NANYANG TECHNOLOGICAL UNIVERSITY

MA2011 MECHATRONICS SYSTEMS INTERFACING

Lecture 6

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RECAP OF LECTURE 5

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- Vacuum Tube Technology Vs Solid State Technology
- Ideal Operational Amplifier
- Various Amplifier Designs

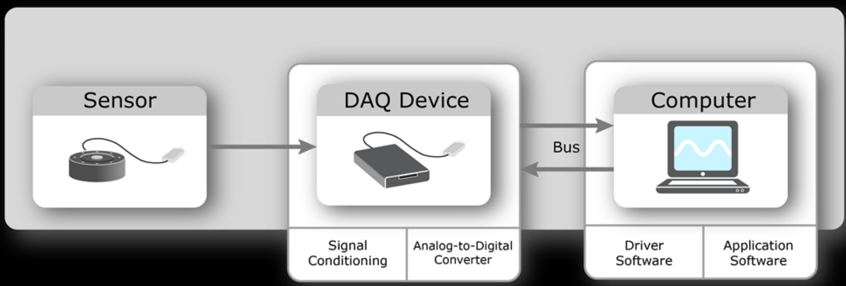
PART 6: A / D CONVERSION

PART 6.1 DATA ACQUISITION DEVICES

DATA ACQUISITION DEVICES

DATA ACQUISITION DEVICES

Data acquisition (DAQ) products with sensors



DATA ACQUISITION DEVICES

DAQ products with sensors

Sensor	DAQ device	Computer Bus	Computer	Driver Software
Application Software	Data Storage Format	Analysis Tools	Visualisation Tools	Reporting Tools

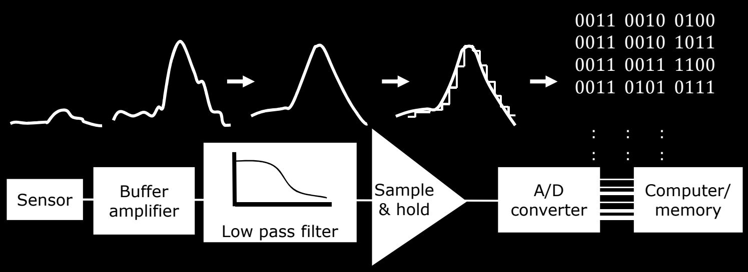
DATA ACQUISITION DEVICES

DAQ products with sensors

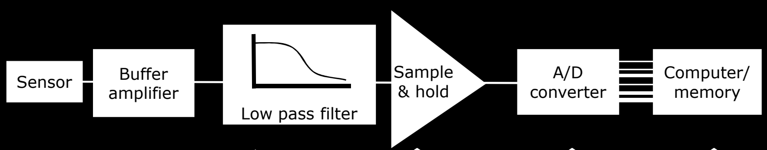
Sensor	Phenomenon
Thermocouple, Thermistor	Temperature
Photo Sensor	Light
Microphone	Sound
Strain Gage, Piezoelectric Transducer	Force and Pressure
Potentiometer, Optical Encoder	Position and Displacement
Accelerometer	Acceleration
pH Electrode	pH

PART 6.2 A/D CONVERSION

A / D CONVERSION



A / D CONVERSION



Buffer amplifier
- Isolates the output from the input
- Provides a signal in a range close to but not exceeding the full input voltage range of the A/D converter

Low pass filter
- Necessary to remove any undesirable high-frequency components in the signal that could produce aliasing
- The cut-off frequency of the low-pass filter <0.5 sampling rate

Sample & hold
- This amplifier maintains a fixed input value (from an instantaneous sample) during the short conversion time of the A/D converter

A/D converter
- The converter should have a resolution and analog quantisation size appropriate to the system and signal

Computer/memory
- The computer must be properly interfaced to the A/D converter system to store and process the data
- To have sufficient memory & storage

WHAT IS ANALOG TO DIGITAL CONVERSION?

- An electronic integrated circuit which transforms a signal from analog (continuous) to digital (discrete) form.
- Analog signals are directly measurable quantities.
- Digital signals only have two states. For digital computer, we refer to binary states: 0 and 1.

