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 HC12 has a 10-bit successive approximation A/D converter (which can be used in 8-bit mode)
- The HC12 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.

\[
\text{If } V_{\text{in}} > V_{\text{ref}} \text{ then } V_{\text{out}} = V_{\text{cc}}
\]

\[
\text{If } V_{\text{in}} < V_{\text{ref}} \text{ then } V_{\text{out}} = 0
\]
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

![3-bit A/D converter diagram]
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
  - Cannot 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 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 \(\Delta V = \frac{5\ V - 0\ V}{2^{10}} = 4.88\) mV.
- The dynamic range of an A/D converter is given in decibels (dB):
  \[
  DR(\text{dB}) = 20 \log 2^b = 20 \log 2 = 6.02b
  \]
- 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

- 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:

\[
V_{\text{out}} = \frac{-R_F}{R_0} V_{R0}
\]
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.

\[
V_{\text{out}} = \frac{-R_F}{R_0} V_{\text{Ref}} - \frac{2R_F}{R_0} V_{\text{Ref}} + \frac{4R_F}{R_0} V_{\text{Ref}} - \frac{8R_F}{R_0} V_{\text{Ref}}
\]

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

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

\[
\begin{align*}
V_{\text{out}} &= -\frac{R_F}{R_0} V_{\text{ref}} \left[ B_0 + 2B_1 + 4B_2 + 8B_3 \right] \\
B &= B_3 B_2 B_1 B_0
\end{align*}
\]
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

Diagram of a slope A/D converter with a clock (CLK), counter, latch, and voltage inputs and outputs (V_in, V_D/A). The diagram illustrates the conversion process over time (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 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.
SUCCESSION APPROXIMATION A/D CONVERTER

V_in → Track/Hold

+ → Start

- → Clk

D/A

Track/Hold

High/Low

Successive Approximation Register

Conversion Complete

LATCH

A/D Value

D/A

V

V_in

110000

101000

100110

100111

100110

100100

100110

100110

Time