# Lecture 22

March 9, 2012

## Analog/Digital Converters

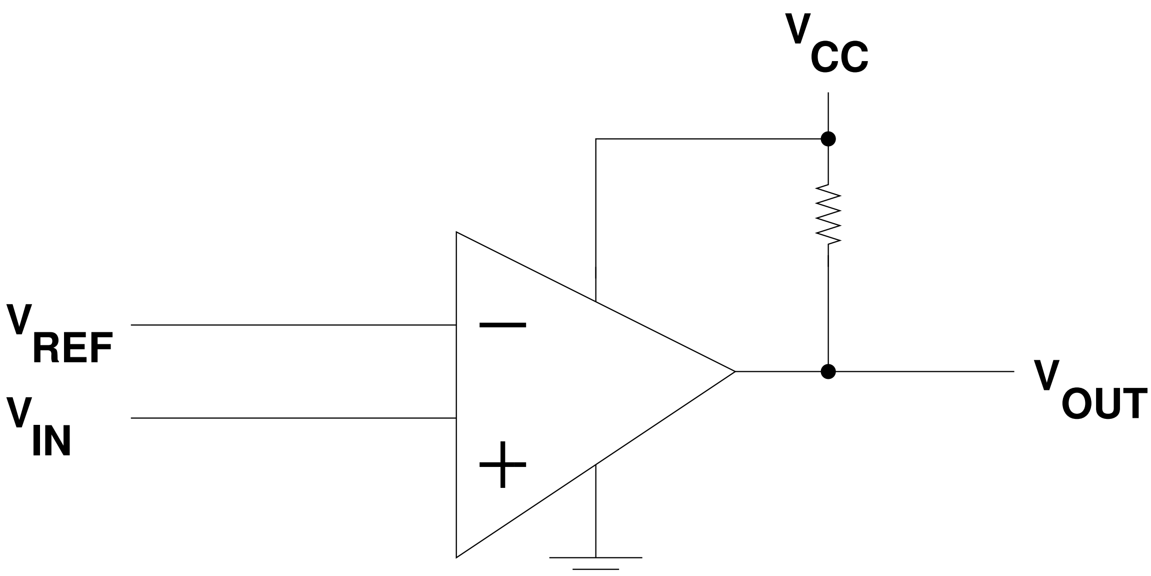
- Introduction to A/D Converters
- The Analog Comparator
- The Flash A/D Converter
- A/D Converter Resolution and Quantization
- A/D Sampling Rates – Nyquist Theorem
- D/A Converters
- Slope A/D Converters
- Successive Approximation A/D Converters

## 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 a 10-bit charge redistribution successive approximation A/D converter (which can be used in 8-bit mode for faster conversions)
- The MC9S12 uses an analog multiplexer to allow eight input pins to connect to the A/D converter