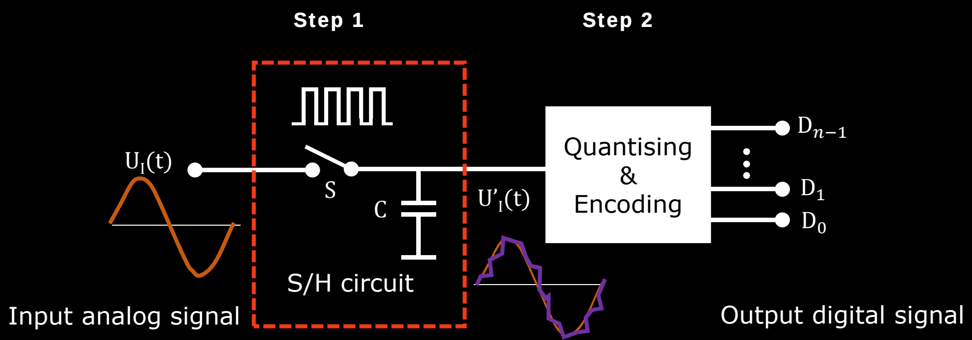
WHY WE NEED ANALOG TO DIGITAL CONVERSION?

- Microprocessors can only perform complex processing on digitised signals.
- When signals are in digital form, they are less susceptible to the deleterious effects of additive noise.
- ADC provides a link between the analog world of transducers and the digital world of signal processing and data handling.

A/D CONVERSION PROCESS (TYPICALLY 2 STEPS)

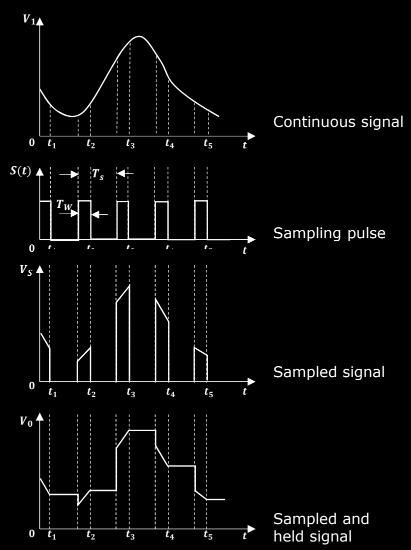
Step 1: Sampling and holding (S/H)

Step 2: Quantising and encoding (Q/E)



SAMPLING AND HOLDING

- Holding signal benefits the accuracy of the A/D conversion.
- Minimum sampling rate should be at least twice the highest data frequency of the analog signal.



QUANTISING AND ENCODING

- The smallest change in analog signal that will result in a change in the digital output.

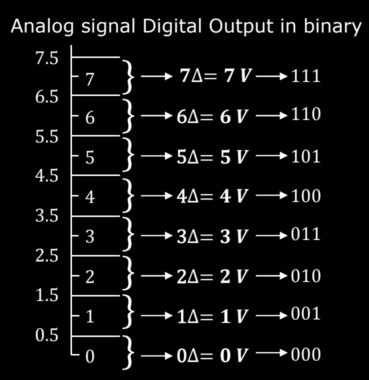
  $\Delta V = V_{ref} / 2^n$
  - o ΔV: Resolution
  - o n: Number of bits in digital output
  - o 2^n: Number of states
  - o V_{ref}: Reference voltage range

- The resolution represents the quantisation error inherent in the conversion of the signal to digital form.

QUANTISING AND ENCODING

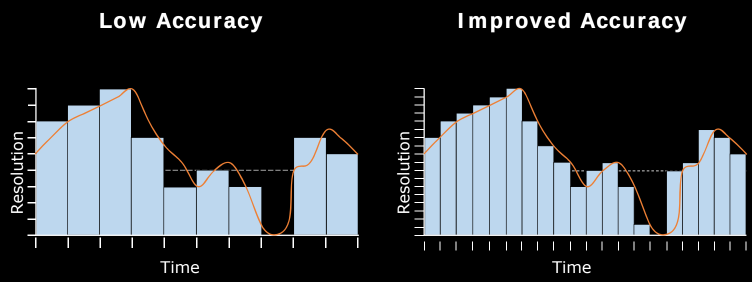
- Quantising: Partition the reference signal range into a number of discrete quanta, then match the input signal to the correct quantum.

- Encoding: Assign a unique digital code to each quantum, then allocate the digital code to the input signal.



TWO WAYS TO IMPROVE THE ACCURACY OF A/D CONVERSION

- Increasing the resolution, which improves the accuracy in measuring the amplitude of the analog signal.
- Increasing the sampling rate, which increases the maximum frequency that can be measured.



ADVANTAGES OF A/D CONVERSION

- A digital signal is superior to an analog signal, because it is more robust to noise and can easily be recovered, corrected and amplified.
- For this reason, most analog signals will be changed to their digital forms.

