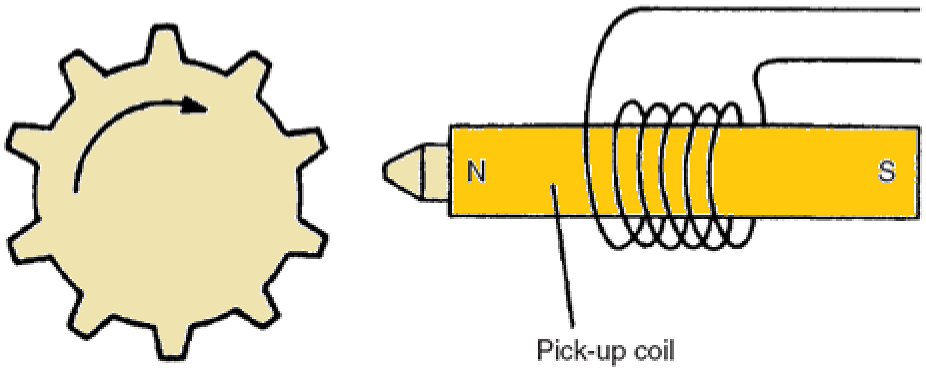
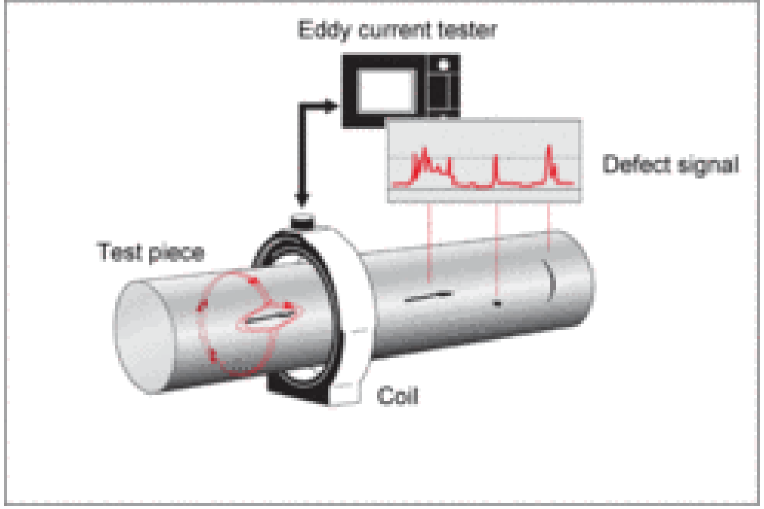
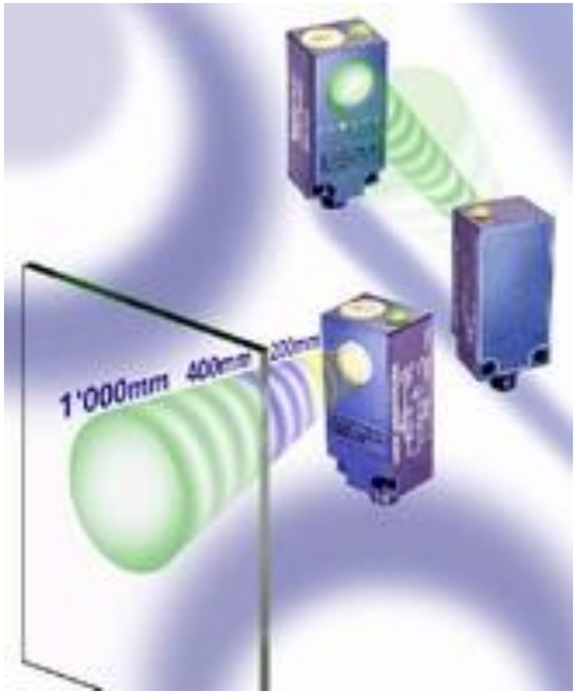
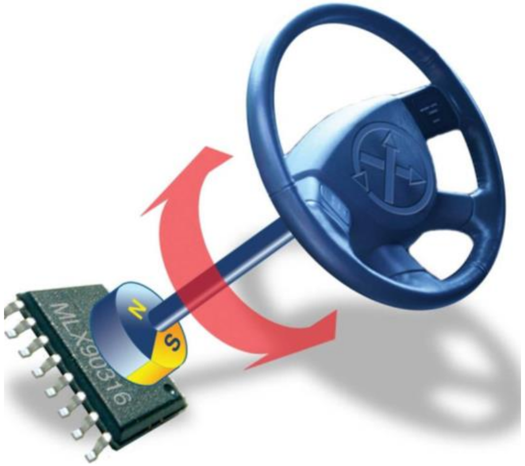
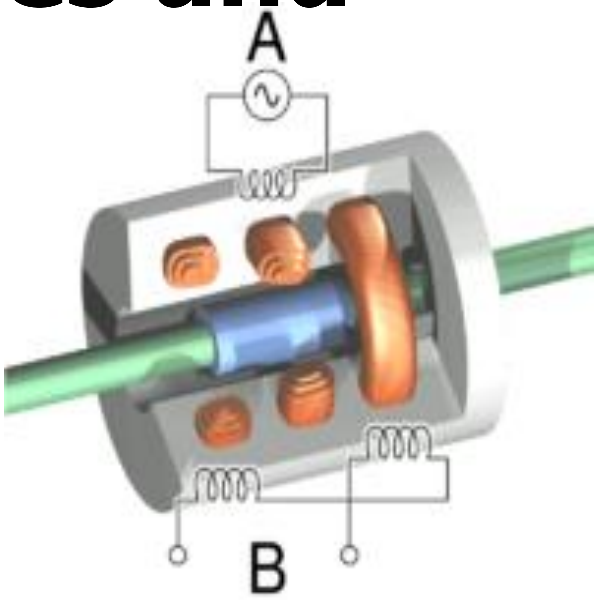




L6- Sensor Technologies and Sensors







Sensor/Transducer Technologies

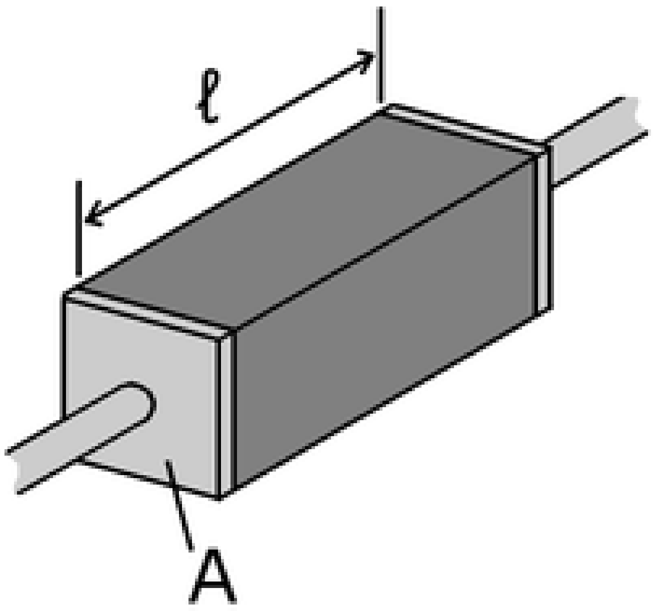
- **Resistive sensors**
- **Piezoresistive sensors**
- **Capacitive sensors**
- **Magnetic Sensors**
- **Hall Effect Sensors**
- **Piezoelectric transducers**
- **Light sensors**
- **Photo Interrupts**
- **Optical Sensors**
- **Infrared Sensors**
- **Ultrasonic Transducers**
- **Translational Motion Transducers**
- **Temperature Transducers**

1. Resistive sensors

- Resistive sensors rely on the variation of the resistance of a piece of material when the measured variable is applied to it.
- Many resistors and conductors have a uniform cross section and their resistance, *R*, is given by:

$$R = \rho(l/A)$$

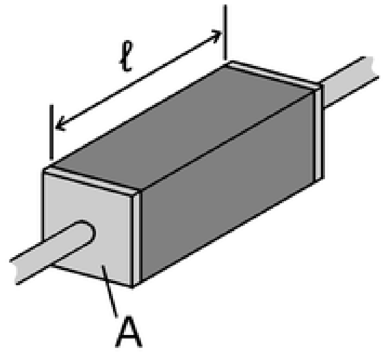
where ρ is the resistivity of the element's material, l is its length and A is its cross sectional area.

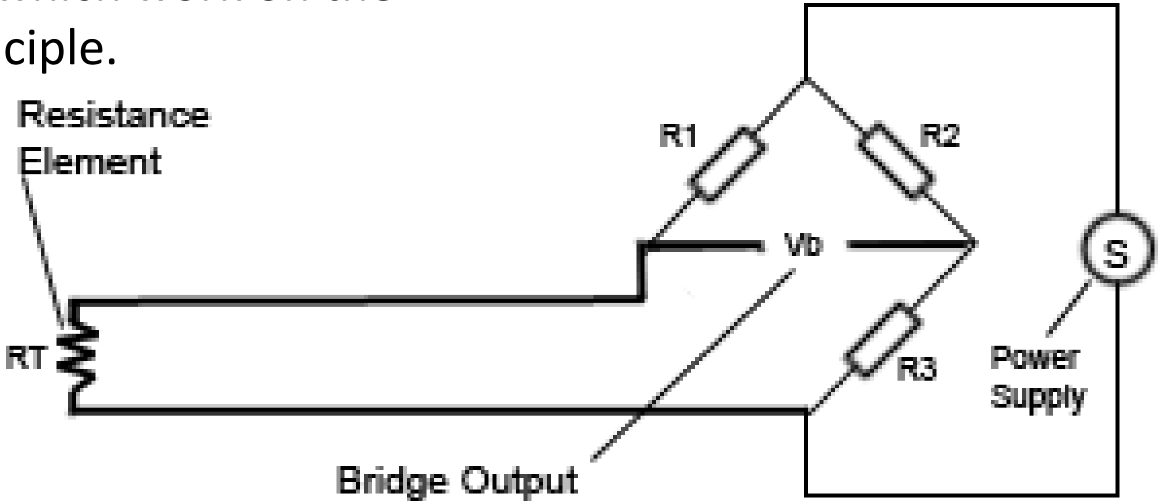


Resistive sensors:

- Many resistive sensors rely on the **variation of the resistivity of the element's material** when measured variable is changed. Common application of this principle is found in:
  - Resistance thermometers or resistive temperature detectors (RTDs)
  - Piezoresistive sensors and Piezoresistive strain gauges.
  - Some moisture meters which work on the resistivity-variation principle.

