analog signals are sequentially switched into the ADC.

Switch delay time can be minimized by using semiconductor switches.

Conversion of four analog inputs by multiplexing through one ADC.



Many integrated ADCs contain the multiplexing circuitry on the same chip as the ADC.

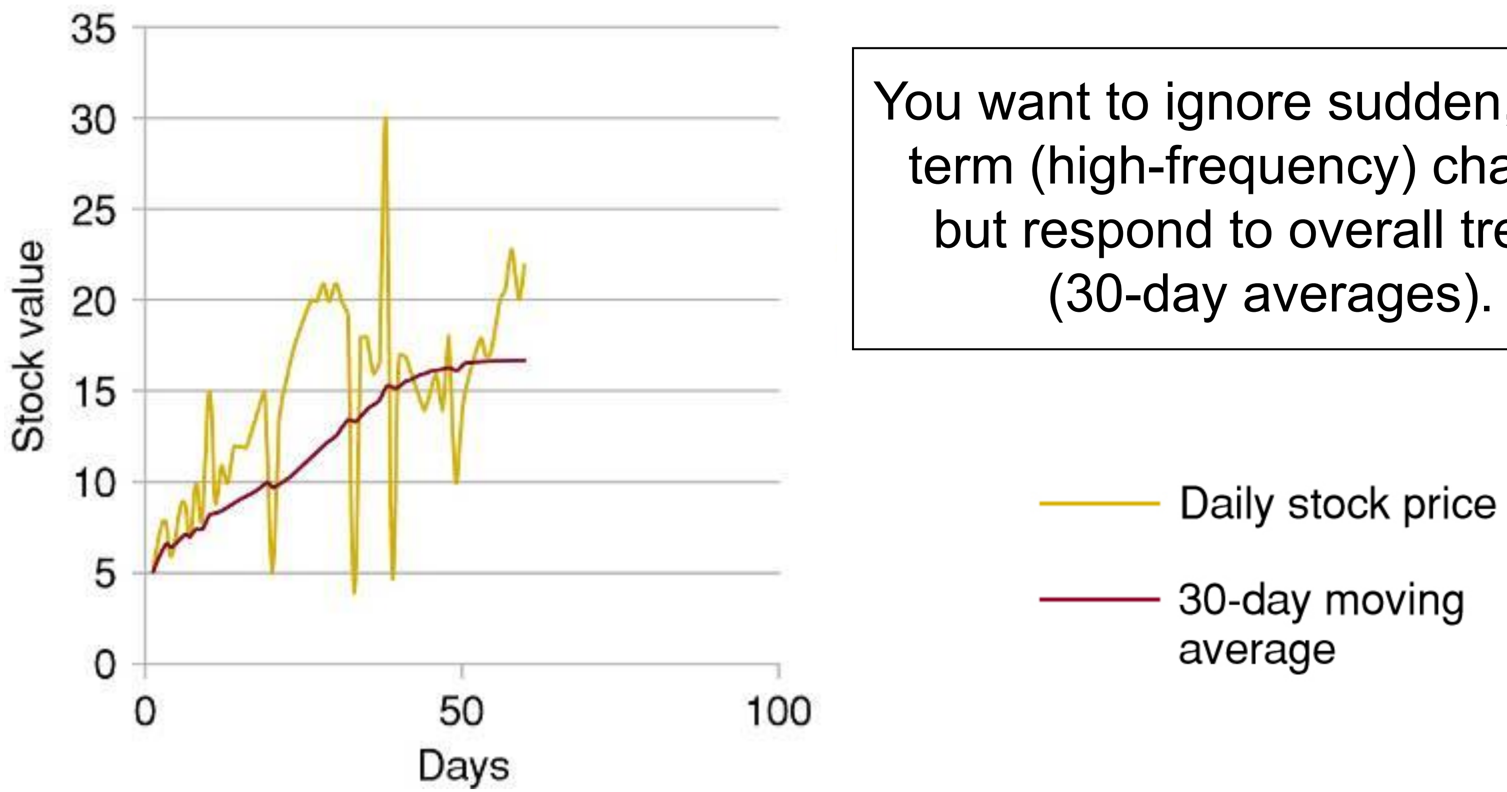
The ADC0808 can multiplex eight different analog inputs into one ADC.

11-17 Digital Signal Processing (DSP)

- A **digital signal processor (DSP)** is a very specialized form of microprocessor, optimized to perform repetitive calculations on streams of digitized data.
  - Digitized data are usually fed to the DSP from an A/D converter.
- A major application for DSP is filtering/conditioning of analog signals.
  - The advantage of DSP over resistors and capacitors is the flexibility of being able to change the critical frequency without switching any components.