APPLICATIONS OF A/D CONVERSION

- ADCs are used virtually everywhere where an analog signal has to be processed, stored, or transported in digital form.
- Some examples of ADCs usage are,
  - Cell phones,
  - Thermocouples,
  - Digital oscilloscopes, and
  - Digital volt meters.

THE CONVERSION TIME

- Setting time depends on
  - the design of the converter,
  - the method used for conversion, and
  - the speed of the components used in the electronic design.

- Because the analog signal changes continuously, the uncertainty when the conversion occurs (in the sample time window), causes the corresponding uncertainty in the digital value.

➔ This is of particular concern if there is no sample and hold amplifier on the A/D input.

THE APERTURE TIME

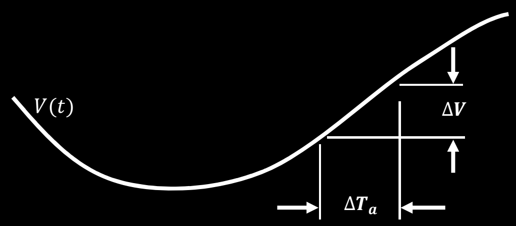
Refers to the duration of the time window and is associated with any error in the digital output due to changes in the input during this time.

The relationship between the aperture time and the uncertainty in the input amplitude is shown in the figure. During the aperture time

The input signal changes $\Delta V(t)$

where

$$\Delta V(t) \approx \frac{dV(t)}{dt} \Delta T_a$$



PART 6.3 A / D CONVERTERS

DESIGN PRINCIPLES OF A/D CONVERTERS

Principle 1: Successive approximation

Principle 2: Flash or parallel encoding

Principle 3: Single-slope and dual-slope integration

Principle 4: Switched capacitor

Principle 5: Delta sigma

Other principles:

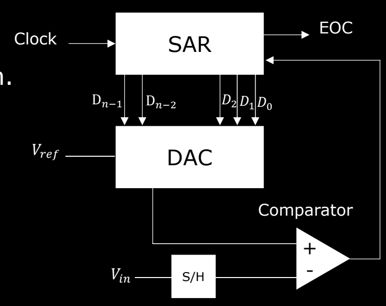
- Voltage-to-frequency
- Staircase ramp or single slope
- Charge balancing or redistribution
- Tracking, synchronising or resolving

SUCCESSIVE APPROXIMATION

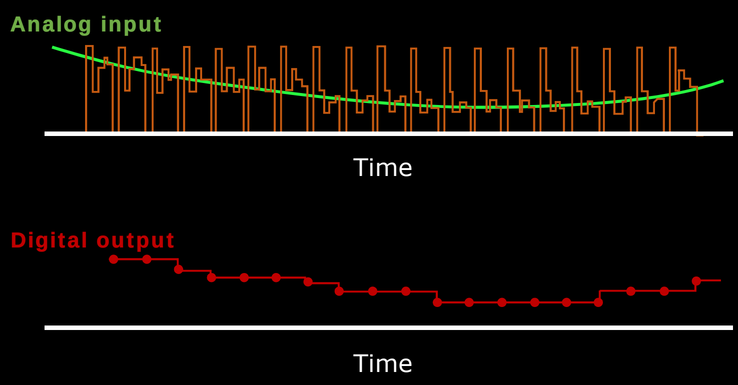
1. A/D Converter designed based on Principle 1 is very widely used because it is relatively fast and cheap.
2. Successive approximation A/D converter uses a D/A converter in a feedback loop.
3. When the start signal is applied, the sample and hold (S&H) amplifier latches the analog input.
4. The control unit begins an iterative process, where the digital value is approximated, converted to an analog value with the D/A converter, and compared to the analog input with the comparator.
5. When the D/A output equals the analog input, the end signal is set by the control unit and the correct digital output is available at the output.

SUCCESSIVE APPROXIMATION ADC CIRCUIT

- Use a n-bit DAC to compare DAC and original analog results.
- Use Successive Approximation Register (SAR) to supply an approximate digital code to DAC of V_{in}.
- Compare the change in digital output to bring it closer to the input value.
- Use Closed-Loop Feedback Conversion.