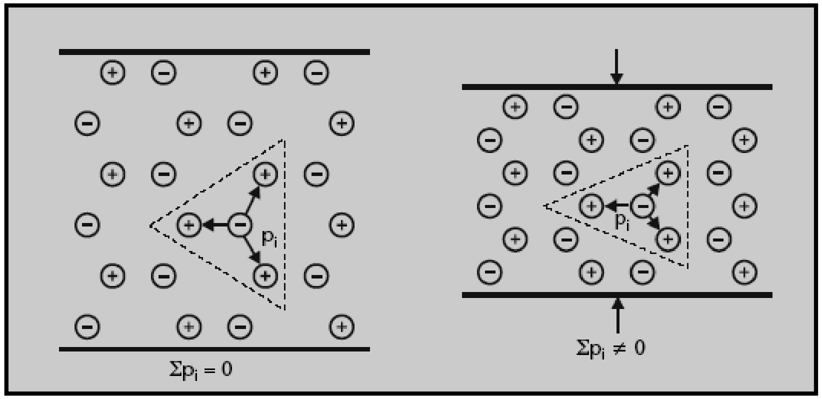
$$R = \rho(l/A)$$





Piezoresistive sensors

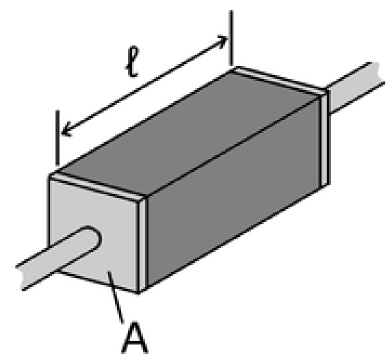
- A piezoresistive sensor **is made from semiconductor material** in which a p-type region has been diffused into an n-type base. The resistance of this varies greatly when the sensor is compressed or stretched.



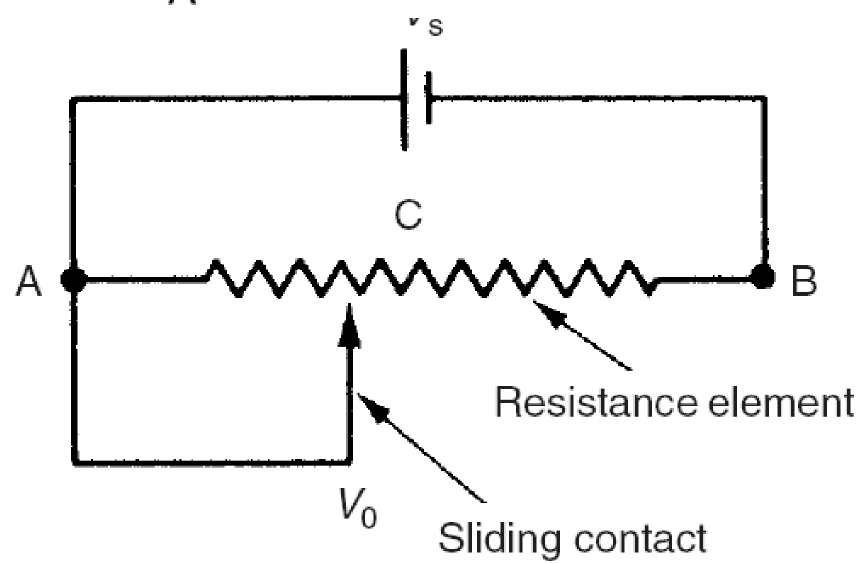
- This is frequently used as a strain gauge, where it produces a significantly higher gauge factor than that given by metal wire or foil gauges. Also, measurement uncertainty can be as low as ±0.1%.
- It is also used in semiconductor pressure sensors and in semiconductor accelerometers.

Resistive sensors: Potentiometers

- The resistive potentiometer is perhaps the best-known displacement-measuring device.
- It relies on changing the length /along which of the resistor is measured
- A linear relationship exists between the length and the resistance.

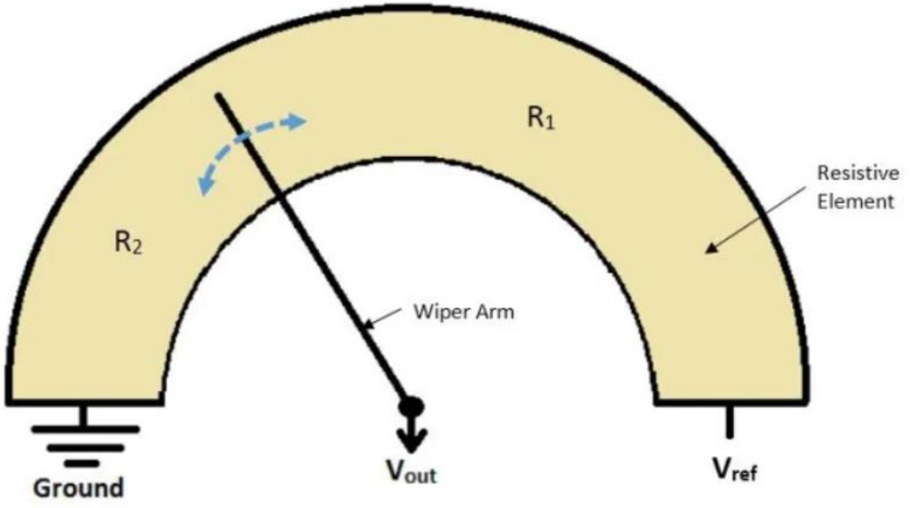


$$R = \rho\left(l/A\right)$$



Example : Electronic Throttle Control (ETC)

- In ETC systems, a vehicle's electronic control unit uses information from the throttle position sensor (TPS), accelerator pedal position sensor (APP sensor), wheel speed sensors, vehicle speed sensor and a variety of other sensors to determine how to adjust throttle position.
- TPS and APP sensors are very simple. The accelerator pedal position sensor and the throttle position sensor work together to translate user input into throttle plate movement.
- Until recently, these sensors have utilized potentiometers that worked as voltage dividers.
- The "divided" voltage is sent to a computer (ECU), which uses it to adjust the position of the throttle.



Example : Electronic Throttle Control (ETC)

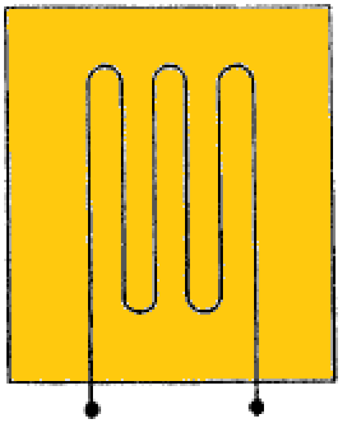
- The ECU takes in this signal, and sends an appropriate signal to a throttle actuator, which moves the throttle plate.
- The throttle position sensor works in a similar way. The potentiometer wiper is connected to the butterfly valve spindle. As the butterfly valve opens and closes, it varies the output voltage from 0 to the reference voltage. This output voltage is sent to the ECU. This is how the ECU knows the position of the throttle plate.
- The problem with potentiometer-based sensors is that, as the wiper arm and the resistive element rub against one another, they eventually wear out.
- Newer accelerator pedal position sensors use Hall effect as their basic operating principle.

https://jalopnik.com/how-electronic-throttle-control-works-499966101

https://www.infineon.com/dgdl/AppNote_Pedal_Position_Sensing_Rev.1.0.pdf?fileId=db3a30432313ff5e0123a38779c5262f

Resistive sensors: Metal Strain Gauges

- Strain gauges are devices that experience a change in resistance when they are stretched or strained.
- They are typically used as part of other transducers, for example diaphragm pressure sensors that convert pressure changes into small displacements of the diaphragm.



- The traditional metal strain gauge consists of a length of metal resistance wire formed into a zigzag pattern and mounted onto a flexible backing sheet.
- The wire is nominally of circular cross-section. As strain is applied to the gauge, the shape of the cross-section of the resistance wire distorts, changing the cross-sectional area.

$$R = \rho(l/A)$$

- As the resistance of the wire per unit length is inversely proportional to the cross-sectional area, there is a consequential change in resistance.
- The input–output relationship of a strain gauge is expressed by the gauge factor, which is defined as the change in resistance (R) for a given value of strain (S).

$$\text{gauge factor} = \frac{\delta R}{\delta S}$$

Strain gauges

- Strain gauges are manufactured to various nominal values of resistance, of which 120, 350 and 1000 are very common.
- The typical maximum change of resistance in a 120 device would be 5 at maximum deflection.
- Semiconductor strain gauges also are available with piezo-resistive elements, which are considered in greater detail in the next section.
- Compared with metal gauges, semiconductor types have a much superior gauge factor (up to 100 times better) but they are more expensive.
- Also, whilst metal gauges have an almost zero temperature coefficient, semiconductor types have a relatively high temperature coefficient

2. Capacitive sensors

- Capacitive sensors consist of two parallel metal plates in which a dielectric between the plates. A dielectric is an electrical insulator that can be polarized by an applied electric field. is either air or some other medium.

