- **Analog-to-Digital Converters**
- Huang Sections 12.1-12.2
    - Review of MC9S12 PWM subsystem
    - Introduction to A/D Converters

Analog/Digital Converters

• An Analog-to-Digital (A/D) converter converts an analog voltage into a digital number

• There are a wide variety of methods used for A/D converters
Examples are:

– Flash (Parallel)
– Successive Approximation
– Sigma-Delta
– Dual Slope Converter

• A/D converters are classified according to several characteristics

– Resolution (number of bits) — **typically 8 bits to 24 bits**
– Speed (number of samples per second) — several samples/sec to several billion samples/sec
– Accuracy — how much error there is in the conversion.

• High-resolution converters are usually slower than low-resolution converters

• The MC9S12 has two 10-bit successive approximation A/D converters (which can be used in 8-bit mode)

• The MC9S12 uses an analog multiplexer to allow eight input pins to connect to any of the A/D converters.

Comparator

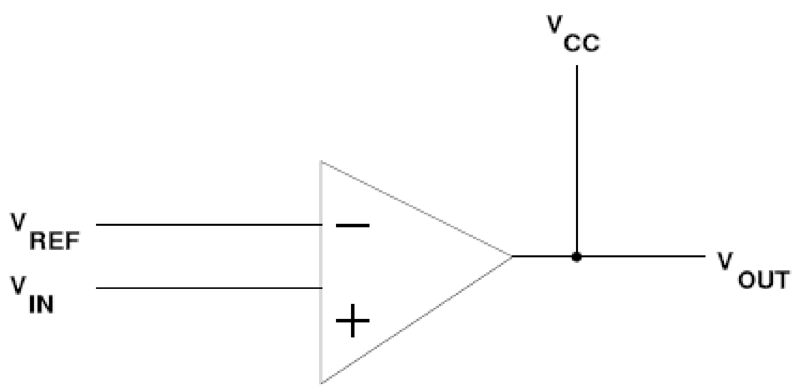
- A comparator is used in many types of A/D converters.

- A comparator is the simplest interface from an analog signal to a digital signal

- A comparator compares two voltage values on its two inputs

- If the voltage on the + input is greater than the voltage on the - input, the output will be a logic high

- If the voltage on the + input is less than the voltage on the - input, the output will be a logic low.



If Vin > Vref then Vout = Vcc

If Vin < Vref then Vout = 0

Flash (Parallel) A/D Converter

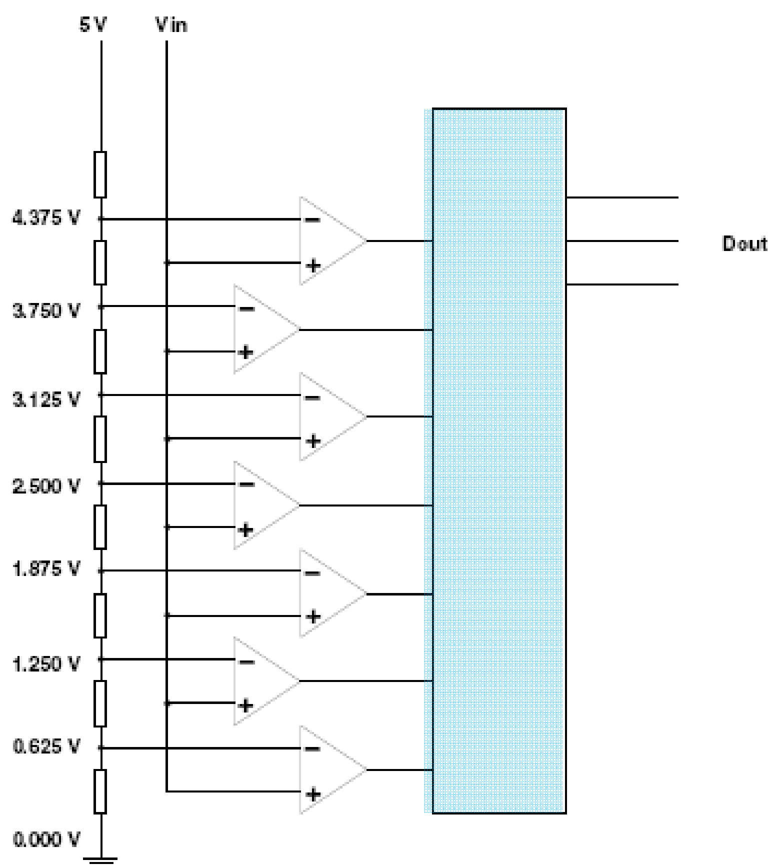
• A flash A/D converter is the simplest to understand