### 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

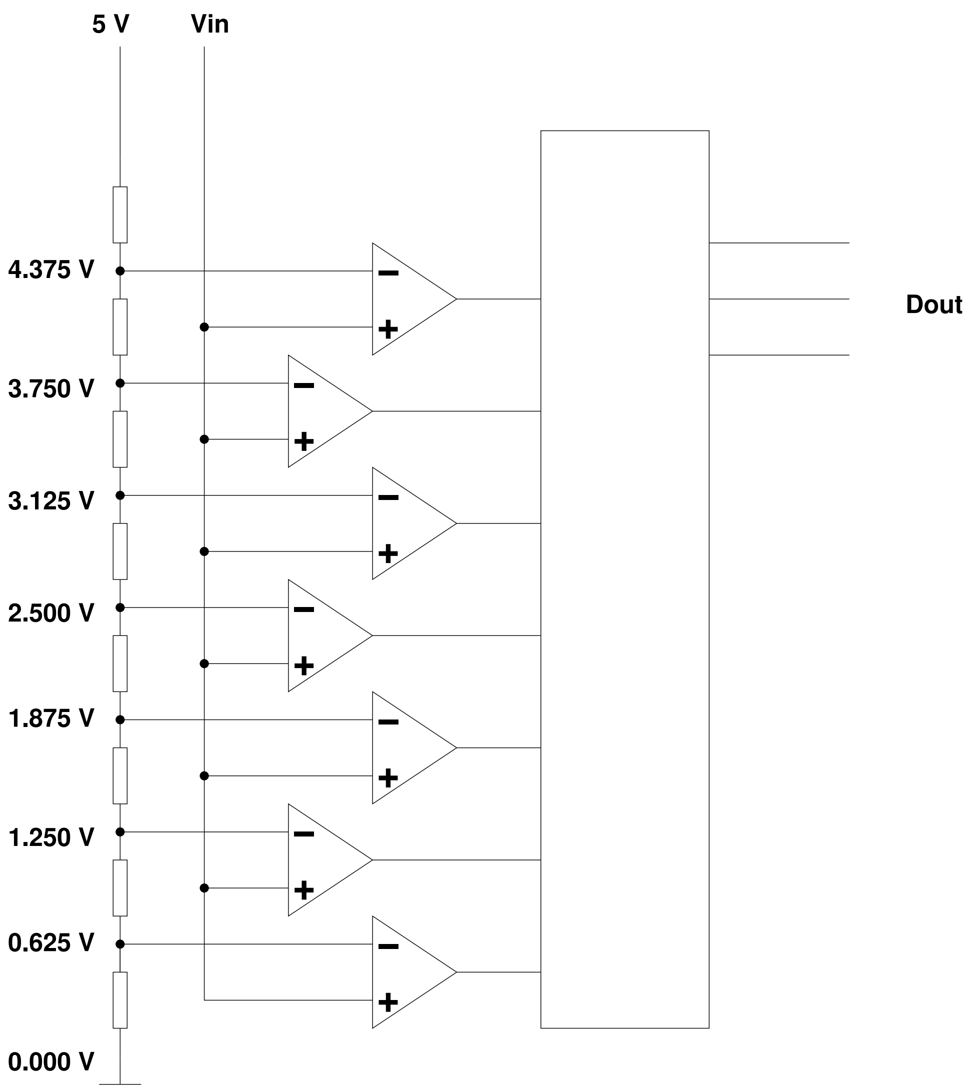



**If Vin > Vref then Vout = Vcc**

**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 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 4,095 comparators
  - Hard to integrate 4,095 comparators onto an IC
- The largest flash A/D converter is 8 bits
- 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

  $$\Delta V = \frac{V_{RH} - V_{RL}}{2^b}$$

  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 MC9S12 has a 10-bit A/D converter. The typical voltage range used for the MC9S12 A/D is $V_{RH} = 5$ V and $V_{RL} = 0$ V, so the MC9S12 has a quantization value of