- The capacitance C is given by:

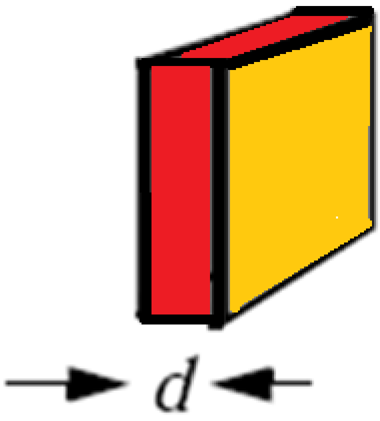
$$C = \varepsilon_o \varepsilon_r \frac{A}{d}$$

where ε_o is absolute permittivity, ε_r is the relative permittivity of the dielectric medium between the plates, A is the area of the plates and d is the distance between them.

Capacitive sensors

- Capacitive devices are often used as displacement sensors, **in which motion of a moveable capacitive plate relative to a fixed one changes the capacitance.**
- Often, the measured displacement is part of instruments measuring pressure, sound or acceleration.
- Alternatively, **fixed plate capacitors** can also be used as sensors, in which the capacitance value is changed by causing the measured variable **to change the dielectric constant** of the material between the plates in some way.
- **This principle is used in devices to measure moisture content, humidity values and liquid level.**
- **Also Capacitive proximity sensors exsist**

$$C = \varepsilon_o \varepsilon_r \frac{A}{d}$$

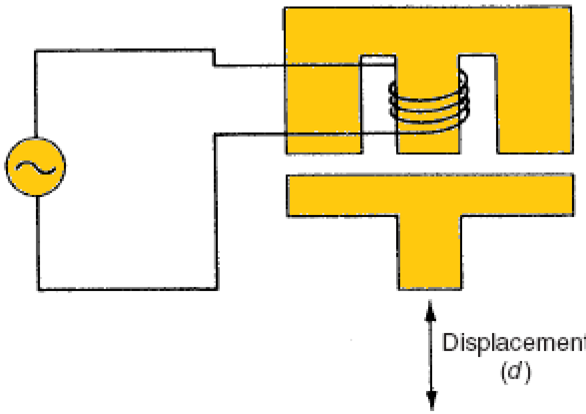


3. Magnetic Sensors

- **Magnetic sensors utilize the magnetic phenomena of:**
  - **inductance,**
  - **reluctance**
  - **eddy currents**
- **Used to indicate the value of the measured quantity, which is usually some form of displacement.**

Inductive Sensors

- In the inductive displacement transducer, the single winding on the central limb of an 'E'-shaped ferromagnetic body is excited with an alternating voltage.
- The displacement to be measured is applied to a ferromagnetic plate in close proximity to the 'E' piece.
- Movements of the plate alter the flux paths and hence cause a change in the current flowing in the winding. The current-voltage relationship in the winding is given by:
- For fixed values of ω and V, I depends only on *L*, which in turn, depends on the displacement *d* applied to the plate.
- The relationship between L and *d*, is a non-linear one, and hence the output-current/displacement characteristic has to be calibrated.



$$v = L\frac{di}{dt},$$

$$i = \frac{1}{L}\int v dt = \frac{V}{L}\int \cos\omega t dt$$

$$= \frac{V}{\omega L}\sin\omega t$$

$$I = \frac{V}{\omega L}$$

Magnetic Reluctance

- Magnetic Reluctance is analogous to resistance in an electrical circuit (although it does not dissipate magnetic energy).
- An electric field causes an electric current to follow the path of least resistance,
- **<u>A magnetic field causes magnetic flux to follow the path of least magnetic reluctance</u>**

- The definition can be expressed as: $\mathcal{R}=F/\Phi$

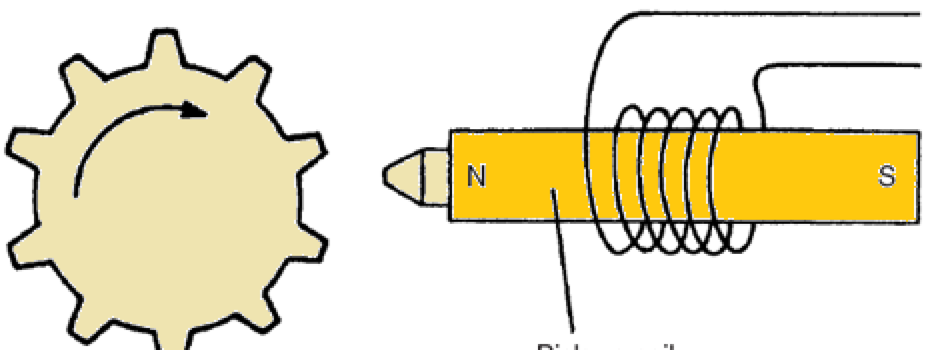
where

- ("$\mathcal{R}$") is the reluctance in ampere-turns per weber (a unit that is equivalent to turns per henry). "Turns" refers to the winding number of an electrical conductor comprising an inductor.
- ("F") is the magnetomotive force (MMF) in ampere-turns
- Φ ("Phi") is the magnetic flux in webers.

Variable Reluctance Sensors

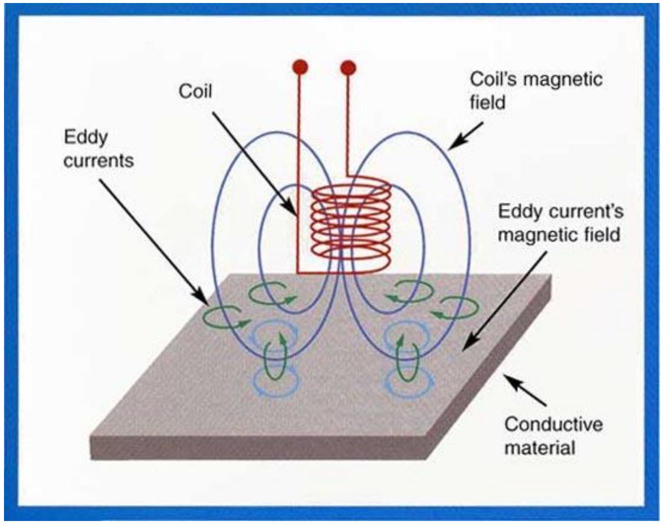
- Variable reluctance sensors are a class of magnetic sensors in **which a coil** is **wound on a permanent magnet** rather than on an iron core as in variable inductance sensors.
- Such devices are commonly used to measure rotational velocities.
- In a typical instrument a ferromagnetic gearwheel is placed next to the sensor.
- As the tip of each tooth on the gearwheel moves towards and away from the pick-up unit, the changing magnetic flux in the pick-up coil causes a voltage **to be induced in the coil** whose magnitude is proportional to the rate of change of flux.
- Thus, the output is a sequence of positive and negative pulses whose frequency is proportional to the rotational velocity of the gearwheel.

https://www.youtube.com/watch?v=37oJtcUTpL8

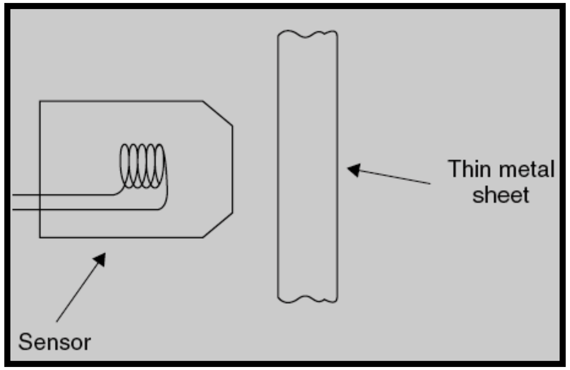


Eddy Current Sensors

- Eddy current sensors are a third class of magnetic sensors and **consist of a probe containing a coil that is excited at a high frequency, which is typically 1MHz**.



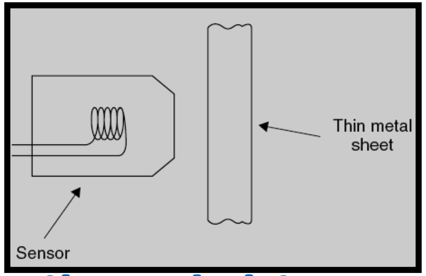
- This is used to measure the displacement of the probe relative to a moving metal target.
- Because of the high frequency of excitation, eddy currents are induced in the surface of the target and the current magnitude reduces to almost zero a short distance inside the target.



