ELEC 207
Instrumentation and Control

11 – Analog to Digital Conversion

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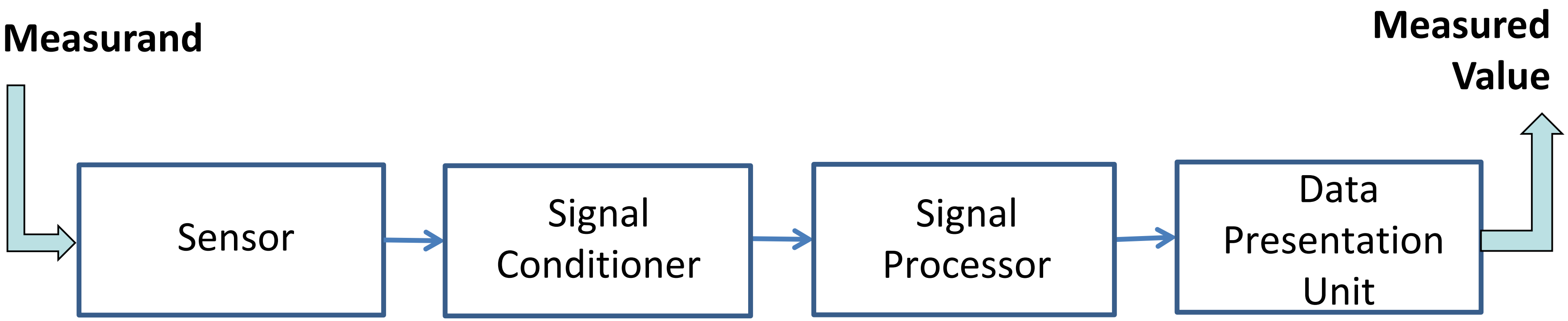
Measurement system

General structure



- Temperature
- Displacement
- Strain
- Acceleration

- Amplifier
- Bridge

- Analog-to-Digital Converter (ADC)
- Microcontroller

- LED (Display)
- Visual display unit
- Chart recorder

Measurement system

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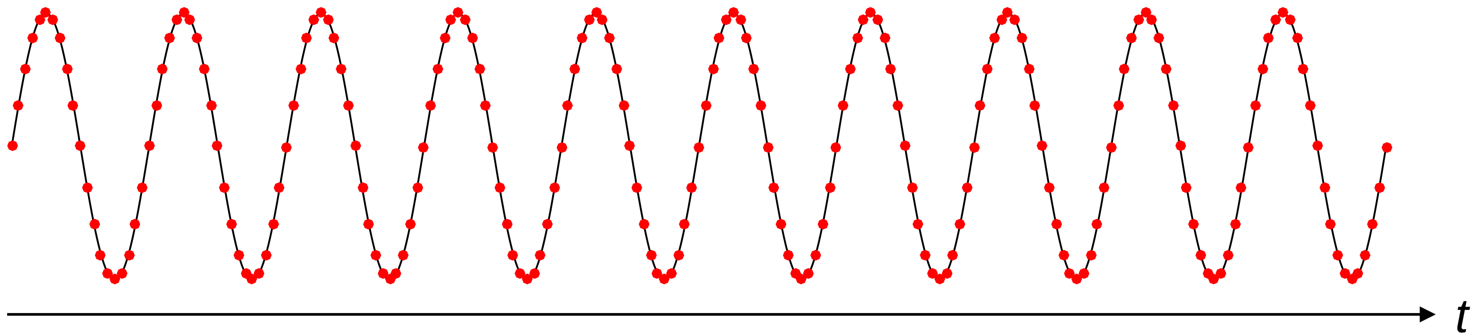
Signal processing
Sampling and A/D conversion

Before converting an analog signal into a digital form, the signal needs to be **sampled**:

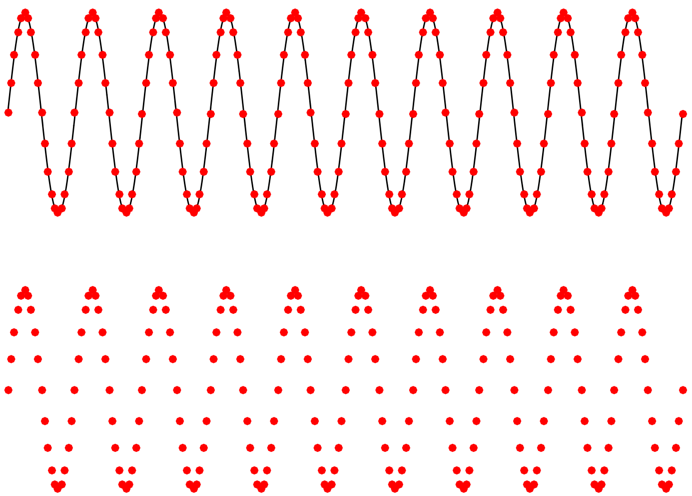
- While the analog signal is defined in the continuous time domain, only some samples at **discrete times** are considered for the A/D conversion;