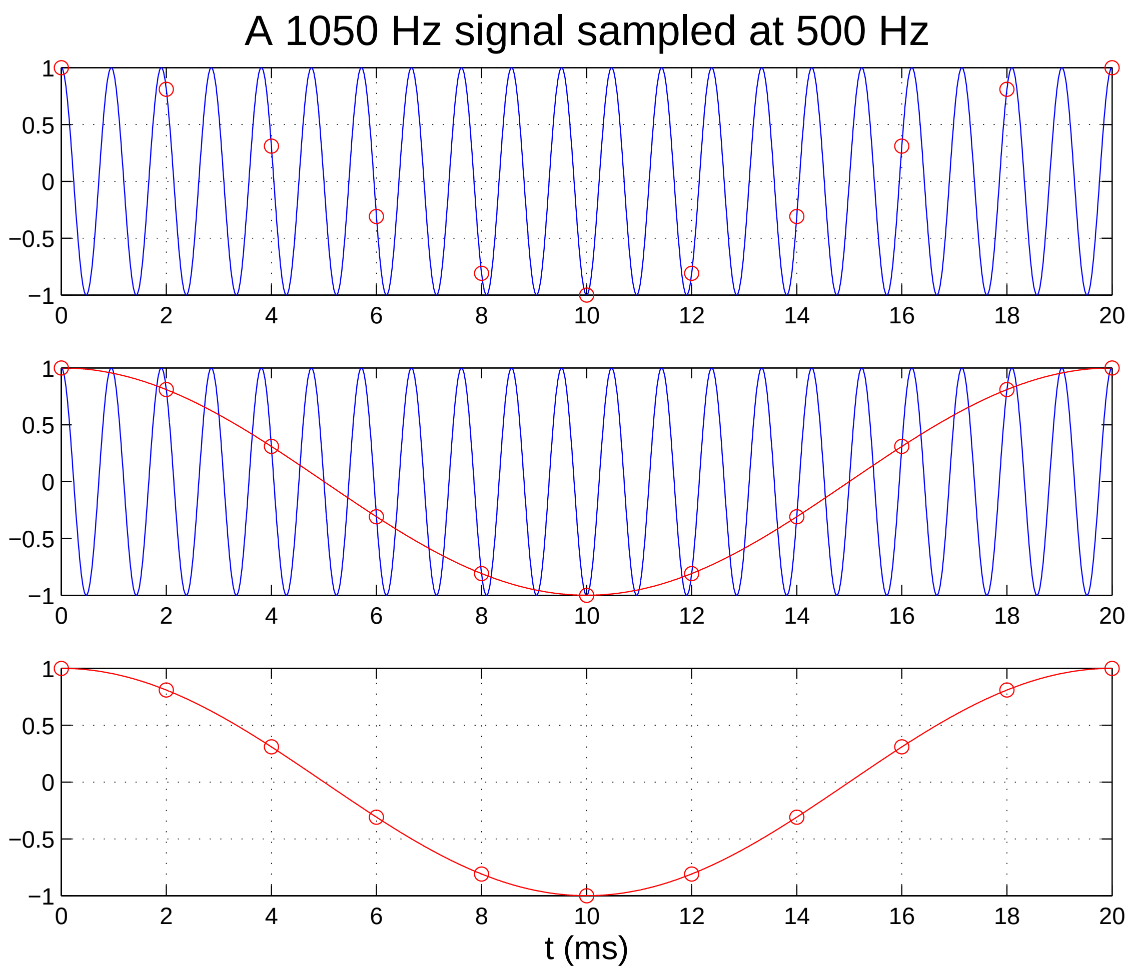
  $$\Delta V = \frac{5\text{ V} - 0\text{ V}}{2^{10}} = 4.88\text{ mV}$$
- The dynamic range of an A/D converter is given in decibels (dB):

  $$DR(\text{dB}) = 20\log 2^b = 20blog2 = 6.02b$$
- A 10-bit A/D converter has a dynamic range of

