

# ITP272 SENSOR TECHNOLOGIES AND PROJECT

L04: Sensors and their Principles

# AGENDA

## Signal Conditioning

- ⦿ Amplifier
- ⦿ Bridge Circuit
- ⦿ Analog to Digital Convertor (ADC)

# SIGNAL CONDITIONING

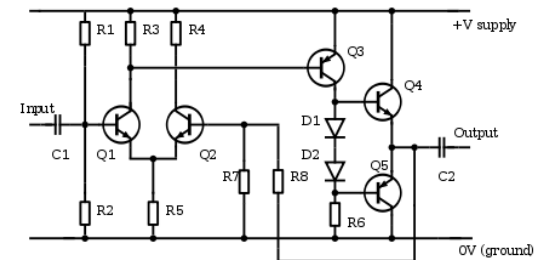
## Signal conditioning

- ④ It is manipulation of a raw analog signal so that it is suitable to be further processed meaningfully
- ⦿ Typically a sensor cannot be directly connected to the instruments that record, monitor, or process its signal
- ⦿ The signal may be incompatible or may be too weak and/or noisy

## Various Signal Conditioning circuits

- ⦿ Amplifier
- ⦿ Bridge Circuit
- ⦿ Analog to Digital Converter (ADC)

# SIGNAL CONDITIONING



## Amplifier

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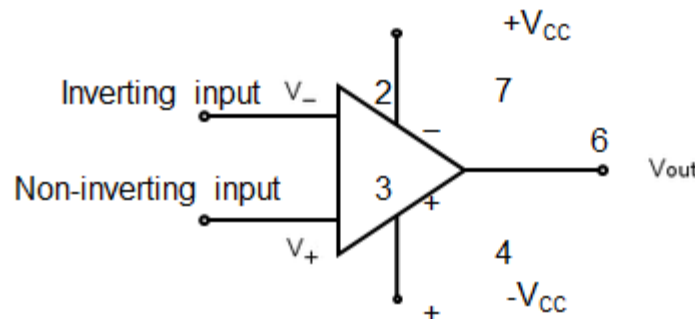
- It is an electronic device that takes in an input signal and produce an output signal with a larger amplitude.
- Most standard electronic data processors, such as A/D converters requires signal to be of sizable (big enough) amplitude.
- Most sensor produce weak output signals where amplitude is too small for the data processor to work on
- Thus signals from the sensors are passed into amplifiers to be magnified so that they could be processed by other electronic data processor

# SIGNAL CONDITIONING

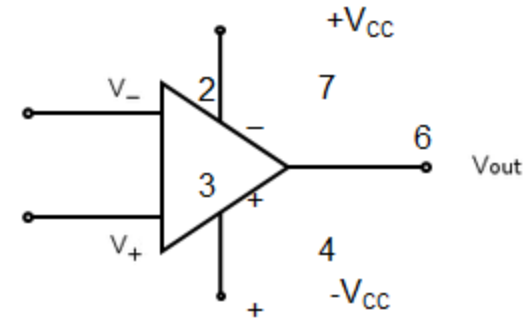
## Operational Amplifier (Op-Amp)

D

- It is a high-gain electronic voltage amplifier with a differential input
- The op-amp has two input terminals
  - Inverting (-), when a signal applied to this terminal is greater than non-inverting input, it produces an amplified output that is  $180^\circ$  out of phase with the input
  - Non-inverting (+), when a signal applied to this terminal is greater than inverting input, it produce an amplified output that is in-phase with the input signal



# SIGNAL CONDITIONING



## Operational Amplifier (Op-Amp)

- ⦿  $+V_{cc}$  and  $-V_{cc}$  is the power supply (Usually  $\pm 12$  V or  $\pm 5$  V)
- ⦿  $V_{out}$  is having maximum value of  $\pm V_{cc}$