• A flash A/D converter compares an input voltage to a large number of reference voltages

• An n-bit flash converter uses 2^n-1 comparators

• The output of the A/D converter is determined by which of the two reference voltages the input signal is between,

• Here is a 3-bit A/D converter



Flash (Parallel) A/D Converter

- A B-bit Flash A/D converter **requires 2^B-1 comparators**
- An 8-bit Flash A/D requires 255 comparators
- A 12-bit Flash A/D converter would require <u>4,095 comparators!</u>
  – Cannot integrate 4,095 comparators onto an IC
- Such A/D are available in IC form up to 8-bit and 10-bit
- Flash A/D converters can sample at several billion samples/sec

A/D Converter Resolution and Quantization

• If the voltage input voltage is 3.2516 V, the lowest 5 comparators will be turned on, and the highest 2 comparators will be turned off

• The output of the 3-bit flash A/D converter will be 5 (101)

• For a 3-bit A/D converter, which has a range from 0 to 5 V, an output of 5 indicates that the input voltage is between 3.125 V and 3.750 V

• A 3-bit A/D converter with a 5 V input range has a quantization value of 0.625 V

• The quantization value of an A/D converter can be found by

$$\Delta V = (V_{RH} - V_{RL})/2^b$$

where V_{RH} is the highest voltage the A/D converter can handle, V_{RL} is the lowest voltage the A/D converter can handle, and b is the number of bits of the A/D converter

• The HC12 has a 10-bit A/D converter. The typical voltage range used for the HC12 A/D is V_{RH} = 5 V and V_{RL} = 0 V, so the HC12 has a quantization value of

$$\Delta V = (5\text{ V} - 0\text{ V})/2^{10} = 4.88\text{ mV}$$

• The dynamic range of an A/D converter is given in decibels (dB):