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

## A/D Sampling Rate

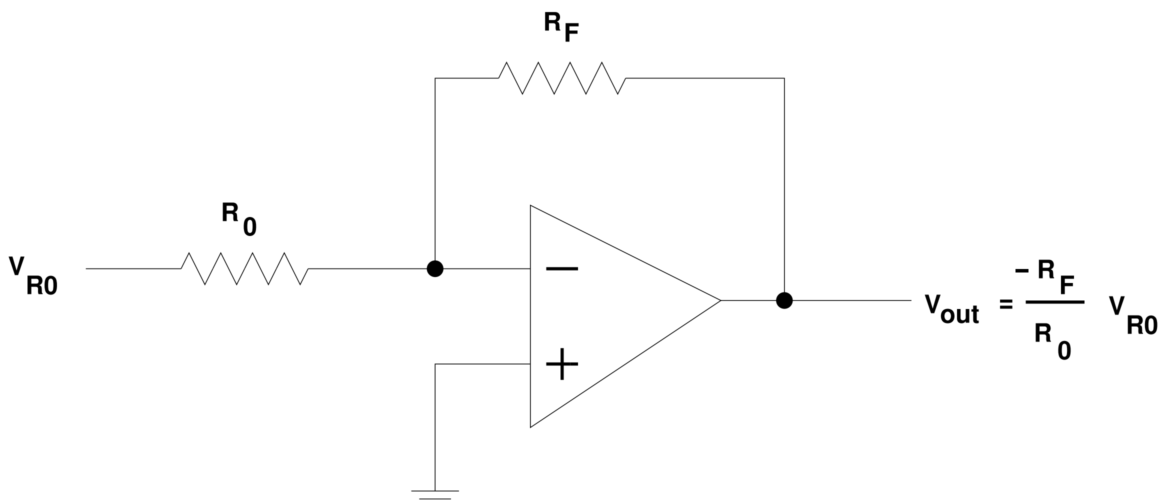
- The rate at which you sample a signal depends on how rapidly the signal is changing
- If you sample a signal too slowly, the information about the signal may be inaccurate