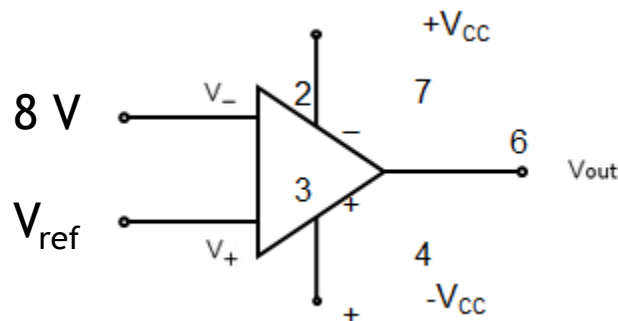
$$V_{out} = A_{OL} (V_+ - V_-)$$

- ⦿  $A_{OL}$  is known as the open loop gain and is typically very large ( $\sim 100$  k and more)
- ⦿ A small difference between  $V_+$  and  $V_-$  drives the amplifier output nearly to the supply voltage due to the high  $A_{OL}$ 
  - $(V_+ - V_-) = 5$  mV,  $V_{out} = 100 \times 10^3 \times 5 \times 10^{-3} = 500$  V  $\Rightarrow +V_{cc}$
  - $(V_+ - V_-) = -5$  mV,  $V_{out} = 100 \times 10^3 \times -5 \times 10^{-3} = -500$  V  $\Rightarrow -V_{cc}$

# SIGNAL CONDITIONING

## Operational Amplifier (Op-Amp)

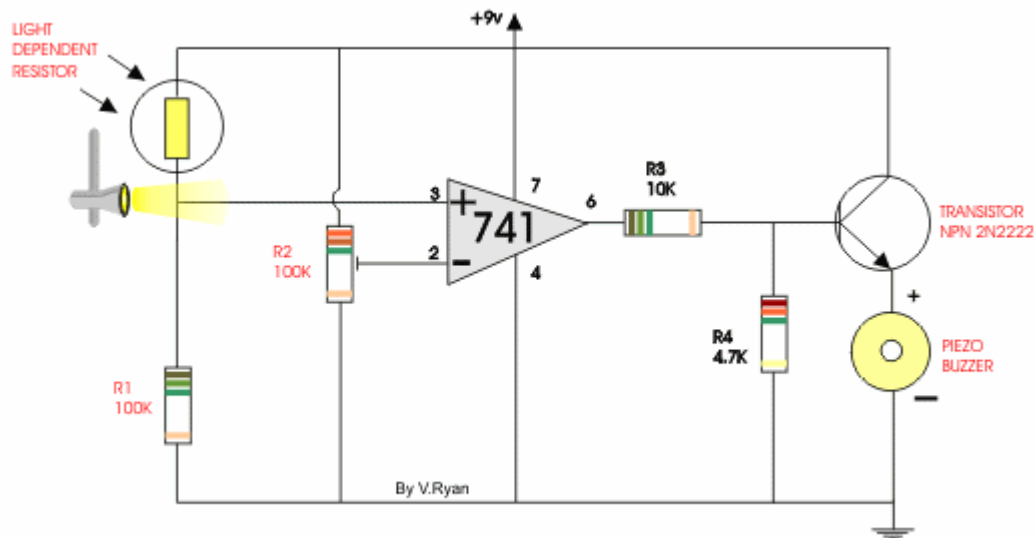
- ⦿ Can be used as a Voltage comparator
- ⦿ For example if we want to compare whether a voltage signal output ( $V_{\text{ref}}$ ) is greater than 8V. We connect
  - $V_-$  to 8 V
  - $V_{\text{ref}}$  to  $V_+$
  - $V_{\text{ref}} > 8 \text{ V}, \quad V_{\text{out}} = +V_{\text{cc}}$
  - $V_{\text{ref}} < 8 \text{ V}, \quad V_{\text{out}} = -V_{\text{cc}}$



# SIGNAL CONDITIONING

## Operational Amplifier (Op-Amp)

- ◉ Example of Voltage comparator used with light detector



# SIGNAL CONDITIONING

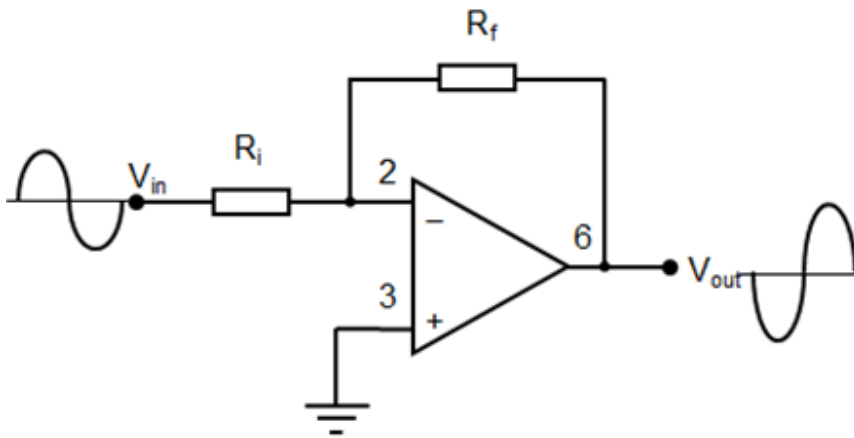
## Operational Amplifier (Op-Amp)