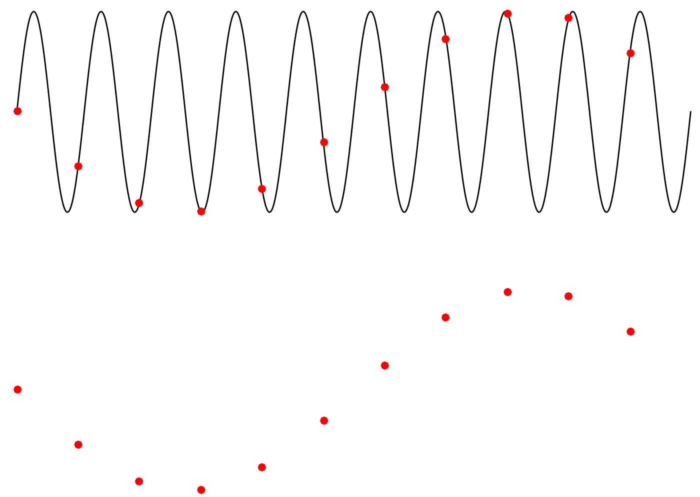
- If sampling is done correctly, no information is lost; otherwise, huge errors may arise.

Signal sampling
Sampling theorem

CORRECT SAMPLING



NOT CORRECT SAMPLING (**ALIASING**)



- The sampling frequency must be **higher than** (<u>not equal to</u>) **twice the highest frequency component** present in the signal:

$$f_s > 2f_{max}$$

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Signal sampling

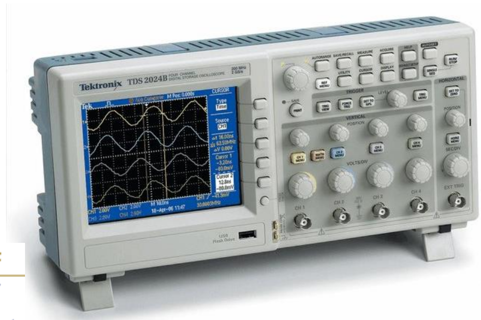
Limitations in the sampling frequency

The maximum achievable sampling frequency is limited by the employed hardware, and in particular by:

- **A/D conversion speed**;
- Communication speed (data transfer);
- Signal processing speed.

Different types of A/D converters allow different sampling frequencies:

- Usually, a higher sampling frequency corresponds to a worse accuracy.

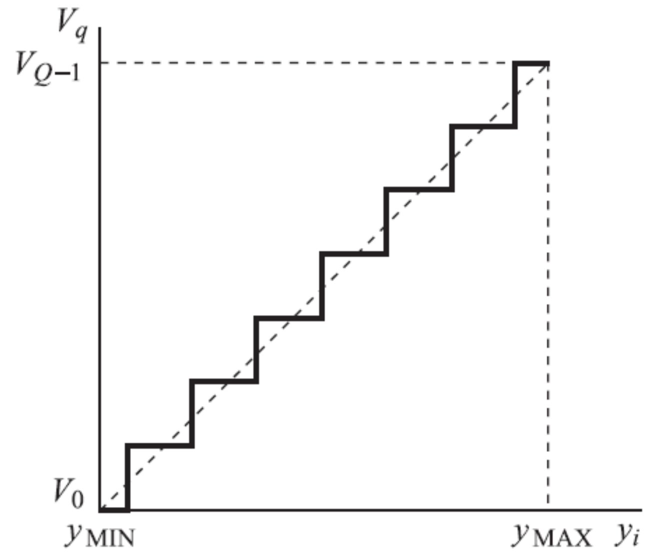


Quantisation

Digital signal resolution

The number of bits used to encode information in digital form determines the number of different codes available and therefore the **resolution of the digital signal**:

- *N* bits allow 2^N different codes:
  - ➢ E.g., with 3 bits we can write: 000, 001, 010, 011, 100, 101, 110, 111;
  - ➢ This is similar to digital numbers in base 10;



- The resolution of a binary signal is therefore:

$$\text{resolution} = \frac{\text{range}}{2^N}$$

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Digital to analog converters (DACs)

General principles

Before considering how a (sampled) analog signal can be converted into a digital form, let's consider the opposite conversion, **from digital to analog**:

- Each bit has to be converted into a voltage and weighted based on its position in the binary number:
  - E.g., the binary number 101101 means:

$$1 \cdot 2^5 + 0 \cdot 2^4 + 1 \cdot 2^3 + 1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0$$

- There are two main types of digital to analog converters (DACs):
  - **Binary weighted resistor network**;
  - **R-2R ladder network**.

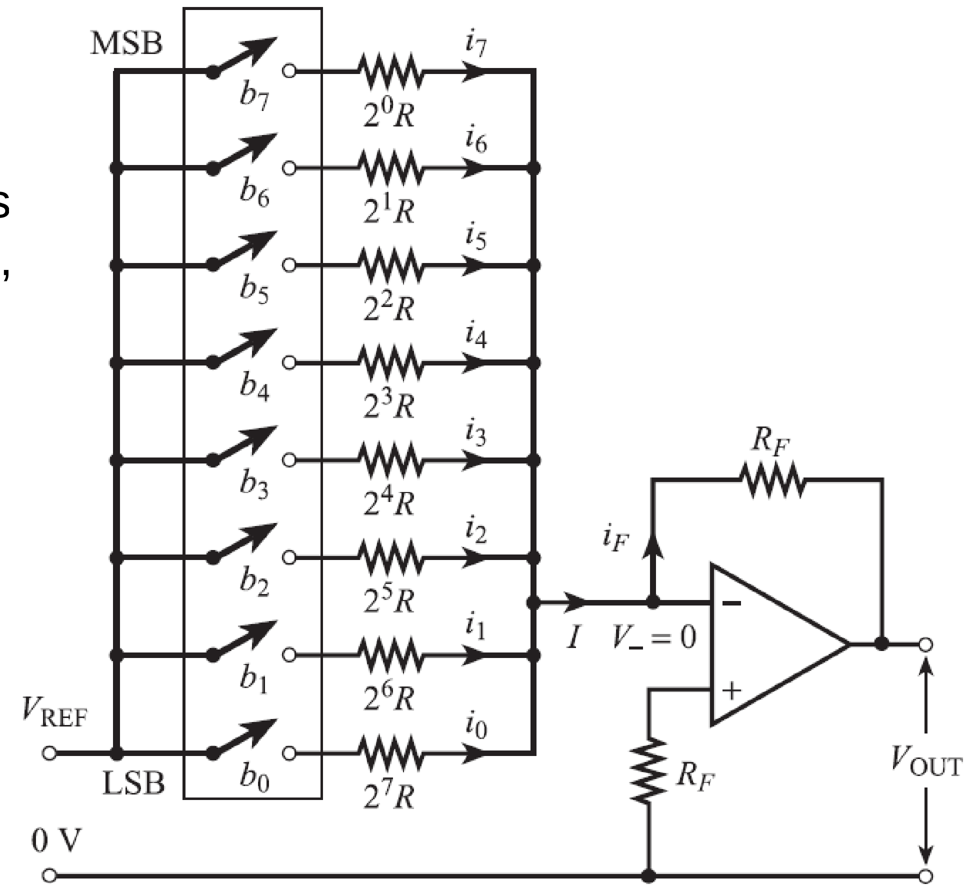
Digital to analog converters (DACs)

Binary weighted resistor network

The conversion is achieved in the following way:

- The value of each bit corresponds to the state of a **switch** (0 = open, 1 = closed);
- The weight of the bit is obtained by using **resistors** with different values, which change the gain of the amplifier for each bit:

$$V_{OUT} = -\frac{R_F}{R} V_{REF} \sum_{i=0}^{N-1} \frac{b_i}{2^{N-1-i}}$$



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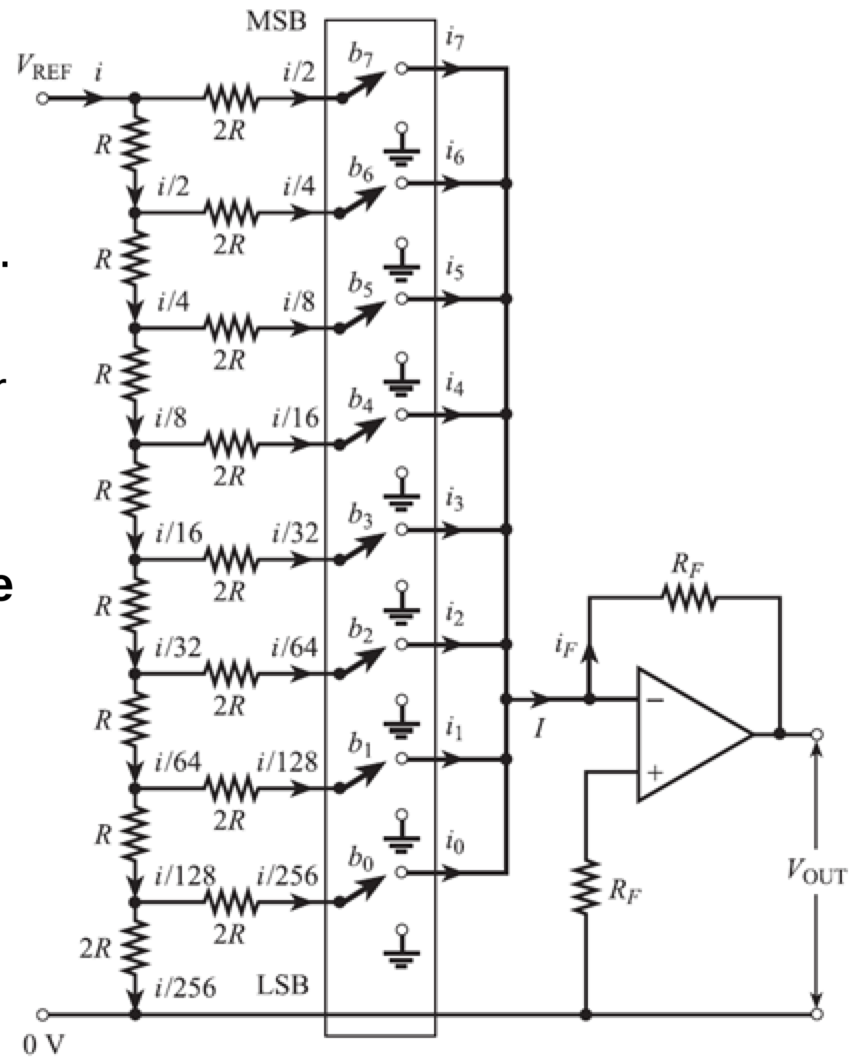
Digital to analog converters (DACs)

R-2R ladder network

The main disadvantage of the previous converter is that it requires a **wide range of resistors**, from *R* to $2^{N-1}R$, and they must all have similar tolerance and stability.

To overcome this problem, the R-2R ladder network can be used instead:

- Only **two (similar) values of resistance** are required: *R* and 2*R*;
- This is the most common DAC:
  - It is fast and low-cost.



Analog to digital converters (ADCs)

General principles

Analog to digital converters (ADCs) convert a (sampled) analog signal into a digital form.

The following two parameters must be considered in the design/choice of an ADC:

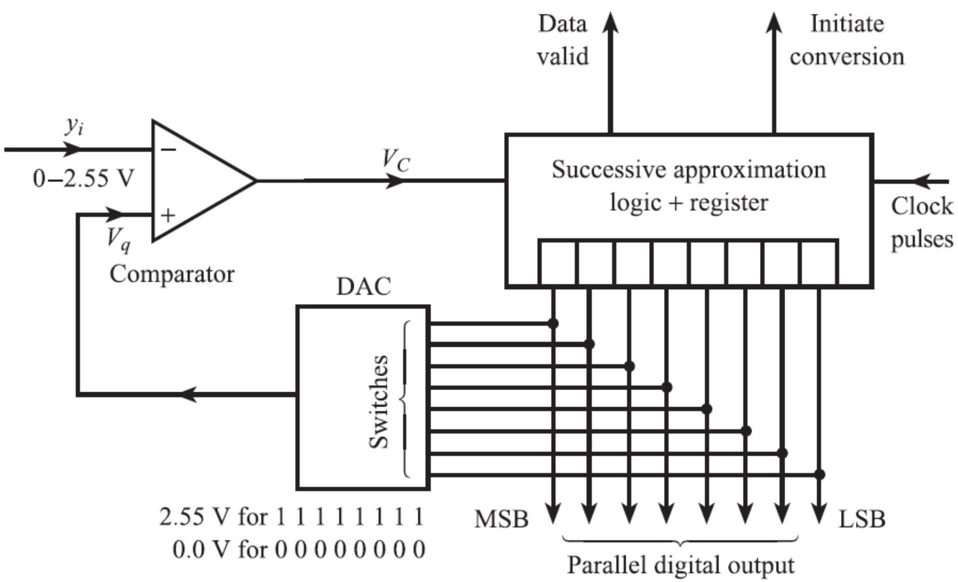
- The **number of bits**, which determines the resolution of the digital signal (note that this does not necessarily correspond to the accuracy!);
- The **conversion time**, which determines the maximum **sampling frequency** and therefore the maximum frequency bandwidth of the input analog signal;
- The cost and complexity of the converter.