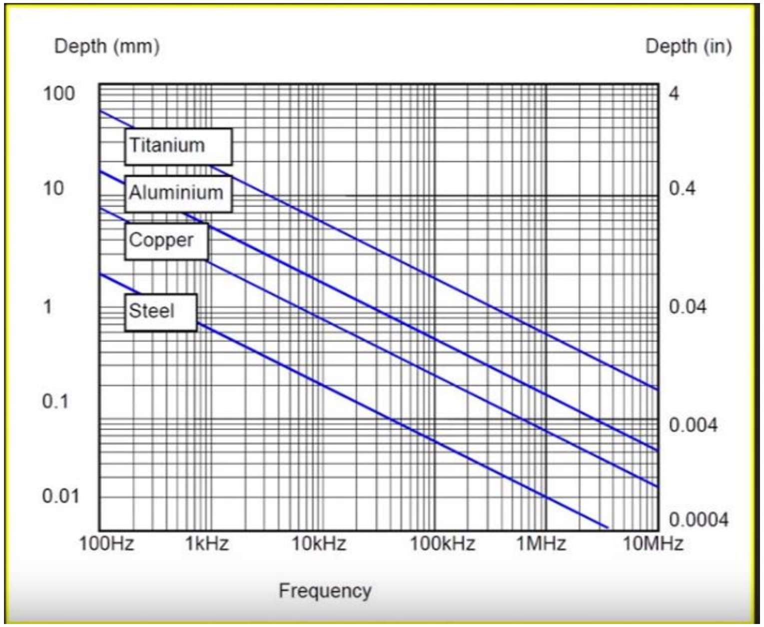
- This allows the sensor to work with very thin targets, such as the steel diaphragm of a pressure sensor.

https://www.youtube.com/watch?v=T0DMHIbaPnc

Eddy Current Sensors



- **The eddy currents alter the inductance of the probe coil, and this change can be translated into a d.c. voltage output that is proportional to the distance between the probe and the target**.
- Measurement resolution as high as 0.1 µm can be achieved.
- A signal conditioning circuit can be used to measure change in dc voltage/current as a function of distance

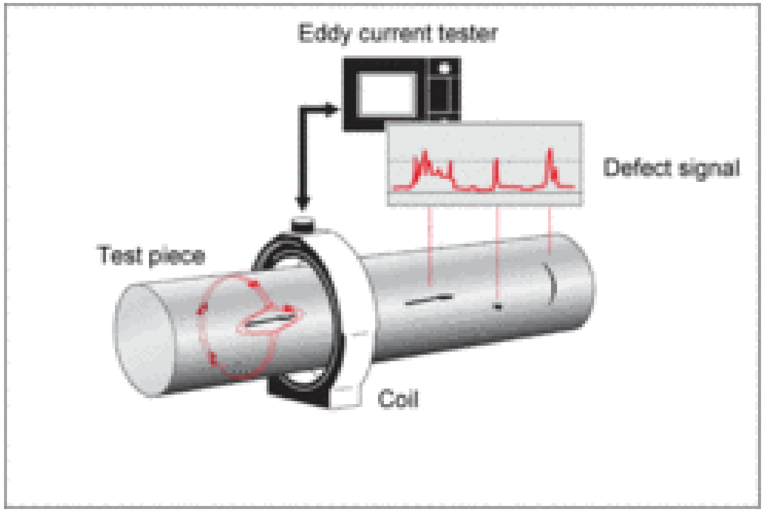


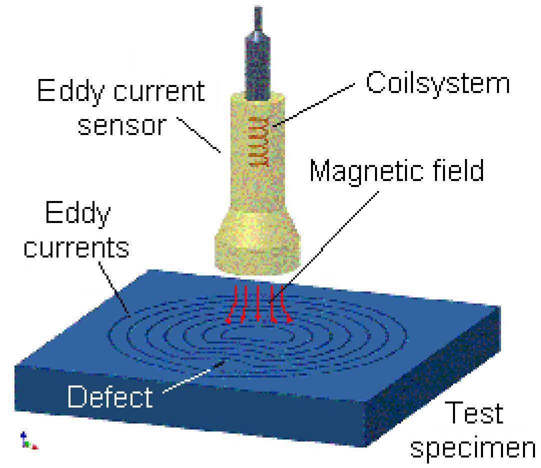
Eddy Current sensor applications

- The sensor can also work with a non-conductive target if a piece of aluminum tape is fastened to it.

__Distance measurement__

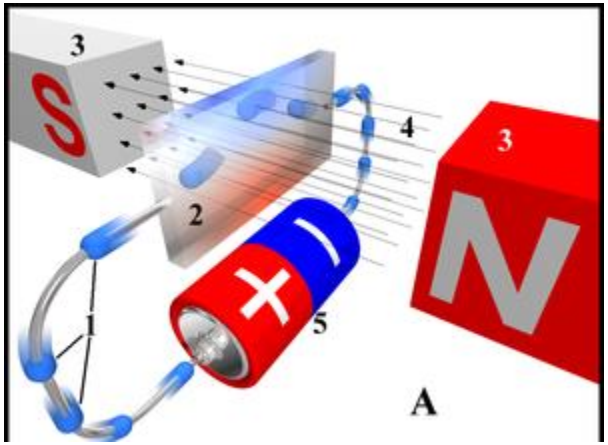
__For product testing__





Hall Effect Sensors

The Hall effect refers to the potential difference (Hall voltage) on the opposite sides of an electrical conductor through which an electric current is flowing, created by a magnetic field applied perpendicular to the current. Edwin Hall discovered this effect in 1879.



Hall effect diagram, showing electron flow (rather than conventional current).

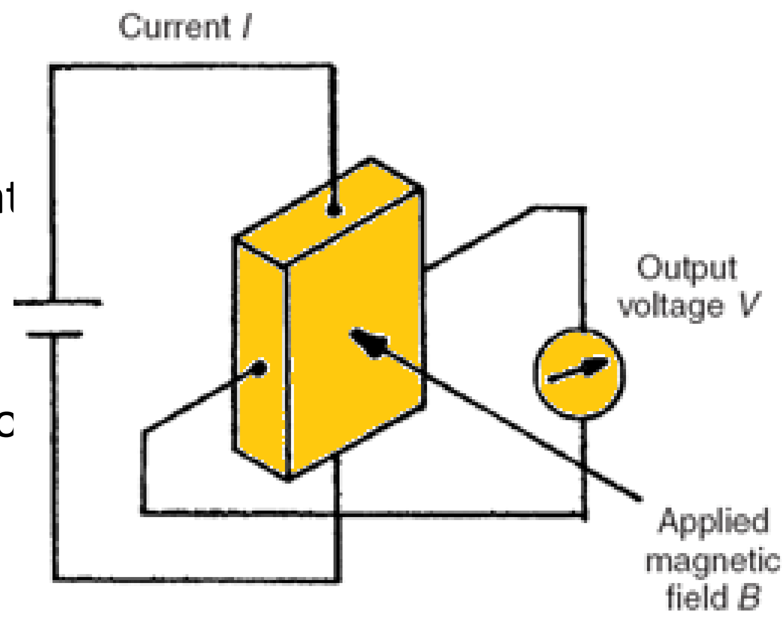
Legend:

1. Electrons
2. Hall element, or Hall sensor
3. Magnets; 4. Magnetic field ;
5. Power source

Description:

In drawing "A", the Hall element takes on a negative charge at the top edge (symbolised by the blue color) and positive at the lower edge (red color).

Hall-effect sensors



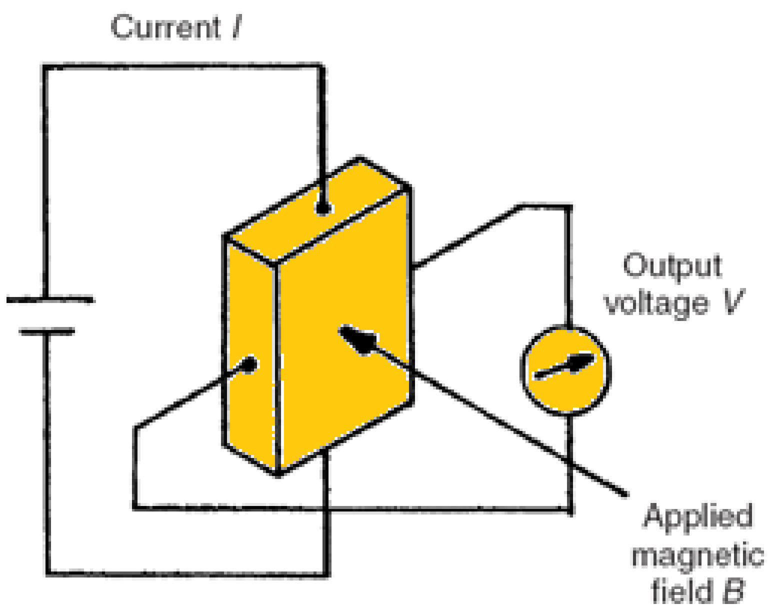
- A Hall-effect sensor is a device that is used to measure the magnitude of a magnetic field.
- It consists of a conductor carrying a current that is aligned orthogonally with the magnetic field.
- This produces a transverse voltage difference across the device that is directly proportional to the magnetic field strength.
- For an excitation current I and magnetic field strength B, the output voltage is given by

  V= KIB,

  where K is known as the Hall constant.
- The conductor in Hall-effect sensors is usually made from a semiconductor material as opposed to a metal, because a larger voltage output is produced for a magnetic field of a given size.