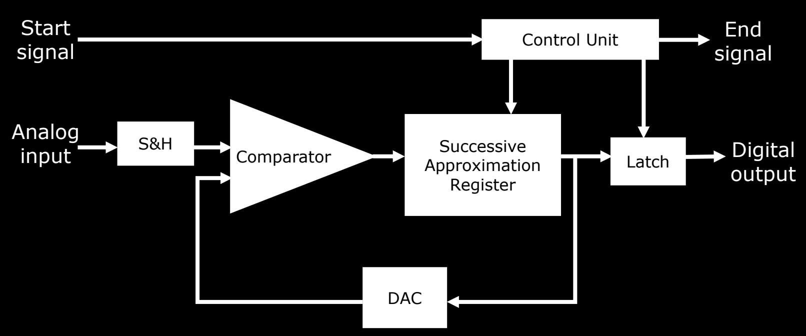
SUCCESSIVE APPROXIMATION OUTPUT



ANALYSIS FOR SUCCESSIVE APPROXIMATION A/D CONVERTER

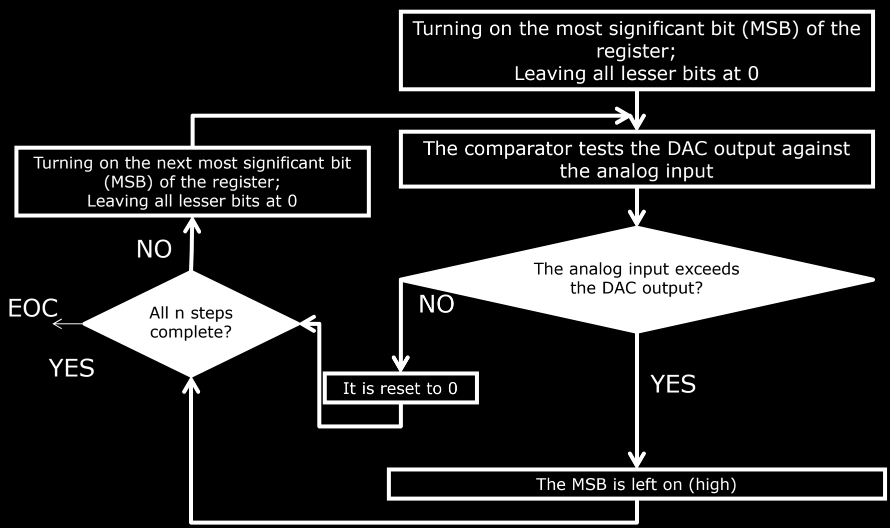
Pros	Cons
High speed and good reliability	For higher resolution successive approximation, ADCs will be slower
Medium accuracy compared to other ADC types	Speed limited to ~5MSPS
Good tradeoff between speed and cost	
Capable of outputting the binary number in serial format (one bit at a time)	

SUCCESSIVE APPROXIMATION



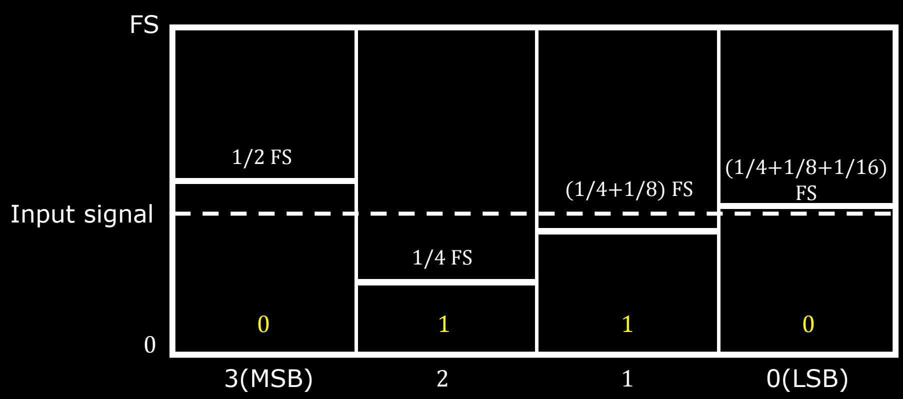
A / D CONVERTERS

n (resolution) steps to complete the conversion



A / D CONVERTERS

Example 1: 4 bits A/D converter



The digital result is 0110

Higher resolution will produce more accurate results

A / D CONVERTERS

CONVERSION TIME

An n-bit successive approximation A/D converter has a conversion time of $n\Delta T$.

Where ΔT is the cycle time of the D/A converter and control unit.

Typical conversion time for 8/10/12-bit successive approximation A/D converters ranges from 1 to 100μs.