Analog to digital converters (ADCs)

Successive approximation converter (1)

The conversion is achieved by a **sequence of guesses**:

- At each cycle, the value of one bit is guessed as 0, starting from the most significant bit (MSB), with all remaining bits set at 1:
  - ➢ The guessed output is then converted into an analog signal by a DAC and compared to the input signal to find whether the guess was correct or wrong;



- The **conversion time** is proportional to the number of bits.

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Analog to digital converters (ADCs)

Successive approximation converter (2)

Example:

- Input voltage: 0.515 V
- 8 bits.

Clock pulse	DAC input	DAC V_q output (volts)	Comparator output V_C	Result
1 Clear register	00000000	0	0	
2 First guess	01111111 $(127)_{10}$	1.27	1 HIGH	$b_7 = 0$
3 Next guess	00111111 $(63)_{10}$	0.63	1 HIGH	$b_6 = 0$
4	00011111 $(31)_{10}$	0.31	0 LOW	$b_5 = 1$
5	00101111 $(47)_{10}$	0.47	0 LOW	$b_4 = 1$
6	00110111 $(55)_{10}$	0.55	1 HIGH	$b_3 = 0$
7	00110011 $(51)_{10}$	0.51	0 LOW	$b_2 = 1$
8	00110101 $(53)_{10}$	0.53	1 HIGH	$b_1 = 0$
9 Final guess	00110100 $(52)_{10}$	0.52	1 HIGH	$b_0 = 0$

Output digital signal = 00110100

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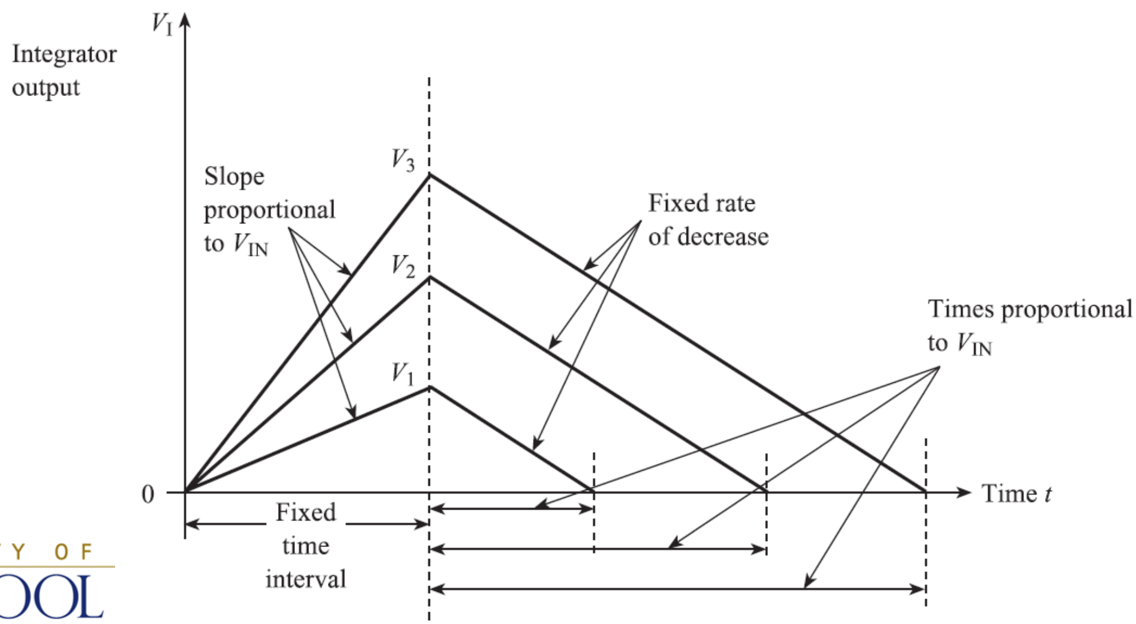
Analog to digital converters (ADCs)

Dual slope converter (1)

Another common ADC is the **dual slope converter**, based on the following principle:

- Firstly, the (positive) input signal is integrated for a fixed time;
- Then, a constant negative signal is integrated, and the time required for the integrator to go back to 0 is measured.