A 1050 Hz signal sampled at 500 Hz
1
0.5
0
−0.5
−1
0 2 4 6 8 10 12 14 16 18 20
t (ms)

- 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
  - This is called the Nyquist theorem
- Practical systems typically use a sampling rate of at least four times the highest frequency in the signal

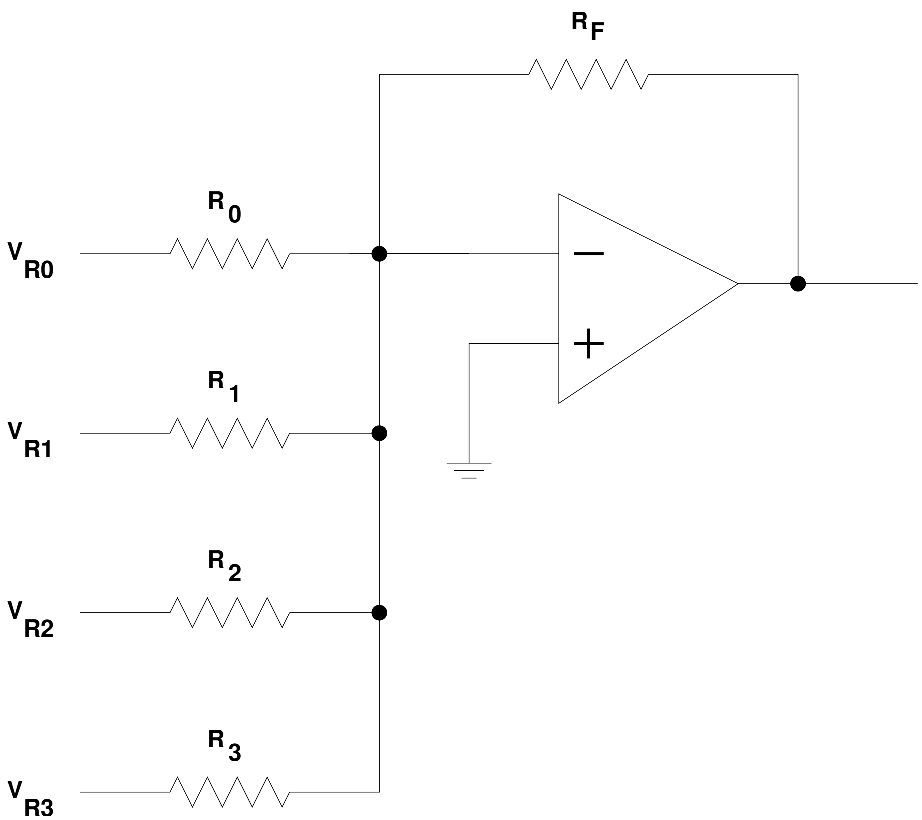
## Digital-to-Analog (D/A) Converters

- 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