A / D CONVERTERS

Example 2: Another working example

- n = 10 bit ADC
- V_{in} = 0.6 volts (from analog device)
- V_{ref} = 1 Volt
- Find the digital value of V_{in}

Bit	Voltage
9	.5
8	.25
7	.125
6	.0625
5	.03125
4	.015625
3	.0078125
2	.00390625
1	.001952125
0	.0009765625

N=2^n=1024 (possible states)

Resolution $\Delta V = (V_{max}\text{-}V_{min})/N = 1$ Volt$/1024 = 0.0009765625V$ of V_{ref}

A / D CONVERTERS

MSB (bit 9)

- Divide V_{ref} by 2, $V = V_{ref}/2 = 0.5$
- Compare V with V_{in}
- If V_{in} is greater than V, turn MSB on (1)
- If V_{in} is less than V, turn MSB off (0)
- $V_{in} = 0.6\text{V}$ and V=0.5
- Since $V_{in} > V$, MSB = 1(on)

Bit	Voltage
9	.5
8	.25
7	.125
6	.0625
5	.03125
4	.015625
3	.0078125
2	.00390625
1	.001952125
0	.0009765625

MSB	MSB-1	MSB-2	MSB-3	...					
1									

A / D CONVERTERS

Next, calculate MSB-1 (bit 8)

- $V = V_{ref}/2 + V_{ref}/4 = 5{+}0.25 = 0.75\,V$
- Compare $V_{in} = 0.6\text{V}$ to V
- Since $0.6 < 0.75$, MSB is turned off

MSB	MSB-1	MSB-2	MSB-3	...					
1	0								

A / D CONVERTERS

Calculate MSB-2 (bit7)

- Go back to the last voltage that caused it to be turned on (Bit 9) and add it to $V_{ref}/8$, $\mathrm{V} = V_{ref}/2 + V_{ref}/8 = 0.625$
- Compare V_{in} with V
- Since $0.6 < 0.625$, MSB is turned off

MSB	MSB-1	MSB-2	MSB-3	...					
1	0	0							

A / D CONVERTERS

Calculate the state of MSB-3(bit 6)

- Go to the last bit that caused it to be turned on (in this case MSB-1) and add it to $V_{ref}/16, V = V_{ref}/2 + V_{ref}/16 = 5{+}0.25 = 0.5625\,V$
- Compare V_{in} to V
- Since $0.6 > 0.5625$, MSB-3=1(turned on)

MSB	MSB-1	MSB-2	MSB-3	...					
1	0	0	1						

A / D CONVERTERS

This process continues for all the remaining bits

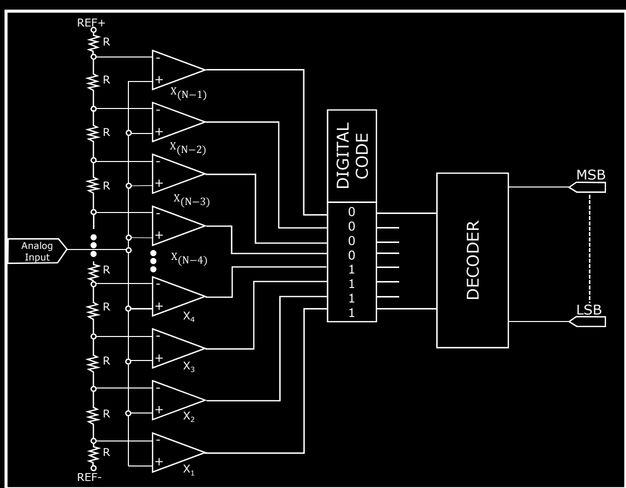
- Digital Results

MSB	MSB-1	MSB-2	MSB-3	MSB-4	MSB-5	MSB-6	MSB-7	MSB-8	LSB
1	0	0	1	1	0	0	1	1	0

- Results: $\frac{1}{2} + \frac{1}{16} + \frac{1}{32} + \frac{1}{256} + \frac{1}{512} = 0.599609375V$

FLASH A / D CONVERTERS

- $N - 1$ comparators
- N resistors
- Control logic



HOW DOES IT WORK?