$$DR(dB) = 20 \log 2^b = 20\, b \log 2 = 6.02b$$

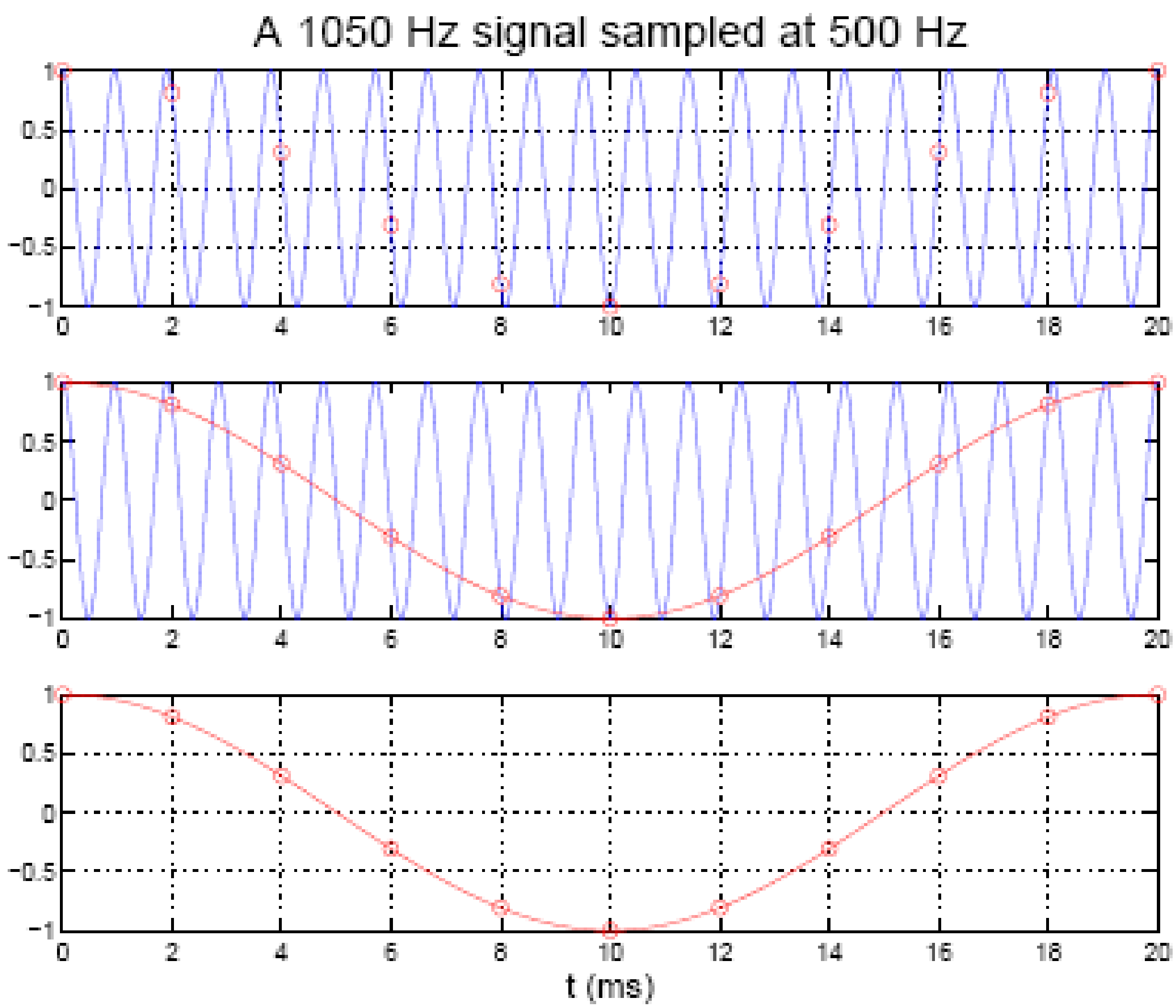
• A 10-bit A/D converter has a dynamic range of

$$DR(dB) = 6.02 \times 10 = 60.2\text{ dB}$$

A/D Sampling Rate

• The rate at which you sample a signal depends on how rapidly the signal is changing

• If you sample a signal too slowly, the information about the signal may be inaccurate.



• A 1,050 Hz signal sampled at 500 Hz looks like a 50 Hz signal

• To get full information about a signal you must sample more than twice the highest frequency in the signal

• Practical systems typically use a sampling rate of at least four times the highest frequency in the signal

Digital-to-Analog (D/A) Converters

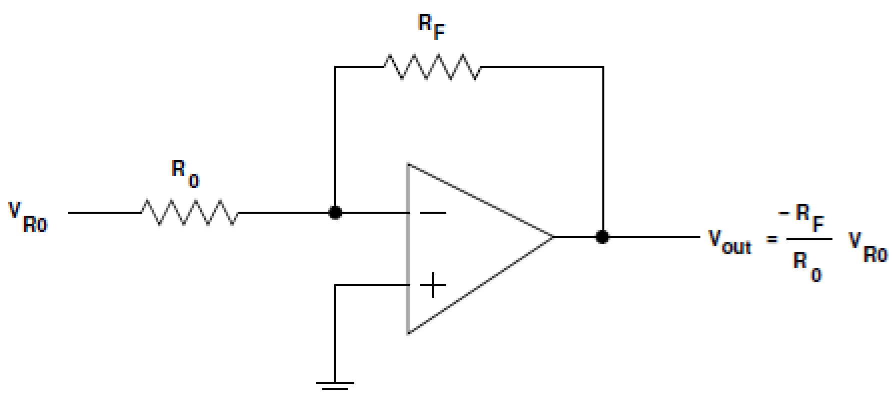
• Many A/D converters use a D/A converter internally

• A D/A converter converts a digital signal to an analog voltage or current

• To understand how most A/D converters work, it is necessary to understand D/A converters