- ◉ Op-Amp is by default operating in Open Loop mode
- ◉ In open loop mode, as its open loop gain is very large, it usually has output either in  $+V_{cc}$  or  $-V_{cc}$
- ◉ Therefore it is not very suitable to be used for amplifying signals
- ◉ An Op-Amp output can be fed back to its input with resistors to control its gain
- ◉ An Op-Amp with output feedback to its input is operating in close mode
  - Inverting Op-Amp
  - Non-Inverting Op-Amp

# SIGNAL CONDITIONING

## Inverting Op-Amp

- $R_i$  and  $R_f$  are resistors used to control the gain
- Input signal ( $V_{in}$ ) is applied at the inverting terminal (-)
- Output signal ( $V_{out}$ ) is inverted in amplitude

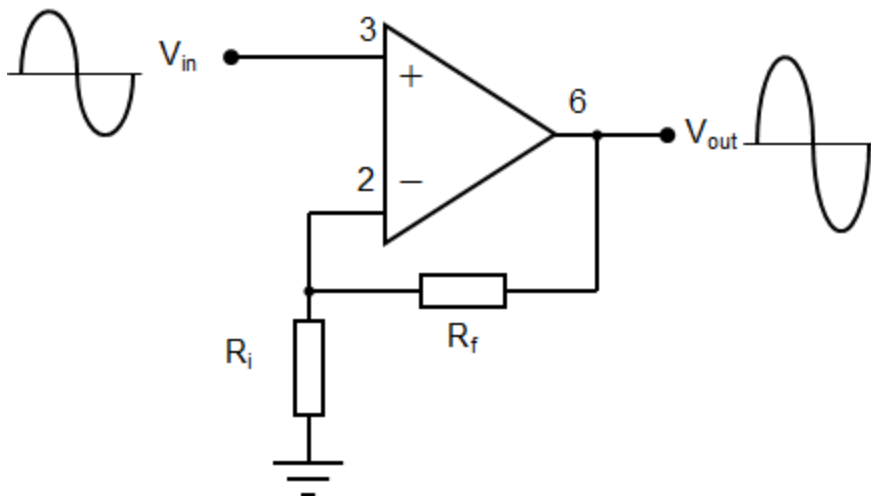


$$\text{Voltage Gain } (A_v) = -\frac{R_f}{R_i}$$
$$\text{Output voltage } (V_{out}) = \left(-\frac{R_f}{R_i}\right) \cdot V_{in}$$

# SIGNAL CONDITIONING

## Non-Inverting Op-Amp

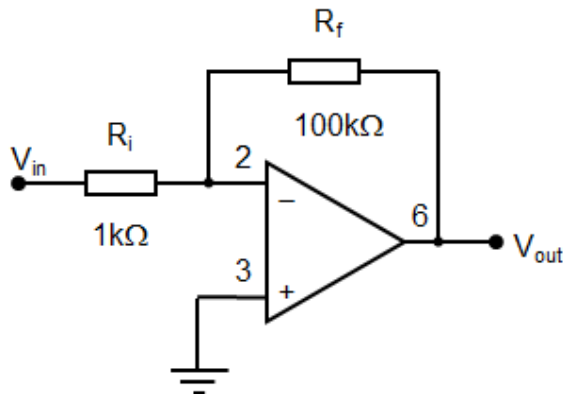
- $R_i$  and  $R_f$  are resistors used to control the gain
- Input signal ( $V_{in}$ ) is applied at the non-inverting terminal (+)
- Output signal ( $V_{out}$ ) amplitude is non-inverted



$$\text{Voltage Gain } (A_v) = 1 + \frac{R_f}{R_i}$$
$$\text{Output voltage } (V_{out}) = \left(1 + \frac{R_f}{R_i}\right) \cdot V_{in}$$