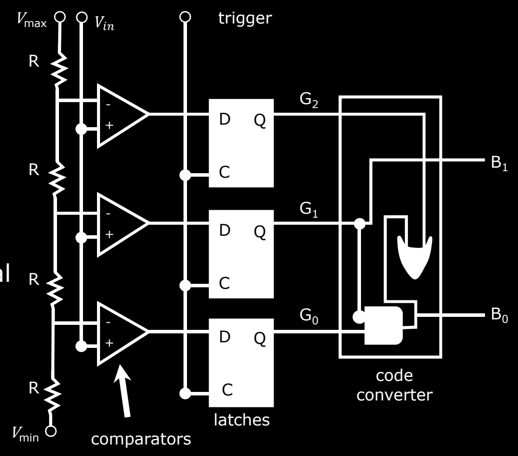
- Uses the N resistors to form a ladder voltage divider, which divides the reference voltage into N equal intervals.
- Uses the $N-1$ comparators to determine in which of these N voltage intervals the input voltage V_{in} lies.
- The Combinational logic then translates the information provided by the output of the comparators.
- This ADC does not require a clock, so the conversion time is essentially set by the settling time of the comparators and the propagation time of the combinational logic.

ANALYSIS FOR FLASH A / D CONVERTER

Pros	Cons
Very fast	Expensive
Very simple operational theory	Prone to produce glitches in the output
Speed is only limited by gate and comparator propagation delay	Each additional bit of resolution requires twice the comparators

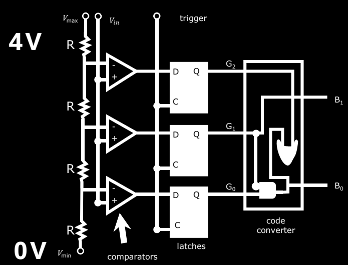
FLASH CONVERTER

- The fastest type of A/D converter.
- Consists of a bank of input comparators acting in parallel to identify the signal level.



Note: The figure shows a 2-bit converter with a resolution for 4 output states.
The output of the latches is in a coded form easily converted to the required binary output with combinational logic.

2-BIT FLASH CONVERTER OUTPUT

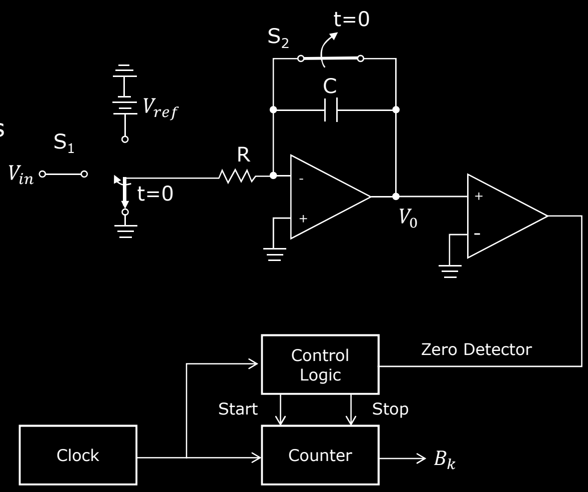


State	Code($G_2G_1G_0$)	Binary(B_1B_0)	Voltage Range
0	000	00	0-1
1	001	01	1-2
2	011	10	2-3
3	111	11	3-4

Note: Assuming the input voltage range of 0 to 4V,
the voltage range is set by the V_{min} and V_{max}
the code converter is a simple combinational logic circuit
For a 2-bit converter, the relationships between the code bit G_i and the binary bits B_i are $B_0 = G_0 \cdot \overline{G_1} + G_2$
$B_1 = G_1$

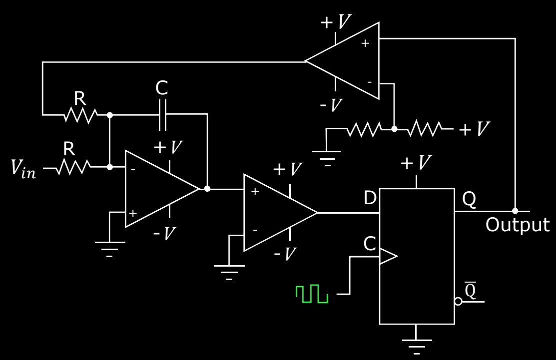
DUAL-SLOPE CONVERTERS

- Integrator
- Electronically Controlled Switches
- Counter
- Clock
- Control Logic
- Comparators
- Resistor
- Capacitor



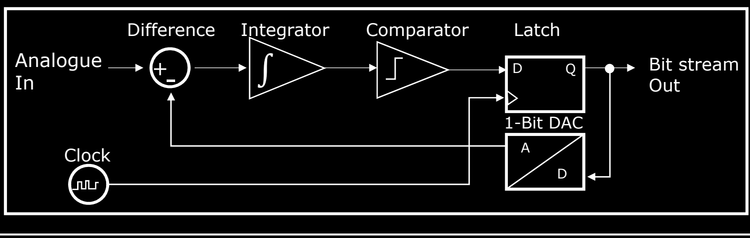
SIGMA-DELTA A / D CONVERTERS

- Resistors
- Capacitor
- Comparators
- Control Logic
- DAC



HOW DOES IT WORK?