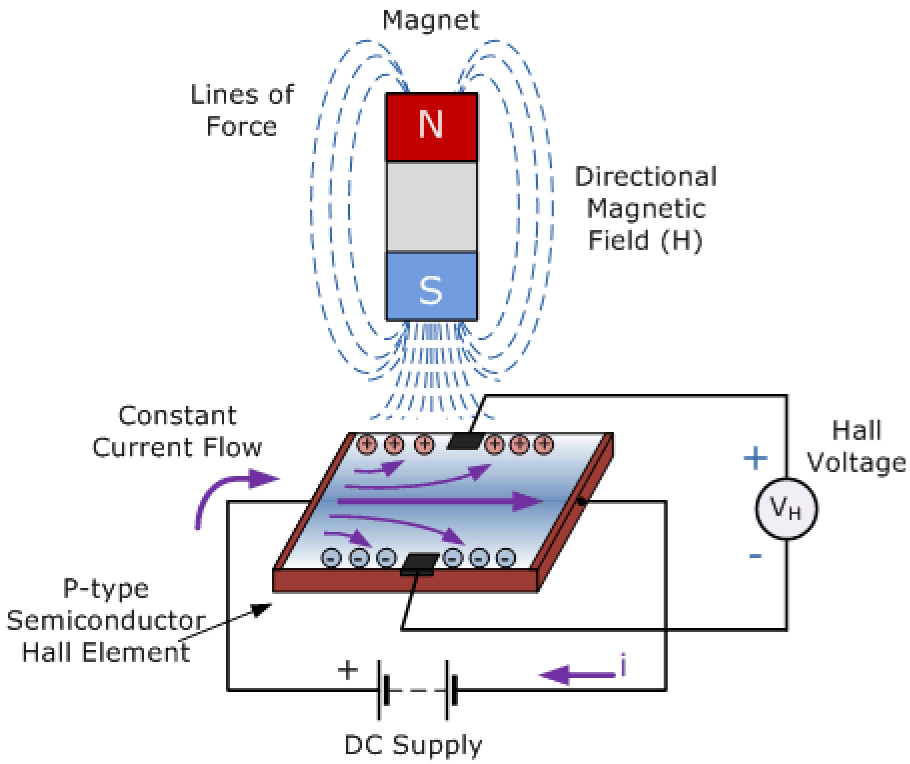
Hall-effect sensors

- In one common use of the device as a **proximity sensor**, the magnetic field is provided by a permanent magnet that is built into the device.
- The magnitude of this field changes when the device becomes close to any ferrous metal object or boundary.
- **The Hall effect is also commonly used in keyboard pushbuttons**, in which a magnet is attached underneath the button.
- When the button is depressed, the magnet moves past a Hall-effect sensor. The induced voltage is then converted by a trigger circuit into a digital output. **Such pushbutton switches can operate at high frequencies without contact bounce.**

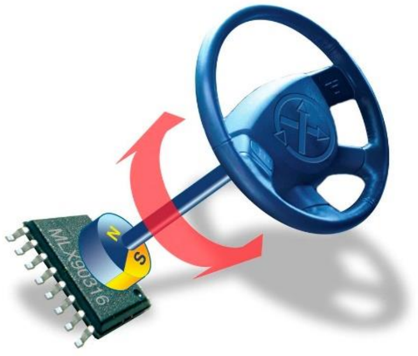


https://www.youtube.com/watch?v=wpAA3qeOYiI

Hall Effect Current Sensor



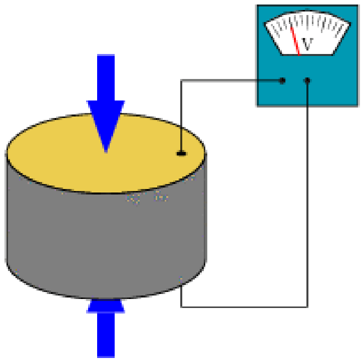
Example : Electronic Throttle Control (ETC)



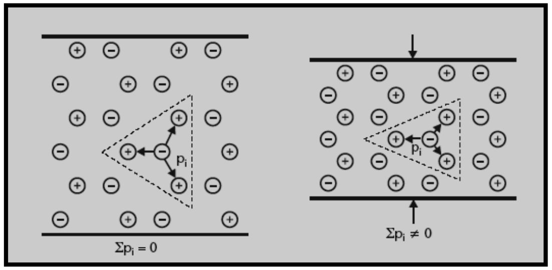
- Newer accelerator pedal position sensors and throttle position sensors use Hall effect as their basic operating principle.
- These sensors contain transducers that convert external magnetic fields into voltage.
- Using magnets placed on the pedal and throttle shaft as reference points, Hall effect sensors output a different voltage depending on the intensity of the magnetic field.
- As the pedal or throttle moves, so does the magnet. This movement changes the magnetic field strength and thus alters output voltage from the sensor to the ECU.
- MLX90316 Non-contact absolute non-contacting rotary sensor IC allows simple implementation of rugged 360 degree position indicators.
- Applications include Throttle position sensing, pedal position drive by wire sensors, ride height, shaft position and other 0 to 360 degree absolute rotary position indication applications.
- The IC is fully programmable to allow the user to set the angular range to any value and still have rail to rail signal for the chosen angular displacement

Piezoelectricity

- **Piezoelectricity** is the ability of some materials **(notably crystals and certain ceramics)** to generate an electric potential in response to applied mechanical stress.
- This may take the form of a separation of electric charge across the crystal lattice. If the material is not short-circuited, the applied charge induces a voltage across the material.
- The word is derived from the Greek *piezein*, which means to squeeze or press.
- **The piezoelectric effect is <u>reversible</u> in that materials exhibiting the direct piezoelectric effect (the production of electricity when stress is applied) also exhibit the converse piezoelectric effect (the production of stress and/or strain when an electric field is applied).**
- For example, lead zirconate titanate crystals will exhibit a maximum shape change of about 0.1% of the original dimension.



Piezoelectric transducers



- Piezoelectric materials have an asymmetrical lattice of molecules that distorts when a mechanical force is applied to it.
- This distortion causes a reorientation of electric charges within the material, resulting in a relative displacement of positive and negative charges.
- The charge displacement induces surface charges on the material of opposite polarity between the two sides. By implanting electrodes into the surface of the material, these surface charges can be measured as an output voltage. For a rectangular block of material, the induced voltage is given by:

$$V = \frac{kFd}{A}$$

where F is the applied force, A is the area of the material, d is the thickness of the material and k is the piezoelectric constant. The polarity of the induced voltage depends on whether the material is compressed or stretched.

Piezoelectric Materials

- Materials exhibiting piezoelectric behavior:

$$V = \frac{kFd}{A}$$

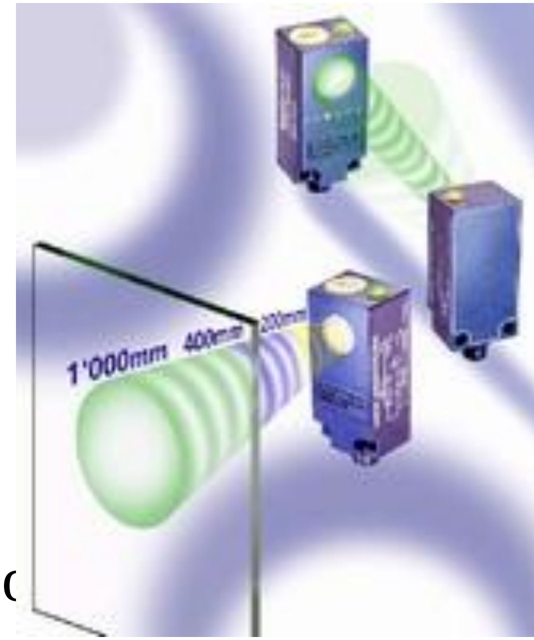
- Natural materials: **quartz**,
- **Synthetic materials : lithium sulphate**
- **Ferroelectric ceramics: barium titanate.**

- The piezoelectric constant "k" varies widely between different materials. Typical values of k are 2.3 for quartz and 140 for barium titanate.
- Applying equation for a force of 1 g applied to a crystal of area 100 mm2 and thickness 1 mm gives an output of 23 μV for quartz and 1.4 mV for barium titanate.
- They are frequently used as **ultrasonic receivers** and also as **displacement transducers**, particularly as part of devices measuring **acceleration**, **force** and **pressure**.

https://www.youtube.com/watch?v=ACsy6xSIBm8

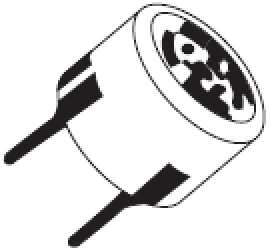
4 min video

Ultrasonic transducers

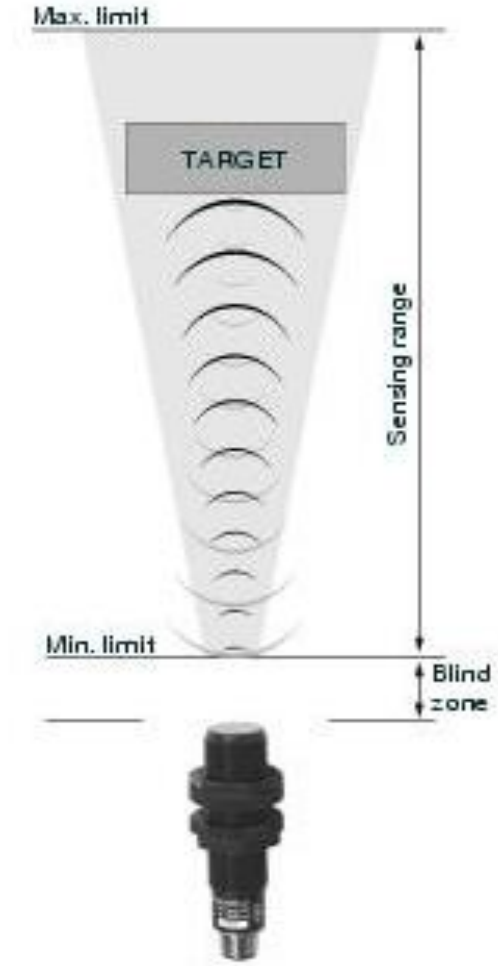


- Ultrasonic devices are used for measuring of different physical quantities
- Ultrasound is a band of frequencies in the range above **20 kHz up to 15 MHz**, that is, above the sonic range that humans can usually hear.
- Measurement devices that use ultrasound consist o one device that transmits (Tx) an ultrasound wave and another device that receives (Rx) the wave
- Changes in **the measured variable** are determined either by measuring the change **in time taken** for the ultrasound wave **to travel between the transmitter and receiver**, or, alternatively, by measuring the **change in phase** or **frequency** of the transmitted wave.