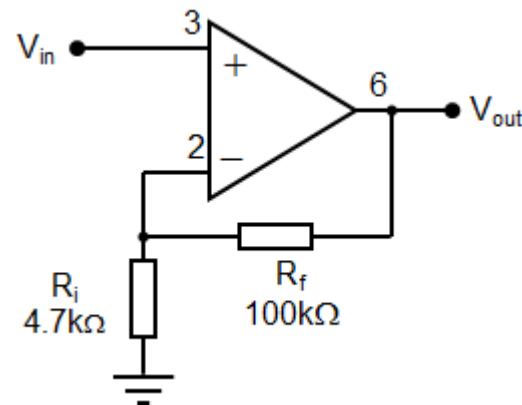
# SIGNAL CONDITIONING

Find the gain for the following Op-Amps



Inverting Op-Amp

$$\text{Gain : } -\frac{R_f}{R_i} = -\frac{100\text{k}}{1\text{k}} = -100$$



Non-Inverting Op-Amp

$$\text{Gain : } 1 + \frac{R_f}{R_i} = 1 + \frac{100\text{k}}{4.7\text{k}} = 22.3$$

# SIGNAL CONDITIONING

## Bridge Circuit

- ⦿ Resistive sensors such as thermistor produce small percentage changes in resistance in response to a change in a stimulus such as temperature
- ⦿ Accurately measuring small resistance changes is therefore critical for processing signals from resistive sensors
- ⦿ The basic Wheatstone bridge is designed to measure small resistance changes accurately
- ⦿ It consists of four resistors connected to form a quadrilateral
- ⦿ The detector measures the difference between the outputs of two voltage dividers connected across

# SIGNAL CONDITIONING

## Bridge Circuit

- Using Voltage divider

$$V_{O+} = \frac{R1}{R1+R4} \times V_B$$

$$V_{O-} = \frac{R2}{R2+R3} \times V_B$$

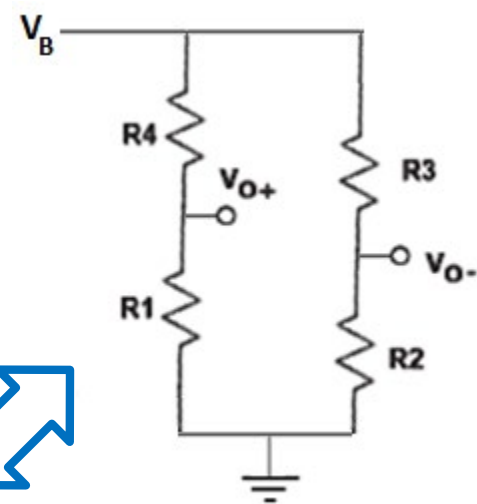
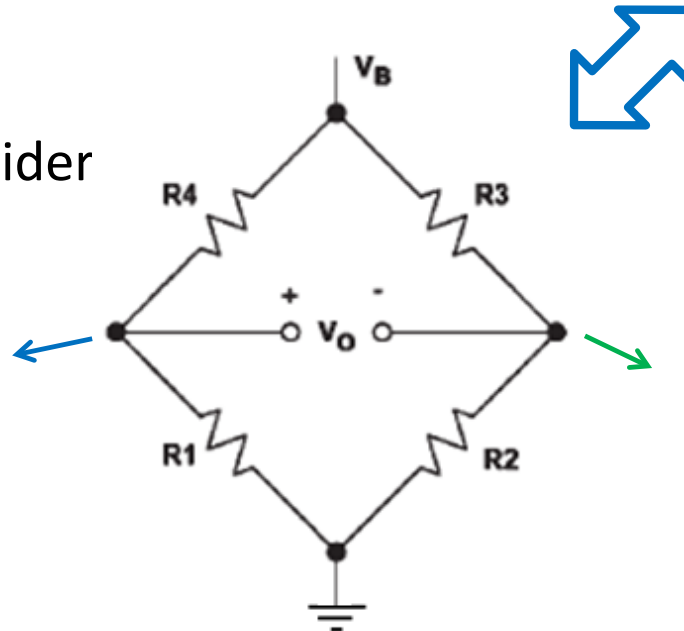
$$V_O = V_{O+} - V_{O-}$$

$$V_O = \frac{R1}{R1+R4} V_B - \frac{R2}{R2+R3} V_B$$

$$= \frac{\frac{R1}{R4} - \frac{R2}{R3}}{\left(1 + \frac{R1}{R4}\right)\left(1 + \frac{R2}{R3}\right)} V_B$$

AT BALANCE,

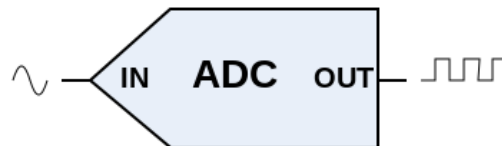
$$V_O = 0 \quad \text{IF} \quad \frac{R1}{R4} = \frac{R2}{R3}$$