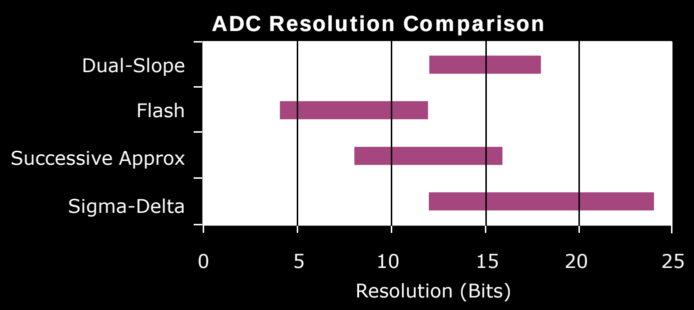
- Input is over sampled and goes to integrator.
- The integration is then compared to ground.
- Iterates and produces a serial bit stream.
- Output is a serial bit stream with # of 1's proportional to V_{in} With this arrangement, the sigma-delta modulator automatically adjusts its output to ensure that the average error at the quantiser output is zero.
- The integrator value is the sum of all past values of the error. So whenever there is a non-zero error value, the integrator value just keeps building until the error is once again forced to zero.



ANALYSIS FOR SIGMA-DELTA A / D CONVERTER

Pros	Cons
High resolution	Slow due to over sampling
No need for precision components	Only good for low bandwidth

COMPARISON OF DIFFERENT TYPES OF A / D CONVERTERS



COMPARISON OF DIFFERENT TYPES OF A / D CONVERTERS

Type	Speed (relative)	Cost (relative)
Dual-Slope	Slow	Med
Flash	Very Fast	High
Successive Approximation	Medium Fast	Low
Sigma-Delta	Slow	Low

A / D CONVERTERS

- Adding more resolution is a simple matter of adding more resistors, comparators and latches.
- The combinational logic code converter would also be different.
- Unlike with successive approximation converter, adding resolution does not increase the time required for a conversion.

PART 7: D / A CONVERSION

PART 7.1 BACKGROUND

WHY DIGITAL-TO-ANALOG CONVERSION?

- There are needs to reverse the process of A/D conversion by changing a digital value to an analog voltage.
- D/A conversion allows a computer or other digital devices to interface with external analog circuits and devices.

D / A CONVERTER

Playing back the digital sound file

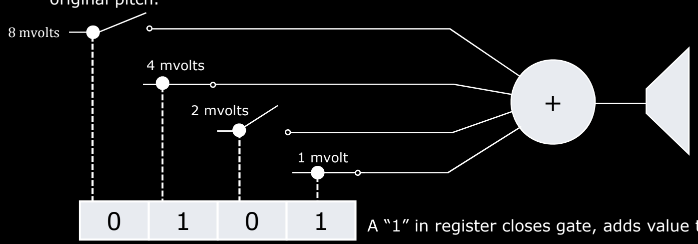
011100011101
Stream of zeros and ones
(digital sound)

Computer
Sound
Card

Waveform
(analog sound)

Digital-to-Analog Converter

Samples (bytes) are clocked into D-to-A converter at sampling rate to reproduce original pitch.



A "1" in register closes gate, adds value to the total

1 byte in register = 5 mvolts

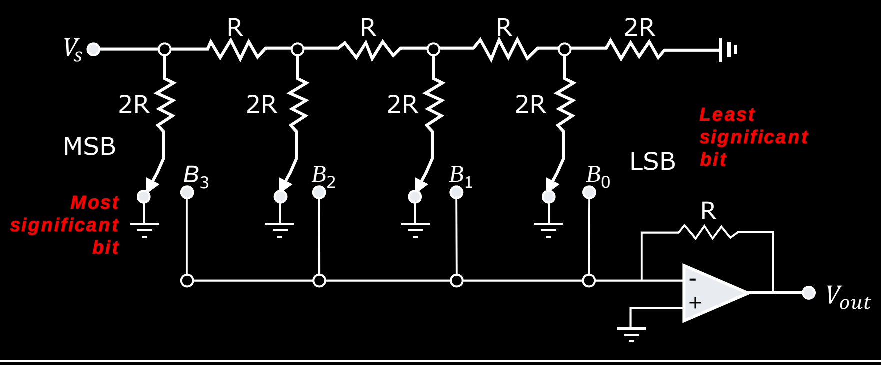
PROBLEMS WITH D / A CONVERSION

- Finite word length
  - Most systems today do 16 bit digitizing.
  - 65536 different levels.
- The loudest sounds need room, so the normal sounds don't use the entire range
  - Problems occur at the low levels where sounds are represented by only one or two bits. High distortions result.
- Dithering adds low level broadband noise.