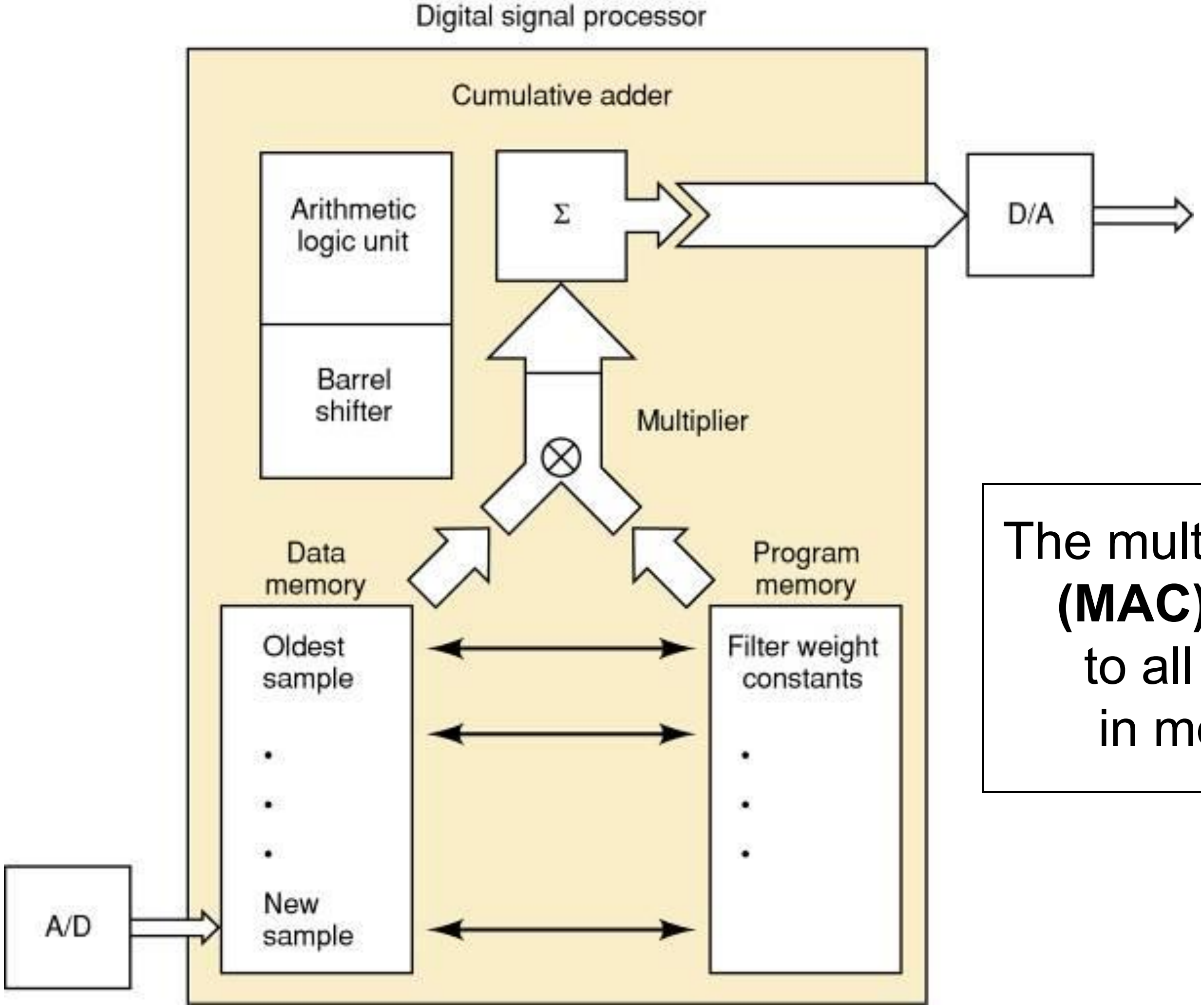
11-17 Digital Signal Processing (DSP)

- To understand digital filtering, consider the buying and selling of stock.
  - To decide when to buy and sell, you need to know what the market is doing.



You want to ignore sudden, short-term (high-frequency) changes but respond to overall trends (30-day averages).

The basic architecture of a DSP.