# SIGNAL CONDITIONING

## Analog to Digital Convertor (ADC)

- ◉ A device that converts a continuous amplitude analog signal (usually voltage) to a digital number that represents the quantity's amplitude
- ◉ Sensors provide electrical output in terms of voltages which is analog and not directly understood by computers
- ◉ Computer processors and micro-controllers process data in digital forms. (binary 1's and 0's)
- ◉ In order for processor to interpret the sensor data, it has to go through an ADC to convert the analog voltage values into digital representation



# SIGNAL CONDITIONING

## Analog to Digital Convertor (ADC)

- ◉ ADC resolution indicates number of bits the ADC output generates
- ◉ For a M bit resolution, we can reach a max number of N known as Max Quantization Level given by

$$N = 2^M - 1$$

- ◉ So for ADC with 3 bit resolution,  $N = 2^3 - 1 = 7$  which means maximum Quantization level = 7
- ◉ ADC Full scale Voltage Range indicates the maximum analog voltage it accepts and is denoted by  $E_{FSR}$
- ◉ ADC Voltage resolution is the difference in voltage between each quantization levels
- ◉ For a 3 bit resolution ADC with  $E_{FSR} = 14 \text{ V}$ 
  - Voltage Resolution, denoted by Q, is given by
  - $Q = 14 / 7 = 2 \text{ V}$

$$Q = E_{FSR} / N$$

# SIGNAL CONDITIONING

## Analog to Digital Converter (ADC)

- ◉ ADC Voltage Resolution,  $Q$ , is used for converting between ADC values and actual Voltage from sensor
- ◉ A voltage from any sensor is often feed into the ADC.
- ◉ If you have  $Q$  and the sensor voltage, you can find the ADC Value as below

$$\text{ADC Value} = \text{Sensor voltage} / Q$$

- ◉ If you have  $Q$  and the ADC Value, you can find the sensor voltage as below

$$\text{Sensor voltage} = \text{ADC Value} * Q$$

- ◉ The sensor voltage is then used to further compute the actual sensor output (Eg. Distance or temperature, etc)

# SIGNAL CONDITIONING

## Analog to Digital Convertor (ADC)

- ◉ Sensor voltage is being used to compute reading from sensors like TMP36's temperature and LV-MaxSonar-EZ3's Distance
- ◉ In this module, we shall term it the Stimulus Formula
- ◉ For TMP36, the Stimulus Formula is

$$\text{Temp in Celsius} = 100 (\text{Sensor voltage} - 0.5)$$

- ◉ For LV-MaxSonar-EZ3, its sensor outputs 9.8mV per 2.5cm, thus the Stimulus Formula is

$$\text{Distance} = \text{Sensor Voltage} / 9.8\text{m} * 2.5$$

# SIGNAL CONDITIONING

## Analog to Digital Converter (ADC)

- ◉ The Stimulus formula is used to convert sensor voltage back to the actual Stimulus
- ◉ The sensor characteristic that describe the output–stimulus relationship is used to derive this formula
- ◉ The Stimulus Formula is derived using the transfer function of the sensor
- ◉ When a sensor is connected to ADC in a Sensor system, putting ADC Voltage Resolution as the sensor voltage into the Stimulus Formula will give you the absolute resolution of the sensor system

# SIGNAL CONDITIONING

## Analog to Digital Convertor (ADC)

- For a 3 bit resolution (M) ADC with  $E_{FSR} = 14 \text{ V}$
- Max quantization level (N) = 7, Voltage Resolution,  $Q = 2 \text{ V}$

ADC values	Binary	Sensor Voltage
0	000	0 V
1	001	2 V
2	010	4 V
3	011	6 V
4	100	8 V
5	101	10 V
6	110	12 V
7	111	14 V

$Q = 2 \text{ V}$

$N = 7$

$M = 3$

$E_{FSR} = 14 \text{ V}$

# SIGNAL CONDITIONING

## Analog to Digital Convertor (ADC)

Given that a micro-controller that has an ADC with 8 bit resolution and ADC Full scale Voltage Range input of 5V.

Find the

- (a) Maximum Quantization level
- (b) Voltage Resolution
- (c) Sensor Voltage output if you receive ADC value of 200.