PART 7.2 D / A CONVERSIONS

HOW TO DO D / A CONVERSIONS?

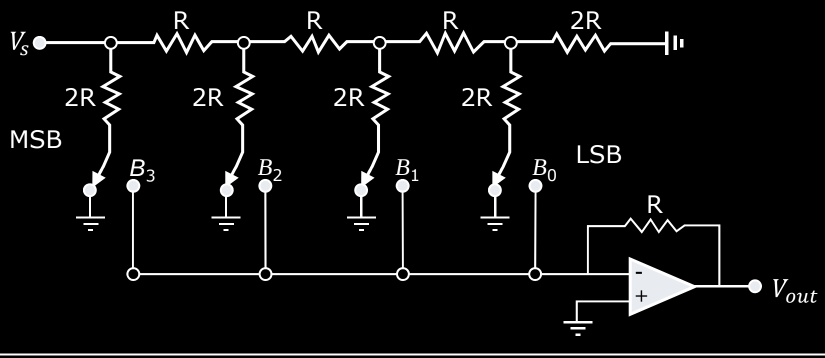
The simplest type of D/A converter is a resistor ladder network connected to an inverting summer operational amplitude circuit. This is a 4 bit R-2R resistor ladder network which requires only two precision resistance values (R & 2R).



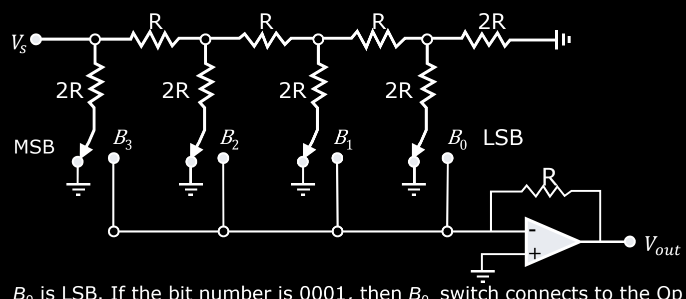
HOW TO DO D / A CONVERSIONS?

Note:

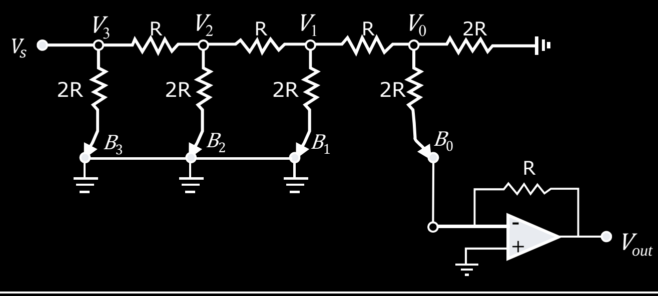
- The digital input to the DAC is a 4-bit binary number represented by bits B_0, B_1, B_2 and B_3
- B_0 is the least significant bit and B_3 is the most significant bit
- Each bit in the circuit controls a switch between ground and the inverting input of the op amp



D / A CONVERSIONS



B_0 is LSB. If the bit number is 0001, then B_0 switch connects to the Op Am, others are grounded.



D / A CONVERSIONS

Since the inverting Op Am is grounded, we have

$$V_{out_0} = -\frac{1}{2}V_0$$

Moreover

$$V_0 = \frac{1}{2}V_1, \qquad V_1 = \frac{1}{2}V_2, \qquad V_2 = \frac{1}{2}V_3 = \frac{1}{2}V_s$$

So

$$V_{out_0} = -\frac{1}{16}V_s$$

Similarly,

$$V_{out_1} = -\frac{1}{8}V_s, \qquad V_{out_2} = -\frac{1}{4}V_s, \qquad V_{out_3} = -\frac{1}{2}V_s$$

Total output:

$$V_{out} = \sum_{i=0}^{n-1} B_i V_{out_i}$$