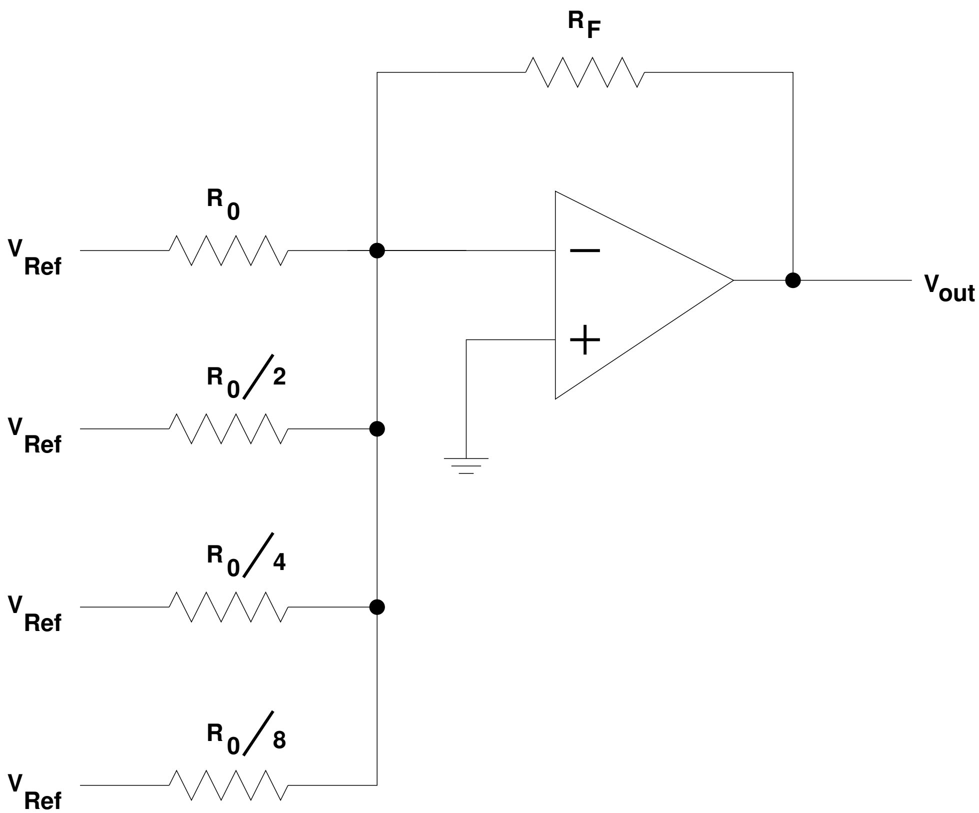
- An inverting op amp can produce an output voltage which is a linear combination of several input voltages




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

## 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




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

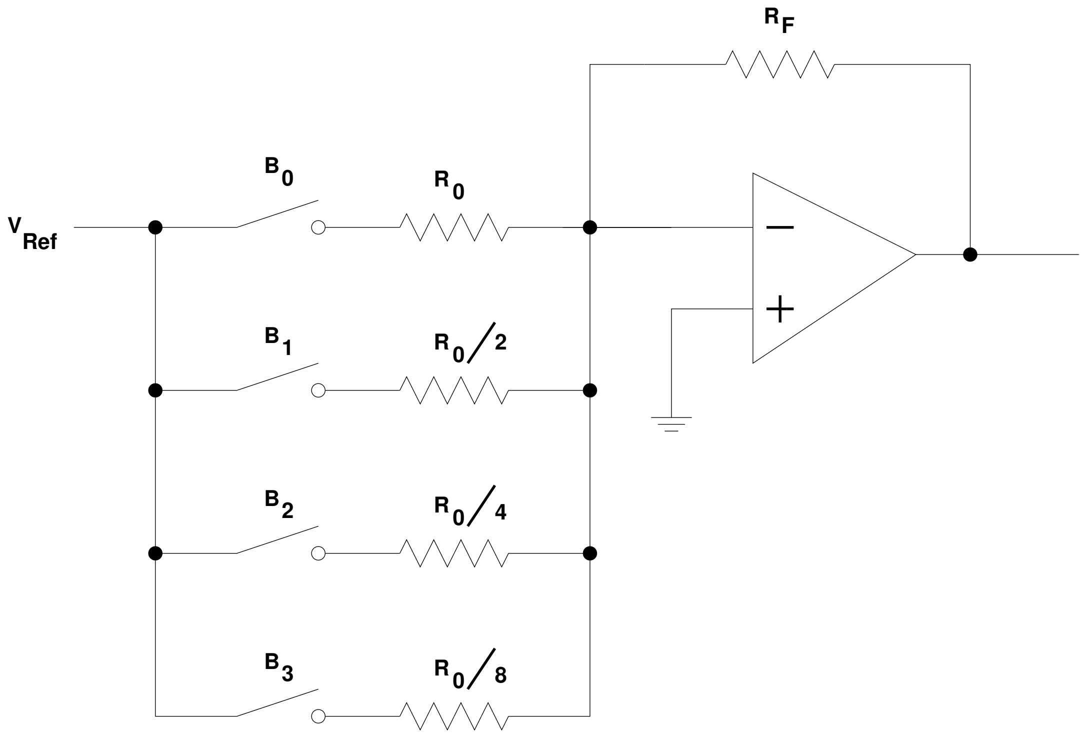
$$= \frac{-R_F}{R_0} \left[ V_{Ref} + 2V_{Ref} + 4V_{Ref} + 8V_{Ref} \right]$$