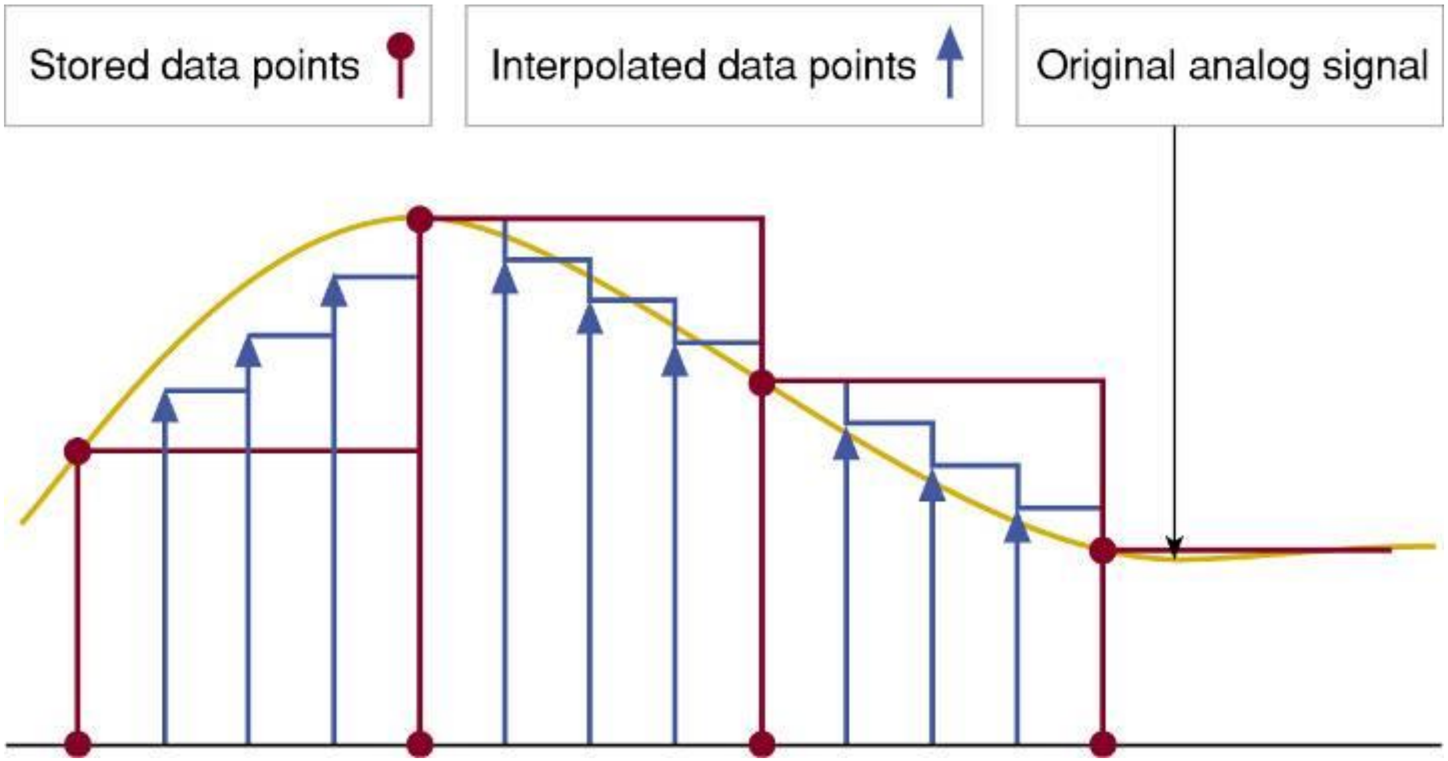
The multiply and accumulate **(MAC)** section is central to all DSPs, and used in most applications.

11-17 Digital Signal Processing (DSP)

- Digital filtering process—weighted average.
  - Read the newest sample.
  - Replace the oldest sample with the new one.
  - Multiply each of the 256 samples by corresponding weight constant.
  - Add all products.
  - Output the resulting sum of products to the D/A.

11-17 Digital Signal Processing (DSP)

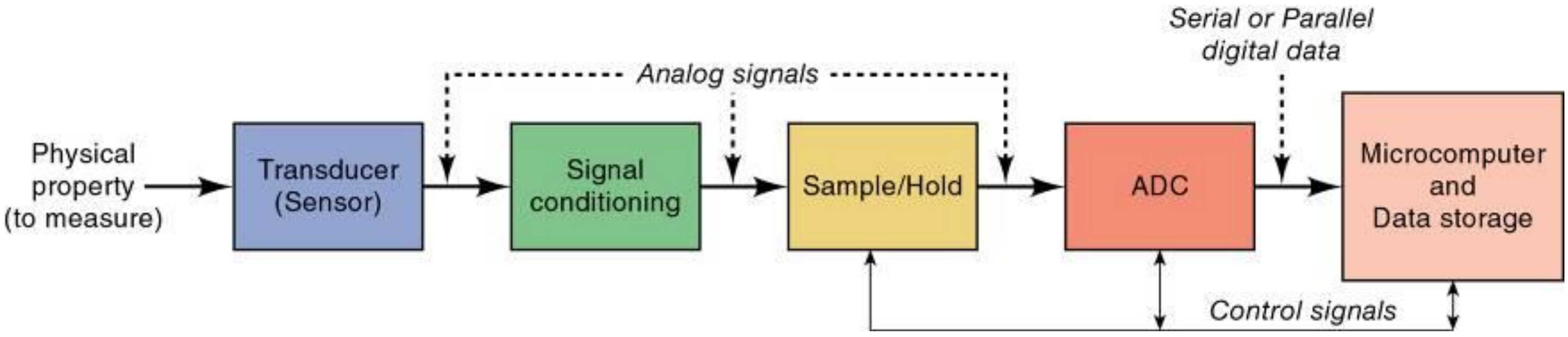
- Another useful application of DSP is called **oversampling or interpolation filtering**.
  – Inserting interpolated data points into a digital signal to reduce noise.