Ultrasonic transducers



- The most common form of ultrasonic element is a piezoelectric crystal contained in a casing.
- Such elements can operate interchangeably as either a transmitter or receiver. These are available with operating frequencies that vary between 20 kHz and 15 MHz.
- As a piezoelectric crystal, , it generates an ultrasonic wave when an alternating voltage is applied.
- It also works in reverse. When it receives a sound wave, it generates an alternating voltage.



- Also capacitive ultrasonic elements exist.
- These consist of a thin, dielectric membrane between two conducting layers.
- Elements with resonant frequencies in the range between 30 kHz and 3MHz can be obtained.

Factors affecting Ultrasonic waves

- When transmitted through air, **the speed of ultrasound** is affected by environmental factors such as **temperature, humidity and air turbulence**.
- Temperature has the largest effect. The velocity of sound through air varies with temperature according to:

$$V = 331.6 + 0.6T \text{ m/s}$$

where T is the temperature in ° C.

- Thus, even for a relatively small temperature change of 20 degrees from 0° C to 20° C, the velocity changes from 331.6 m/s to 343.6 m/s.

Table 13.1 Transmission speed of ultrasound through different media

Medium	*Velocity* (m/s)
Air	331.6
Water	1440
Wood (pine)	3320
Iron	5130
Rock (granite)	6000

Other factors affecting Ultrasonic waves

- Humidity changes have a much smaller effect. If the relative humidity increases by 20%, the corresponding increase in the transmission velocity of ultrasound is 0.07% (corresponding to an increase from 331.6m/s to 331.8m/s at 0° C).
- Changes in air pressure itself have negligible effect on the velocity of ultrasound.
- Similarly, air turbulence normally has no effect (though note that air turbulence **may deflect ultrasound waves away from their original direction of travel**).
- However, if turbulence involves currents of air at different temperatures, then random changes in ultrasound velocity occur according to equation (6.2).

Ultrasound Range Sensor (distance sensor)

- $X = v_{sound} \cdot t$
- Where:
  - V_{sound} is known
  - t = 0.5 (time of flight)
  - X is distance between sensor head and object
- Range of sensor varies between 5 cm to 20 m
- Sensor is not appropriate for very short distance measurements
- Frequency response (distance measurement update rate) varies with distance measured
  - In general, it is about 100 Hz

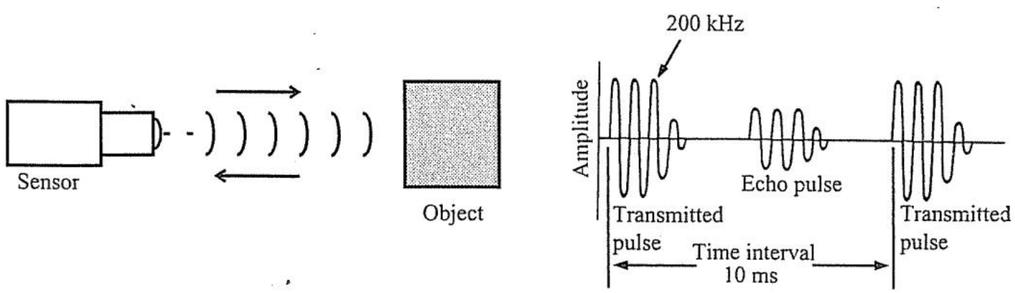


FIGURE 6.26: Operating principle of a sonic distance sensor.

Temperature Effect

- An obvious difficulty in applying this equation is the variability of v with temperature .
- One solution to this problem is to include an extra ultrasonic transmitter/ receiver pair in the measurement system in which the two elements are positioned a known distance apart.
- This allows measurement of transmission time of energy between this fixed pair which provides compensation of temp effects

Ultrasound Technology Applications

- **Translational Displacement (motion in straight line)**
- **Wind speed and direction (anemometer),**
- **Speed through air or water**
- **Fluid flow rates.**
- Level (amount) of liquid in tank
  - sensor measures distance to surface of fluid.
- Other applications include:
  - in robots for obstacle avoidance
  - Burglar alarms
  - Non-destructive testing, and etc

Wavelength, frequency and directionality of ultrasound waves

- The frequency and wavelength of ultrasound waves are related according to:

  $\lambda = v/f$

- where λ is the wavelength,
- v is the velocity and
- f is the frequency of the ultrasound waves.
- v is also affected by Humidity and temperature

Attenuation of ultrasound waves

- Ultrasound waves suffer attenuation in the amplitude of the transmitted energy according to the distance traveled.
- The amplitude Xd of the ultrasound wave at a distance d from the emission point can be expressed as:
-

$$\frac{X_d}{X_0} = \frac{\sqrt{e^{-\alpha d}}}{f d}$$

-
- where X_0 is the magnitude of the energy at the point of emission, f is the nominal frequency of the ultrasound
- and α is the attenuation constant that depends on frequency, medium and pollution such as dust

Resolution and Accuracy

- Best resolution of ultrasonic ranging system is equal to wavelength of the transmitted wave

$$\lambda = v/f$$

- High frequency elements seem to be preferable since λ is smaller, but range is less for higher frequency due to higher attenuation of the wave as it travels from Tx to Rx
- Here frequency choice is a compromise between resolution and range.

Ultrasonic Imaging

- **<u>The main applications of ultrasound in imaging are found in medical diagnosis and in industrial testing procedures.</u>**
- In both of these applications, a short burst of ultrasonic energy is transmitted from the ultrasonic element into the medium being investigated and the energy that is reflected back into the element is analyzed using advanced signal processing techniques.
- Ultrasound is reflected back at all interfaces between different materials, with the proportion of energy reflected being a function of the materials either side of the interface.
- The principal components inside a human body are water, fat, muscle and bone, and the interfaces between each of these have **different reflectance** characteristics.
- Measurement of the time between energy transmission and receipt of the reflected signal gives the depth of the interface.

Ultrasound **in medical diagnosis procedures**

- **Diagnosis procedures**:

1) The reflected energy appears as a series of peaks, with the magnitude of each peak corresponding to the type of interface that it is reflected from

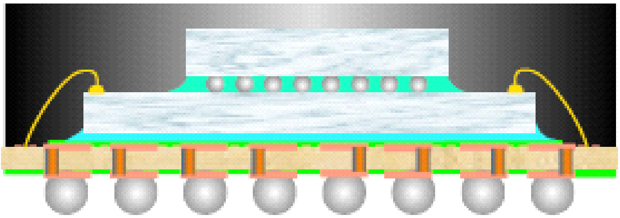
2) The time of each peak corresponding to the depth of the interface in the body.

3) Thus, a ‘map’ of fat, muscle and bone in the body is obtained. A fuller account can be found elsewhere (Webster, 1998).

- **Applications in industrial test procedures usually involve detecting internal flaws (defects) within components**.

Identifications of Solder Bump Defects in Chip Packages

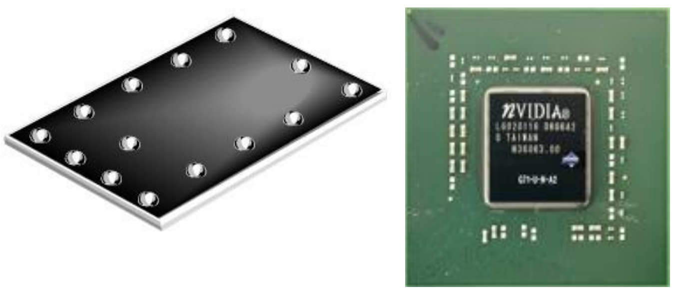
Examples of Emerging Microelectronic Packages:



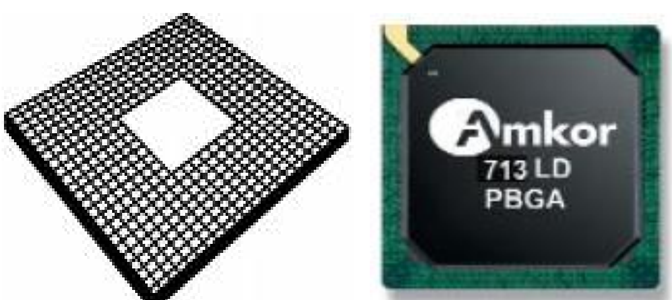
3-D Packaging: Stacked Die

Chip Scale Package

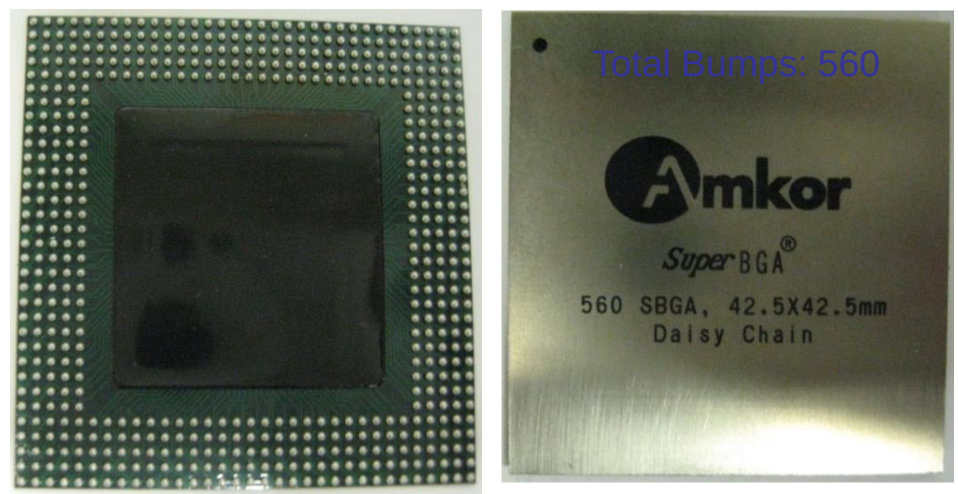
Quad Flat Package (QFP)



Flip Chip

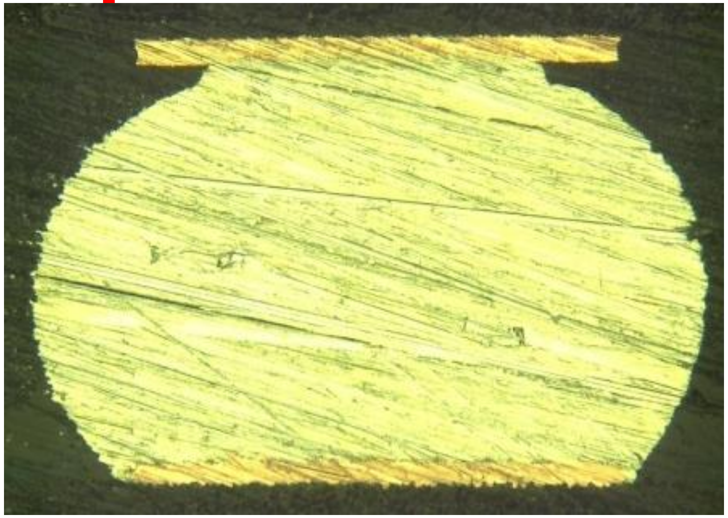


Ball Grid Array (BGA)

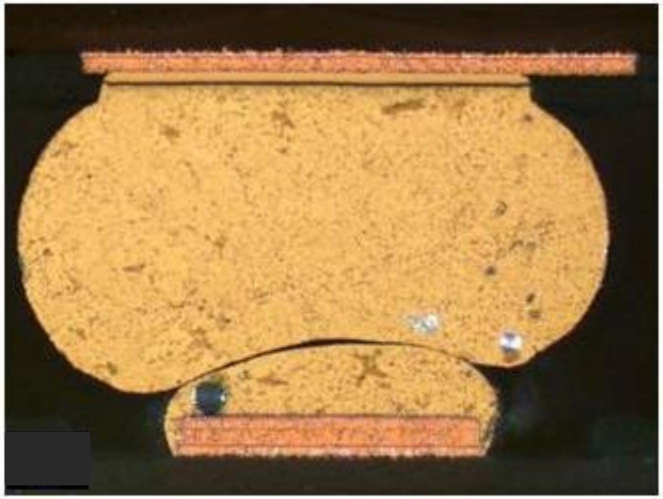


Amkor Super BGA

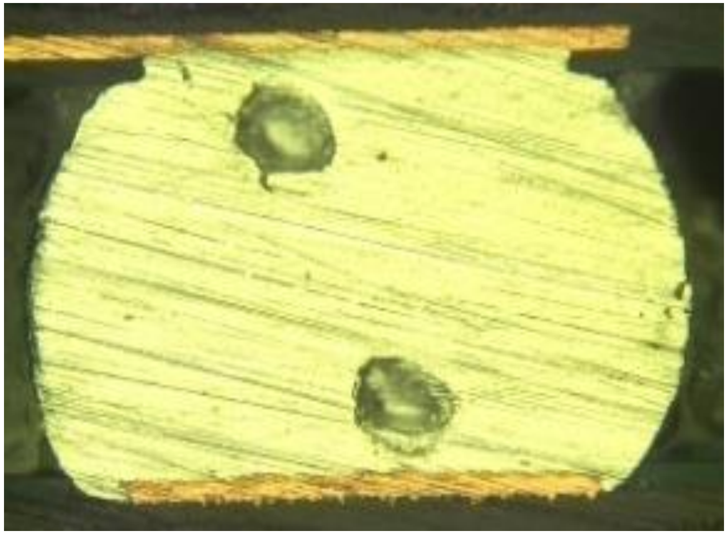
Optical Micrographs of Good and Bad Solder Bump Cross Sections