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

# 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**



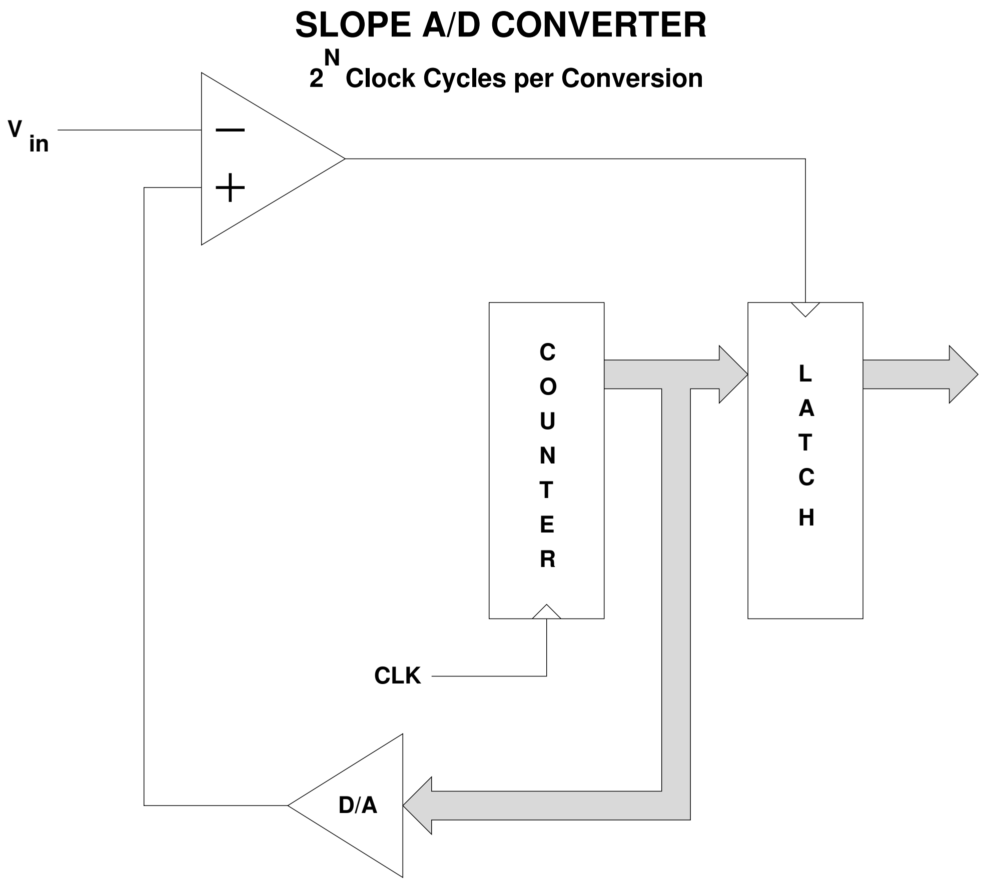

$$V_{out} = \frac{-R_F}{R_0} V_{Ref} \left[ B_0 + 2B_1 + 4B_2 + 8B_3 \right]$$

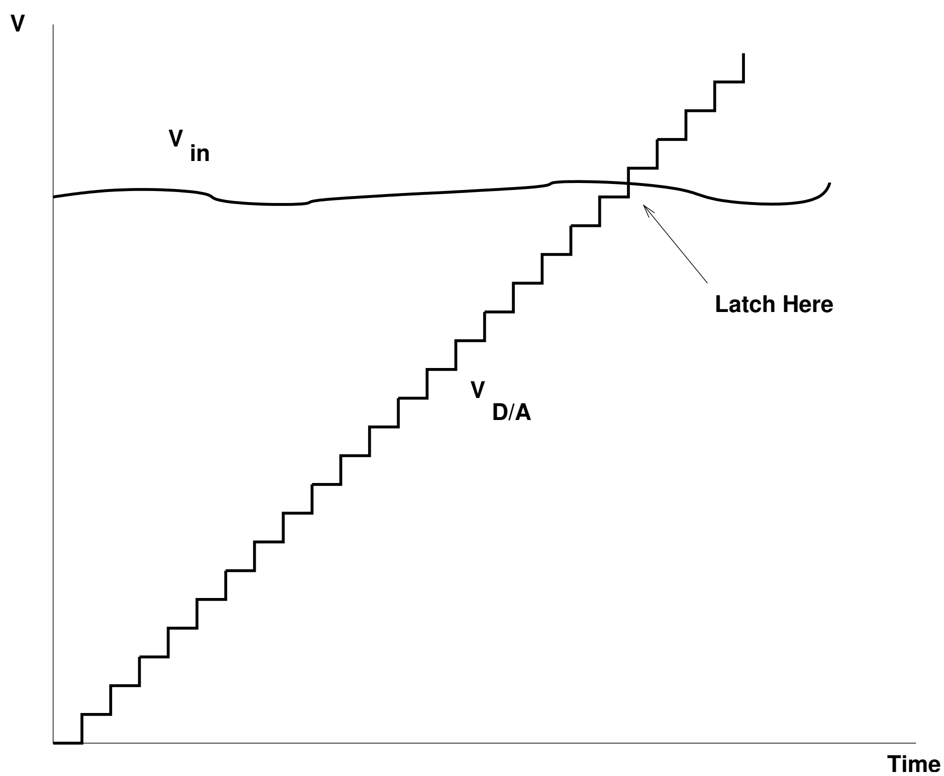
$$= \frac{-R_F}{R_0} V_{Ref} \; \mathbf{B}$$

$$\mathbf{B} = B_3 B_2 B_1 B_0$$

## 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: Takes $2^b$ clock cycles to test all possible values of reference voltages