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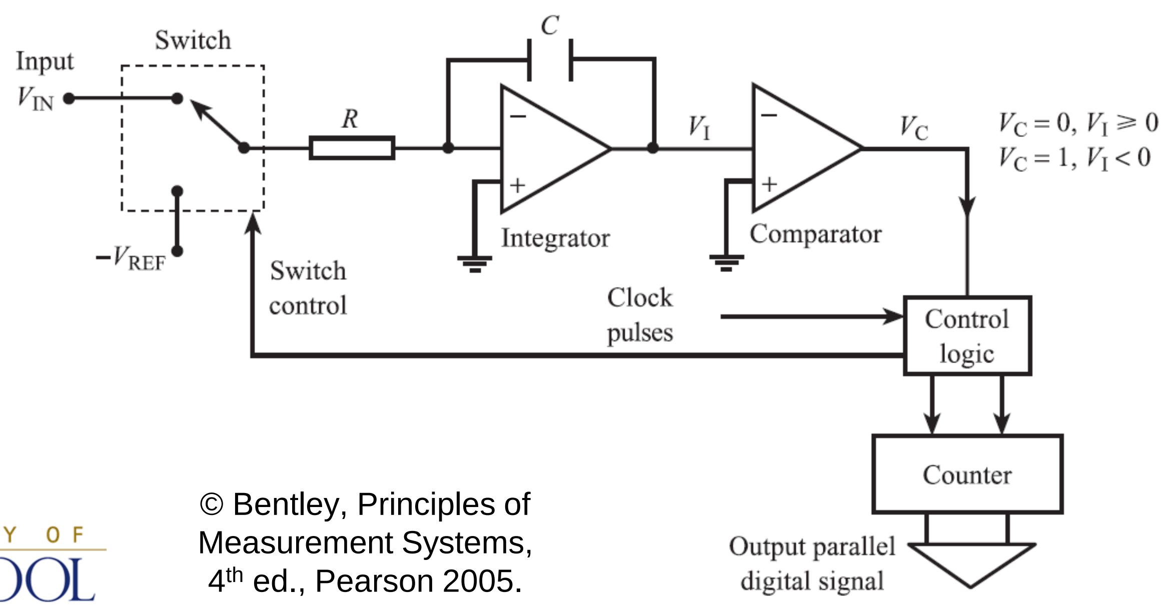
Analog to digital converters (ADCs)

Dual slope converter (2)

This principle is implemented by the following circuit:

- The digital output is the **counter output** when the negative ramp reaches 0, which is proportional to the input signal:
  - ➢ The converter resolution is given by the number of bits in the counter and does not affect the conversion time.



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References

Textbook: Principles of Measurement Systems, 4th ed.

For further explanation about the points covered in this lecture, please refer to the following chapters and sections in the **Bentley** textbook:

- Chapter 10, Sec. 10.1.1: **Sampling**;
- Chapter 10, Sec. 10.1.2: **Quantisation**;
- Chapter 10, Sec. 10.1.5: **Digital-to-analogue converters (DACs)**;
- Chapter 10, Sec. 10.1.6: **Analogue-to-digital converters (ADCs)**.

<u>NOTE</u>: Topics not covered in the lecture are not required for the exam.

References

Textbook: Measurement and Instrumentation, 2nd ed.

For further explanation about the points covered in this lecture, please refer to the following chapters and sections in the **Morris-Langari** textbook:

- Chapter 6, Sec. 6.1: **Introduction**;
- Chapter 6, Sec. 6.2: **Preliminary definitions**;
- Chapter 6. Sec. 6.3: **Sensor signal characteristics**;
- Chapter 6, Sec. 6.4: **Aliasing**;
- Chapter 6, Sec. 6.5: **Quantization**.

NOTE: Topics not covered in the lecture are not required for the exam.