- ⦿  $M = 8$ , thus Max Quantization level,  $N = 2^M - 1 = \underline{255}$
- ⦿  $E_{FSR} = 5$ ,  $N = 255$ , Thus Voltage resolution,  $Q = E_{FSR}/N = \underline{19.6\text{m V}}$
- ⦿  $Q = 19.6\text{mV}$ , ADC value = 200,
  - Thus Sensor Voltage = ADC value \*  $Q = 200 * 19.6\text{m} = \underline{3.92\text{ V}}$

# SIGNAL CONDITIONING

## Analog to Digital Convertor (ADC)

Given that a micro-controller that has an ADC with 10 bit resolution and ADC Full scale Voltage Range input of 3.3V.

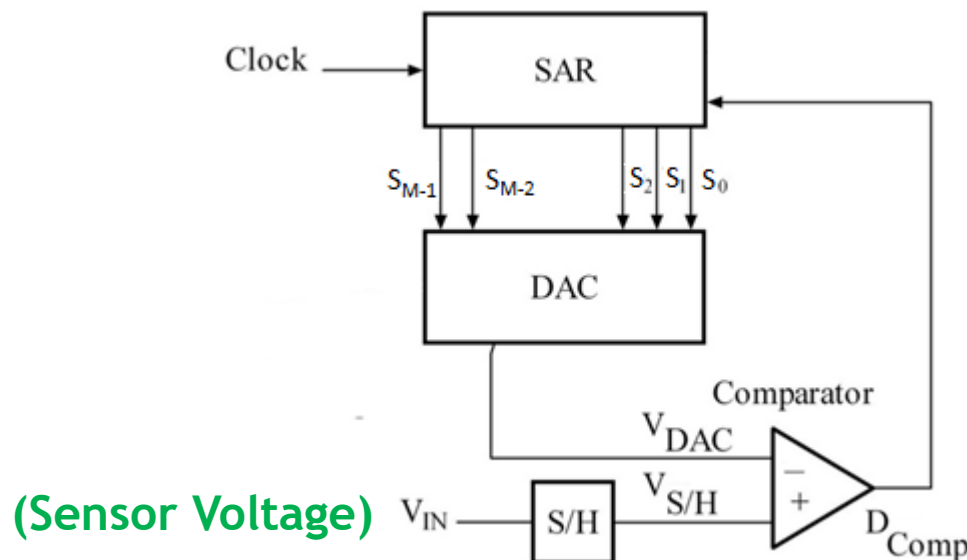
Find the

- (a) Maximum Quantization levels
  - (b) Voltage Resolution
  - (c) ADC value received if Sensor voltage is 0.8V.
- 
- ⦿  $M = 10$ , thus Max Quantization levels,  $N = 2^M - 1 = \underline{1023}$
  - ⦿  $E_{FSR} = 3.3$  ,  $N = 1023$ , Thus Voltage resolution,  $Q = E_{FSR}/N = \underline{3.2 \text{ m V}}$
  - ⦿  $Q = 3.2\text{mV}$ , Sensor voltage = 0.8V,
    - Thus ADC value = Sensor voltage /  $Q = 0.8 / 3.2\text{m} = \underline{250}$

# SIGNAL CONDITIONING

## Analog to Digital Converter (ADC)

- Successive Approximation ADC consist of 4 components
  - Sample and Hold (S/H) circuit to ensure analog input is constant during operation
  - Successive Approximation Register (SAR) for forming up the digital code output
  - Digital to analog convertor (DAC) for providing analog voltage equivalent of the digital code output of the SAR
  - Voltage comparator that outputs either 0 or 1 to feedback to the SAR



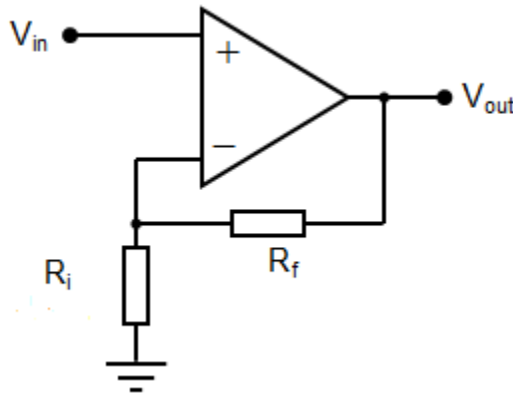
# REVIEW QUESTIONS



# REVIEW QUESTION

Draw a circuit diagram of an Non-Inverting Amplifier and write down a formula for the circuit.