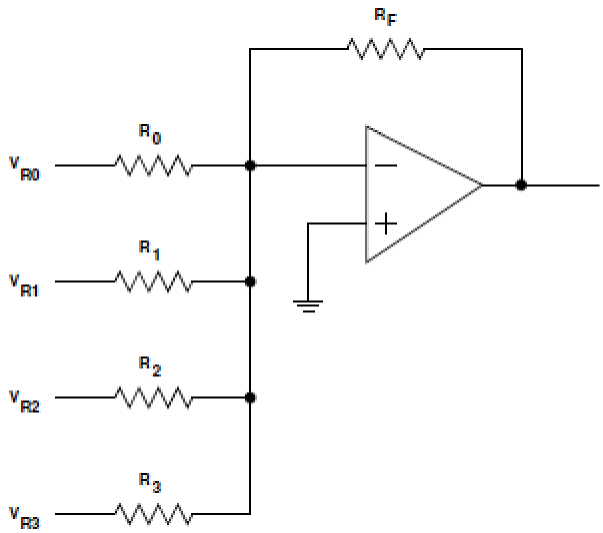
• The heart of a D/A converter is an inverting op amp circuit

• The output voltage of an inverting op amp circuit is proportional to the input voltage:



Digital-to-Analog (D/A) Converters

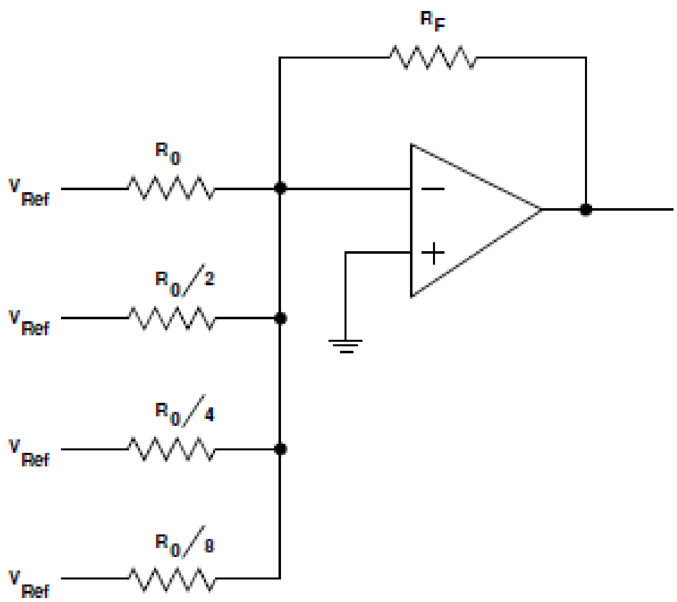
• An inverting op amp can produce an output voltage which is a linear combination of several input voltages



$$V_{out} = \frac{-R_F}{R_0} V_{R0} - \frac{R_F}{R_1} V_{R1} - \frac{R_F}{R_2} V_{R2} - \frac{R_F}{R_3} V_{R3}$$

Digital-to-Analog (D/A) Converters

• By using input resistors which scale by factors of 2, a summing op amp can produce an output which follows a binary pattern



$$V_{out} = \frac{-R_F}{R_0} V_{Ref} - \frac{2R_F}{R_0} V_{Ref} - \frac{4R_F}{R_0} V_{Ref} - \frac{8R_F}{R_0} V_{Ref}$$