11-17 Digital Signal Processing (DSP)

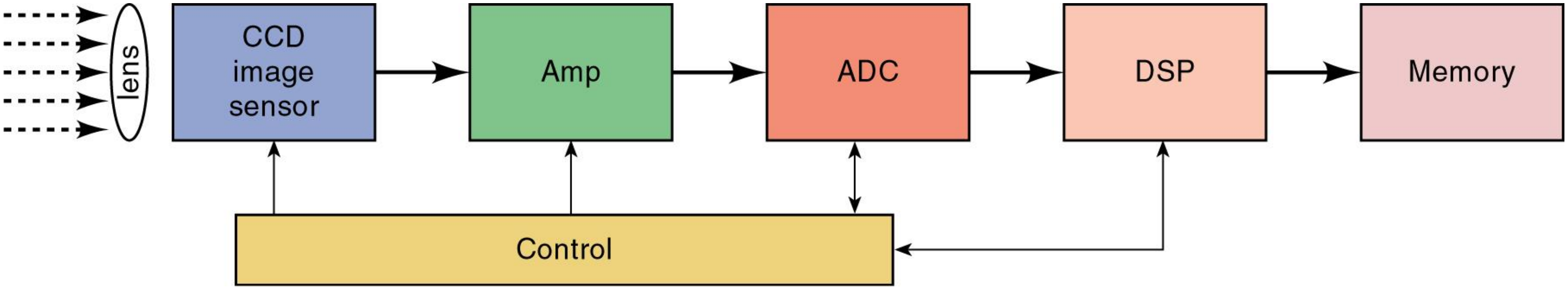
- DSP applications:
  - Filters in CD players to minimize quantization noise.
  - Echo canceling in telephone systems.
  - PC modems.
  - Musical instrument special effects.
  - Digital television.
  - Voice recognition.

Block diagram of a data acquisition system.



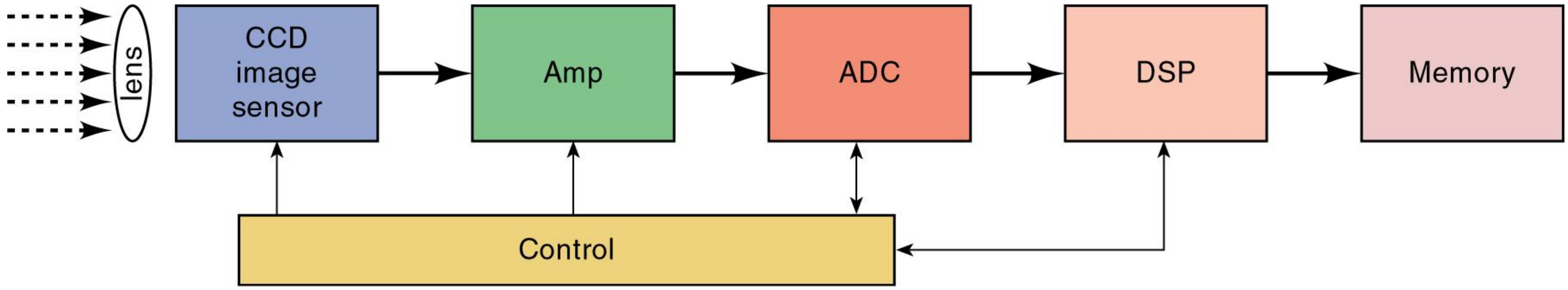
11-18 Applications of Analog Interfacing

- A familiar application that interfaces analog devices to a digital system is a digital camera.
  - Transducer typically a charge-coupled device (CCD).
- Analog signals are read out of the CCD by shifting the electric charges through successive capacitors under the control of drivers and timing circuits.
  - Amplified (signal conditioning) and then digitized by the ADC.



11-18 Applications of Analog Interfacing

- The DSP block applies image signal-processing algorithms to the digital data before storing the information in a memory device.
  - Data are usually compressed.
- **Data compression** is the process of encoding information with fewer bits representing the data.
  - Only works when both the sender and receiver of the information understand the specific encoding scheme.



END

ELEVENTH EDITION

Digital Systems

Principles and Applications

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