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

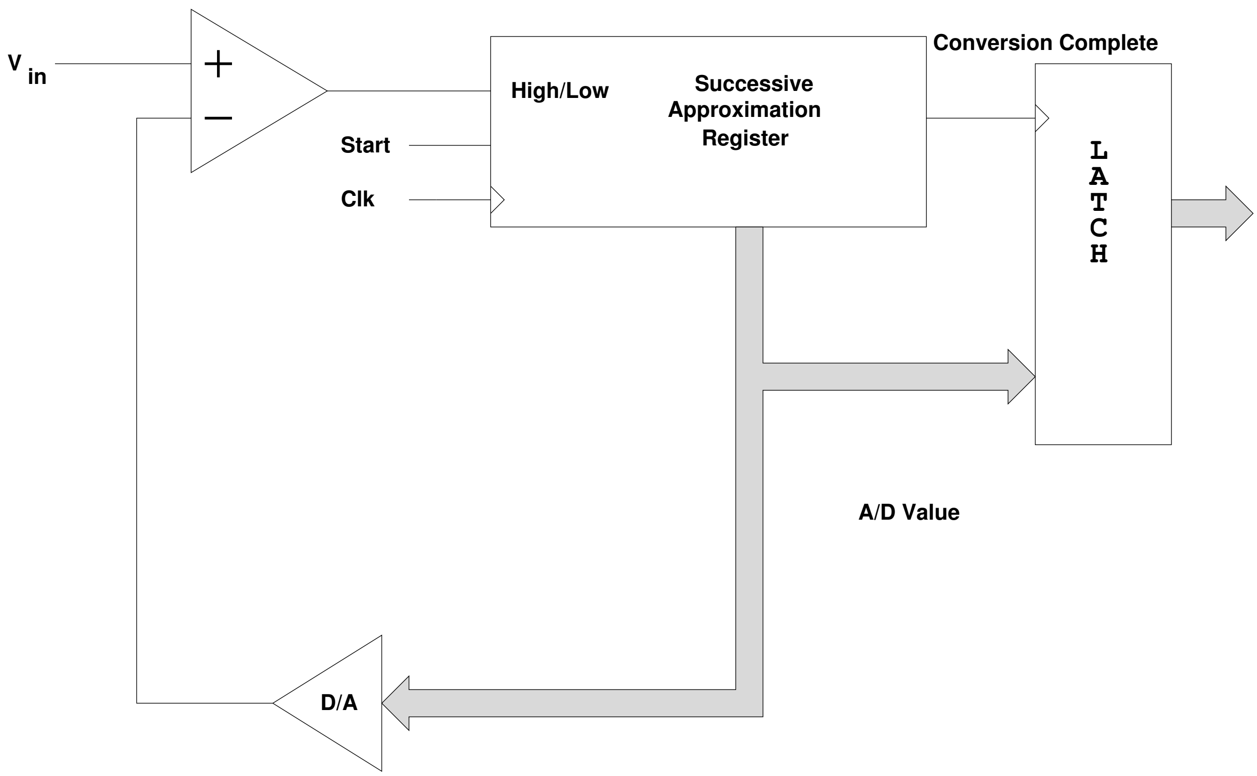

V
V in
Latch Here
V D/A
Time

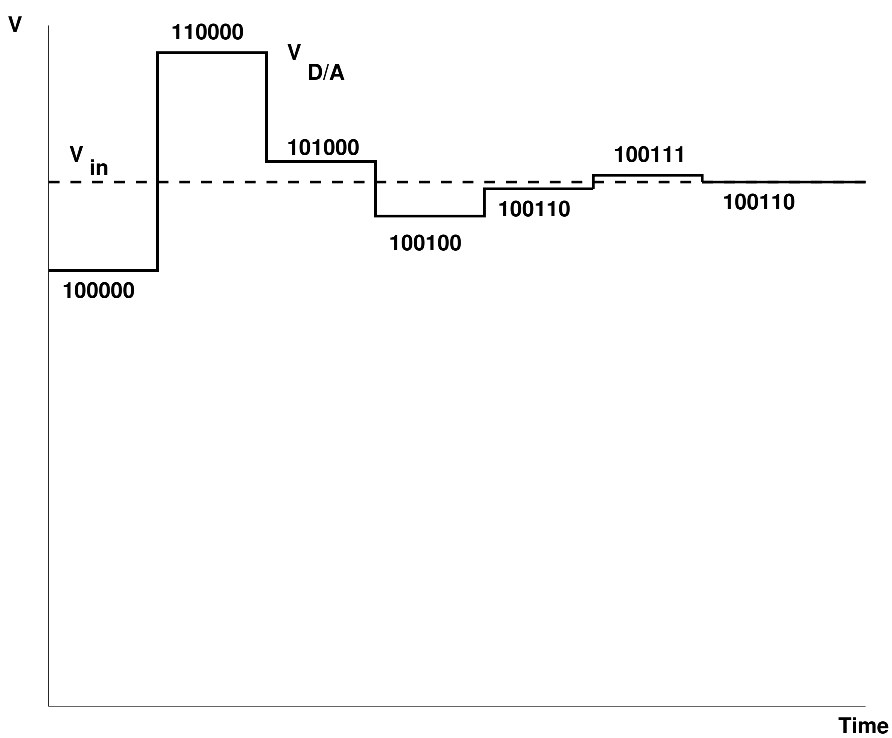
## Successive Approximation A/D Converter

- 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
- Each successive clock cycle reduces the range another factor of two
- 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 MC9S12 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