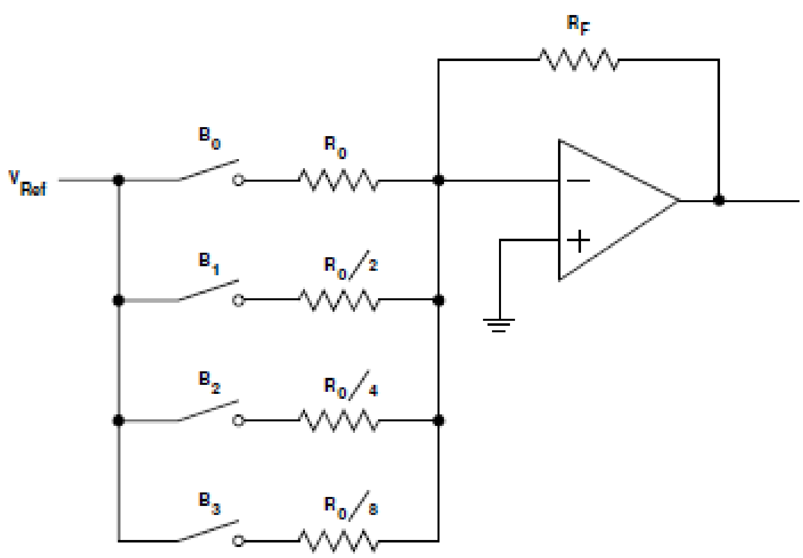
$$= \frac{-R_F}{R_0}\left[V_{Ref} + 2V_{Ref} + 4V_{Ref} + 8V_{Ref}\right]$$

$$= \frac{-R_F}{R_0} V_{Ref}\left[1 + 2 + 4 + 8\right]$$

Digital-to-Analog (D/A) Converters

• By using switches on the input resistors, a summing op amp can produce an output which is a binary number (representing which switches are closed) times a reference voltage

4–Bit Digital–to–Analog Converter



$$V_{out} = \frac{-R_F}{R_0} V_{Ref} \left[B_0 + 2B_1 + 4B_2 + 8B_3 \right]$$

$$= \frac{-R_F}{R_0} V_{Ref} \; B$$

$$B = B_3 B_2 B_1 B_0$$

Slope A/D Converter

• A simple A/D converter can be constructed with a counter and a D/A converter

• The counter counts from **0 to 2^b-1**

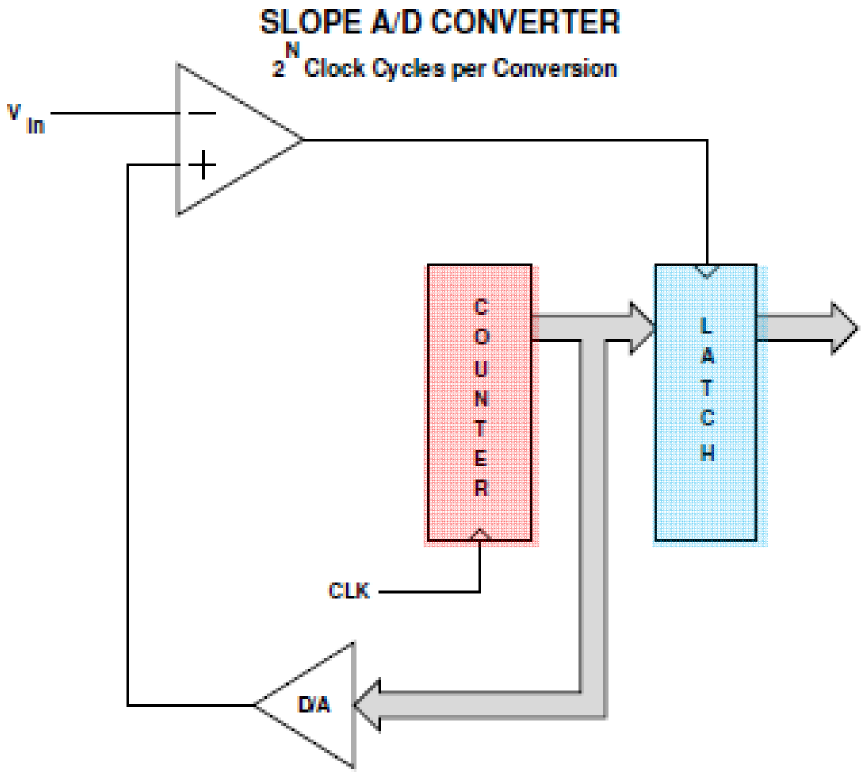
• The counter drives the input of the D/A converter