Answer:

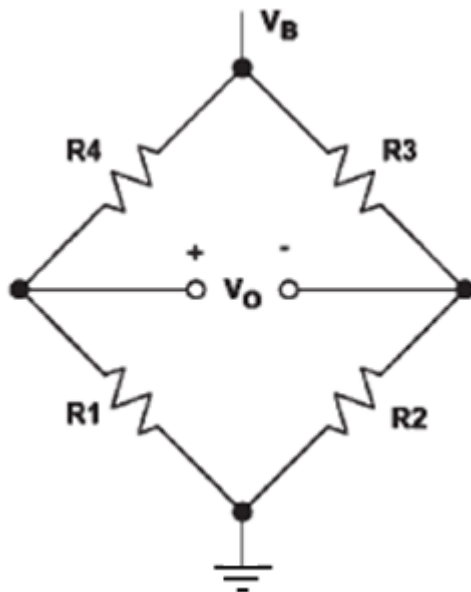


$$V_{out} = \left(1 + \frac{R_f}{R_i}\right) V_{in}$$

# REVIEW QUESTION

Draw a circuit diagram of a Bridge Circuit and write down a formula for the circuit.

Answer:



$$V_O = \frac{R1}{R1+R4} V_B - \frac{R2}{R2+R3} V_B$$

# REVIEW QUESTION

Genie Land Pte Ltd has a sensor based Data Acquisition System which uses a micro-controller that has a 10 bit ADC and takes in 3.3V.

A sensor system is connected to the micro-controller for measuring temperature (in Celsius) using the following Stimulus formula

$$\text{Temp in Celsius} = 100 (\text{Sensor voltage} - 0.5)$$

- (a) Determine the following
  - i. ADC Resolution
  - ii. Maximum ADC Quantization level
  - iii. ADC Full scale Voltage Range
  - iv. ADC Voltage Resolution
- (b) The micro-controller reads an ADC value of 233 from the sensor output.
  - i. Calculate the equivalent Sensor Voltage
  - ii. Calculate its Temperature
- (c) Determine the ADC value when the measured temperature is 23 °C.

# ANSWER

(a) (i) ADC resolution,  $M = 10$ ,

(ii) Maximum Quantization level,  $N = 2^M - 1 = \underline{1023}$

(iii) ADC Full scale Voltage Range,  $E_{FSR} = \underline{3.3V}$ ,

(iv)  $N = 1023$

Thus ADC Voltage Resolution,  $Q = E_{FSR}/N = \underline{3.23m\ V}$

(b) (i)  $Q = 3.23m$  , ADC value = 233

Thus Sensor Voltage = ADC value \*  $Q = 233 * 3.23m = \underline{0.75\ V}$

(ii) Temperature in Celsius =  $100 (0.75 - 0.5) = \underline{25\ ^\circ C}$

(c) When temperature =  $23\ ^\circ C$ ,

$23 = 100 (\text{Sensor Voltage} - 0.5)$ ,  $\Rightarrow$  Sensor Voltage =  $0.73\ V$

ADC value = Sensor Voltage /  $Q = 0.73 / 3.23m = \underline{226}$

# REVIEW QUESTION

Draw the Successive Approximation ADC circuit and describe the usage of the 4 components

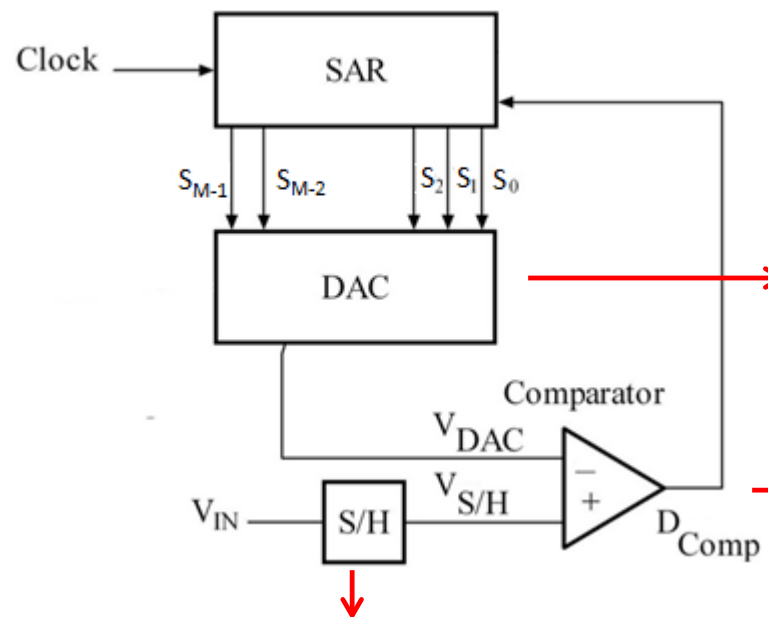
Answer:

Successive Approximation Register (SAR) for forming up the digital code output

Digital to Analog Converter (DAC) for providing analog voltage equivalent of the digital code output of the SAR

Voltage comparator that outputs either 0 or 1 to feedback to the SAR

Sample and Hold (S/H) circuit to ensure analog input is constant during operation



# REVIEW QUESTION

Signal conditioning circuit in sensor interfacing is not used for which of the following?

- A. Coupled with raw active sensor output to generate them into electric output
- B. Change Alternating Current (AC) sensor output to Direct Current (DC) output
- C. Amplify weak sensor signals
- D. Convert raw analog sensor signals into digital form

**Answers => B**

# REVIEW QUESTION

What are Amplifier, Bridge circuit and Analog to Digital Convertor (ADC) known as?

- A. Successive Approximation circuits
- B. Transformer Circuits
- C. Signal Conditioning circuits
- D. Voltage comparator circuits

**Answers => C**

# REVIEW QUESTION

What is the definition of an electronic device that takes in an input signal and produce an output signal with a larger magnitude?

- A. Amplifier
- B. Wheatstone bridge
- C. Analog to Digital Convertor (ADC)
- D. Successive Approximation Register

**Answers => A**

# REVIEW QUESTION

Which of the following is not true regarding an Operational Amplifier (Op-Amp)?

- A. It only has 3 terminals which are the Inverting input, Non-inverting input and output
- B. It is a electronic voltage amplifier with a differential input
- C. It has an open loop gain and is typically very large
- D. If the inverting input is greater than the non-inverting input, the output will be  $180^\circ$  out of phase with the input

**Answers => A**

# REVIEW QUESTION

What is used to accurately measure small resistance changes which is critical for processing signals from resistive sensors?

- A. Non-Inverting Amplifier
- B. Inverting Amplifier
- C. Successive Approximation Register
- D. Wheatstone bridge

**Answers => D**

# REVIEW QUESTION

Which of the following is not true about a Bridge circuit?

- A. It is used for processing signals from resistive sensors
- B. It has an open loop gain which is typically very large
- C. It consists of four resistors connected to form a quadrilateral
- D. It measures the difference between the outputs of two voltage dividers connected across

**Answers => B**

# REVIEW QUESTION

What tells us directly the number of bits a Analog to Digital Convertor (ADC) output generates?

- A. ADC Resolution
- B. ADC Max Quantization Level
- C. ADC Full Scale Voltage Range
- D. ADC Voltage Resolution

**Answers => A**

# REVIEW QUESTION

What indicates to us the maximum voltage a Analog to Digital Convertor (ADC) accepts?

- A. ADC Resolution
- B. ADC Quantization Voltage
- C. ADC Full Scale Voltage Range
- D. ADC Voltage Resolution

**Answers => C**

# REVIEW QUESTION

The largest digital output of a Analog to Digital Convertor (ADC) is known as \_\_\_\_\_?

- A. ADC Resolution
- B. ADC Max Quantization Level
- C. ADC Full Scale Voltage Range
- D. ADC Voltage Resolution

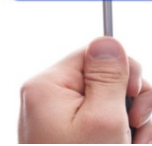
**Answers => B**

# REVIEW QUESTION

What of the following states the difference in voltage between each quantization levels?

- A. ADC Resolution
- B. ADC Differential Voltage
- C. ADC Full Scale Voltage Range
- D. ADC Voltage Resolution

**Answers => D**



# STRUCTURED QUESTIONS

Steady Sensor Pte Ltd has recently bought a new ultrasonic sensor. The sensor output is connected to a processor which has an internal 10 bit Analog to Digital Convertor (ADC) and takes in 5V.

A sensor system is connected to the micro-controller for measuring distance using the following Stimulus formula

$$\text{Distance} = \text{Sensor Voltage} / 9.8\text{m} * 2.5$$

- (a) Determine the following:
  - i. ADC Resolution
  - ii. Maximum ADC Quantization level
  - iii. ADC Full scale Voltage Range
  - iv. ADC Voltage Resolution
- (b) The micro-controller reads an ADC value of 60 from the sensor output.
  - i. Calculate the equivalent Sensor Voltage.
  - ii. Calculate the actual distance
- (c) Determine the ADC value when the measure distance is 100 cm.