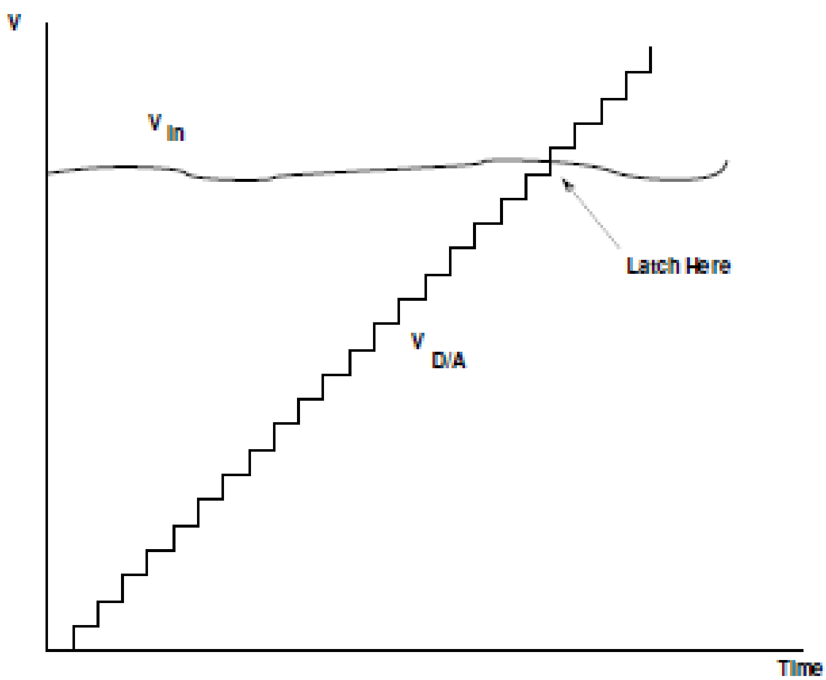
• The output of the D/A converter is compared to the input voltage

• When the output of the comparator switches logic level, the generated voltage passed the input voltage

• By latching the output of the counter at this time, the input voltage can be determined (with the accuracy of the quantization value of the converter)

• **Problem** with Slope A/D converter: <u>Could take 2^b clock cycles to test possible values of reference voltages</u>


SLOPE A/D CONVERTER
2^N Clock Cycles per Conversion
V In
COUNTER
LATCH
CLK
D/A


V
V In
Latch Here
V D/A
Time

Successive Approximation A/D Converter

• A successive approximation (SA) A/D converter **uses an intelligent scheme** to determine the input voltage

• It first tries a voltage half way between V_{RH} and V_{RL}

• It determines if the signal is in the **lower half** or the **upper half** of the voltage range

– If the input is in the upper half of the range, it sets the most significant bit of the output
– If the input is in the lower half of the range, it clears the most significant bit of the output

• The first clock cycle eliminates half of the possible values

• On the next clock cycle, the SA A/D tries a voltage in the middle of the remaining possible values

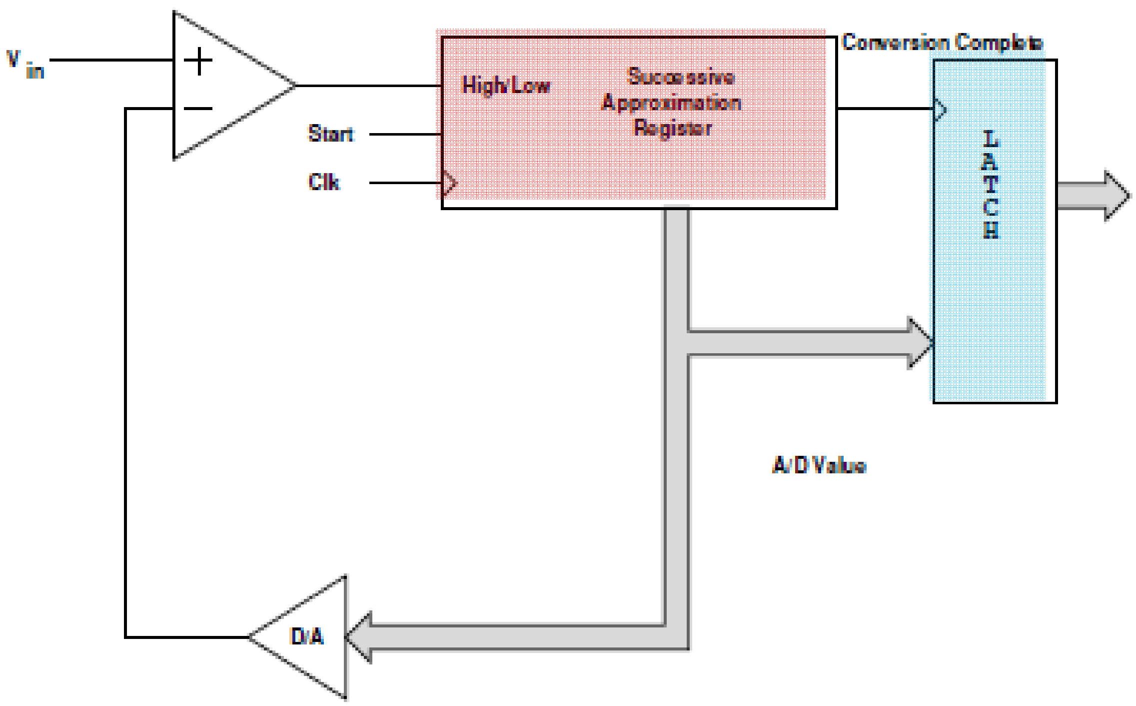
• The second clock cycle allows the SA A/D to determine the second most significant bit of the result

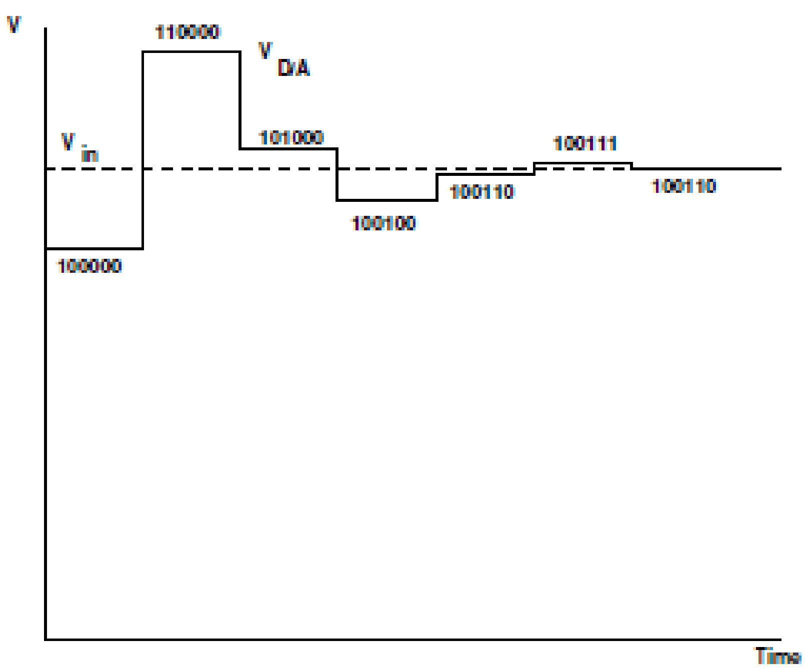
• <u>Each successive clock cycle reduces the range another factor of two</u>

• For a B-bit SA A/D converter, it takes B clock cycles to determine the value of the input voltage

SUCCESSIVE APPROXIMATION A/D CONVERTER

N Clock Cycles per Conversion





Successive Approximation A/D Converter

• An SA A/D converter can give the wrong output if the voltage changes during a conversion

• An SA A/D converter **needs an input buffer** which holds the input voltage constant during the conversion

• This input buffer is called a **Track/Hold** or **Sample/Hold** circuit

• It usually works by charging a capacitor to the input voltage, then disconnecting the capacitor from the input voltage during conversion

• The voltage on the capacitor remains constant during conversion

• The HC12 has a Track/Hold amplifier built in

• SA A/D converters have resolutions of up to 16 bits

• SA A/D converters have speeds up to several million samples per second

SUCCESSIVE APPROXIMATION A/D CONVERTER