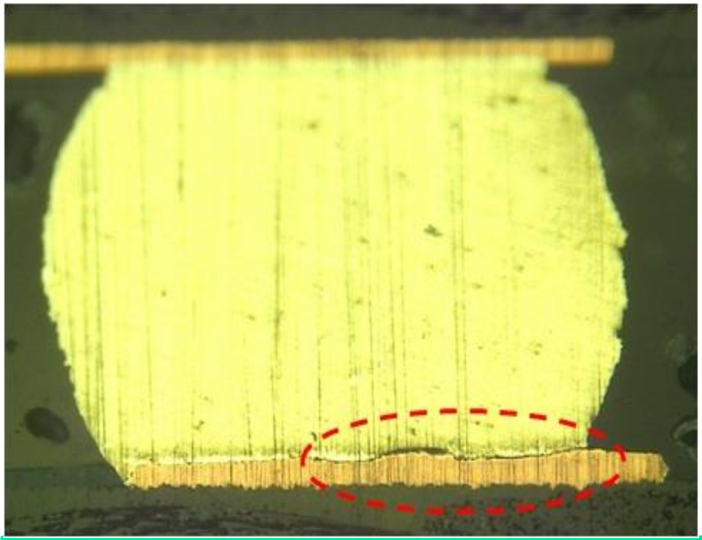
Good Solder Bump



Head-in-Pillow defects

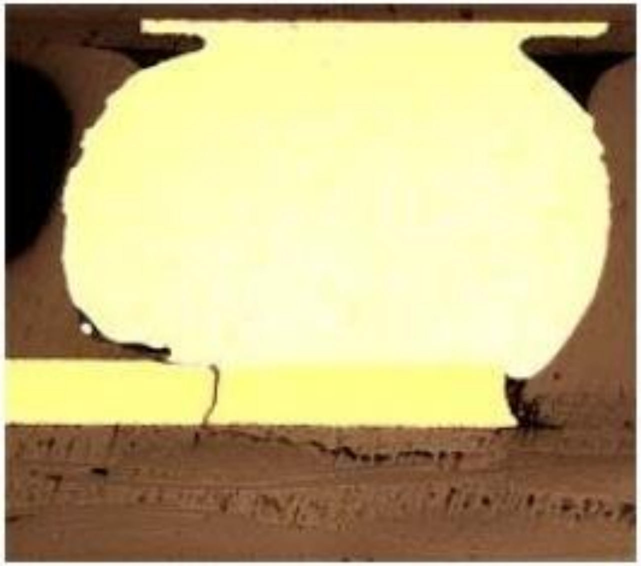


Two medium size voids near the interface

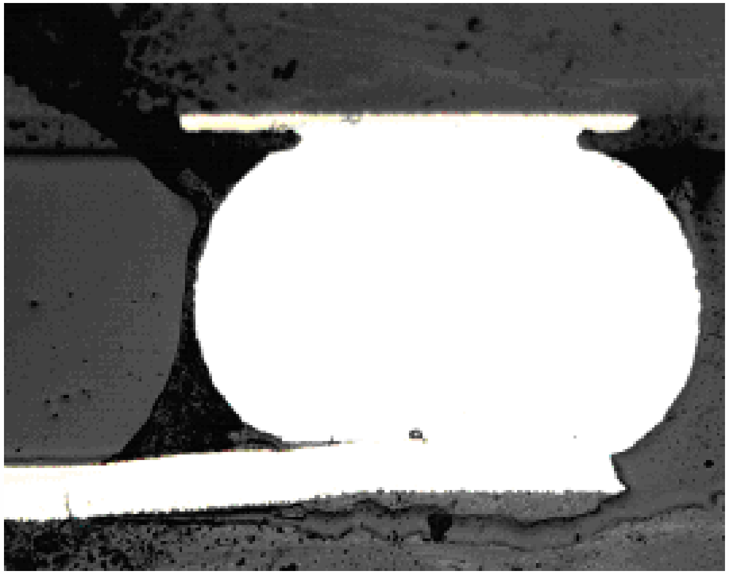


Poor wetting, an intermittent connection

Optical micrographs of Good and Bad Solder Bump Cross Sections



Pad crater with crack initiating at the trace



Crack initiates at the edge of the pad

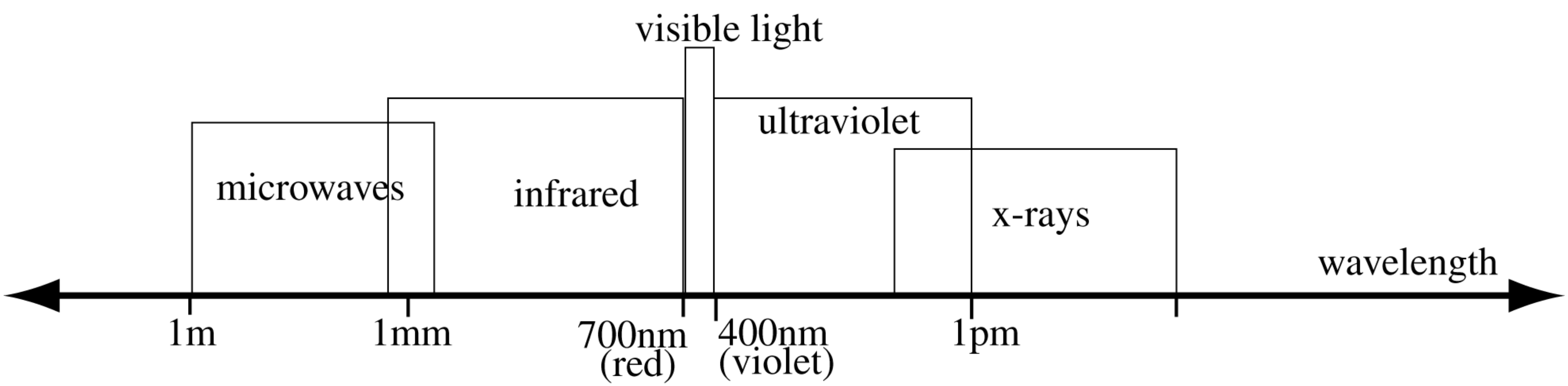
Inspection of solder bumps is crucial process in microelectronics manufacturing industry.

Optical sensors

- Optical sensors are those sensors that detect electromagnetic radiation in the broad optical range – from **far infrared** to **ultraviolet**
- Approximate range of wavelengths from **1mm** ($3x10^{11}$ Hz or far infrared) to **1 nm** ($3x10^{17}$ Hz or upper range of the ultraviolet range).
- **Direct methods** of transduction from light to electrical quantities (photovoltaic or photo-conducting sensors)
- **Indirect methods** such as conversion first into temperature variation and then into electrical quantities (PIR sensors).

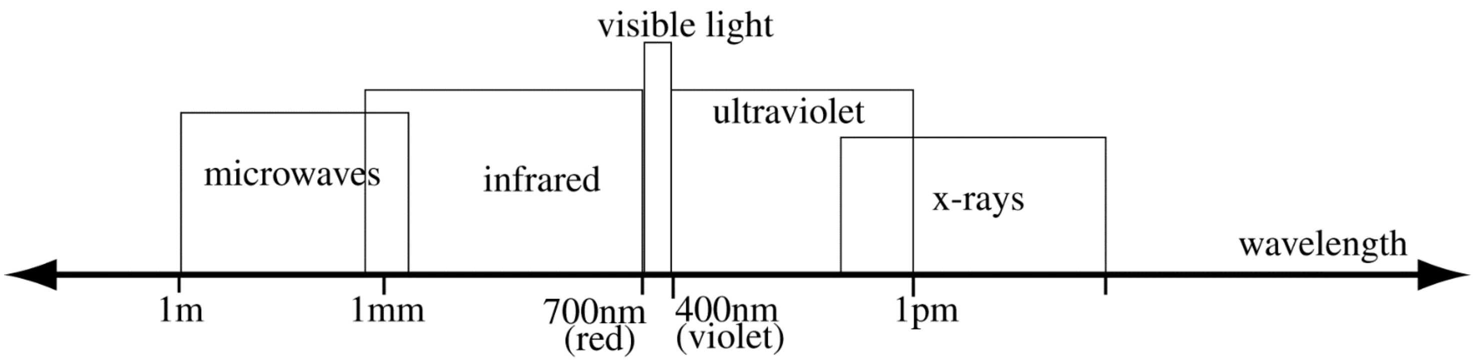
Spectrum of “optical” radiation

- Nomenclature: (المصطلحات)
  - Visible light
  - Infrared radiation (not infrared “light”)
  - Ultraviolet radiation (not UV “light”)



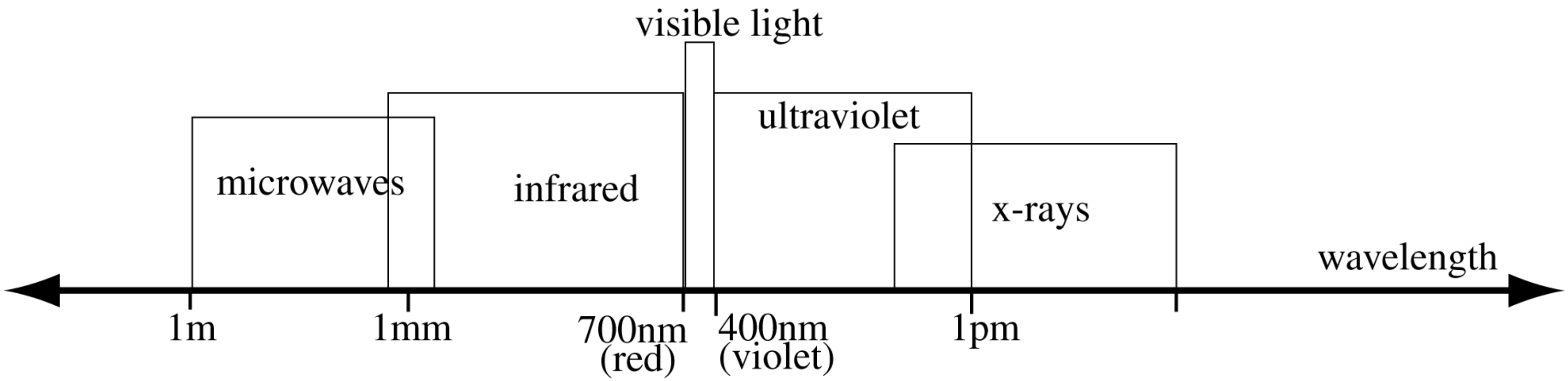
Infrared radiation

- Approximate spectrum
  - 1mm (300 GHz) to 700nm (430 THz)
- Meaning: below red
- Near infrared (closer to visible light)
- Far infrared (closer to microwaves)
- ***Invisible radiation, usually understood as "thermal" radiation***
- 1nm=10^{-9}m, 1GHz=10^{9} Hz, 1THz=10^{15} Hz



Visible light

- Approximate spectrum
  - 700nm (430 THz) to 400nm (750 THz)
- Based on our eye's response
- From red (low frequency, long wavelength)
- To violet (high frequency, short wavelength)
- Our eye is most sensitive in the middle (green to yellow)
- **Optical sensors may cover the whole range, may extend beyond it or may be narrower**

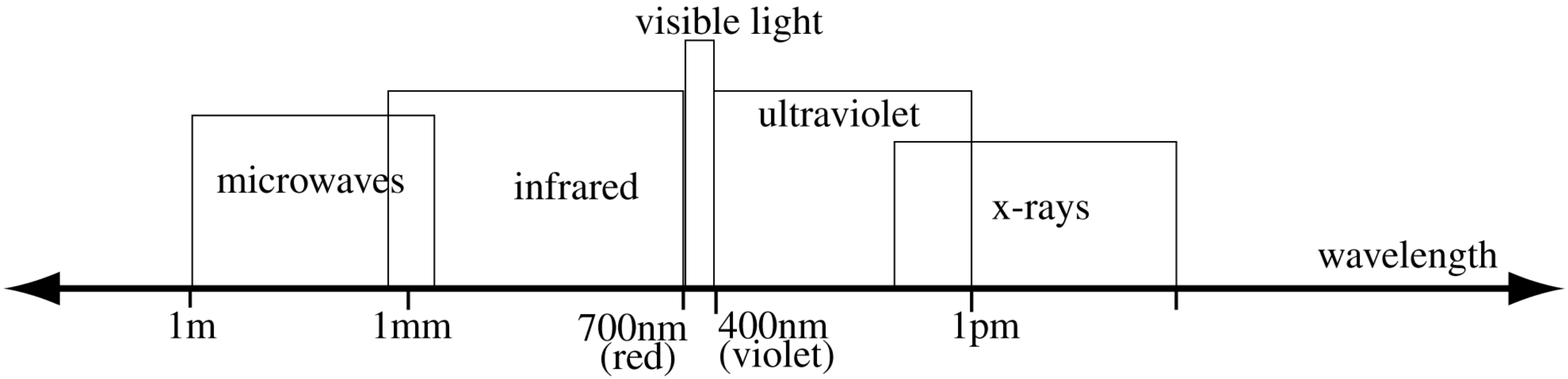


Light Power

- **For a sensor, we're interested in the light power that falls on a unit area, and how well the sensor converts that into a signal.**
- A common unit **is the lux** which measures apparent brightness (power multiplied by the human eye's sensitivity).
- Sunlight corresponds to about **50,000** lux
- Artificial light typically **500-1000 lux**

Ultraviolet (UV) radiation

- Approximate spectrum
  - 400nm (750 THz) to 400pm (300 PHz)
- Meaning - above violet
- Understood as “penetrating” radiation
- Only the **lower end** of the UV spectrum is usually sensed
- Exceptions: radiation sensors based on ionization



The photoelectric effect

- Photons collide with electrons at the surface of a material
- The electrons acquire energy and this energy allows the electron to:
  - Release them selves from the surface of the material by overcoming the ***work function*** of the substance.
  - Excess energy imparts the electrons kinetic energy.

Photo-conducting effect

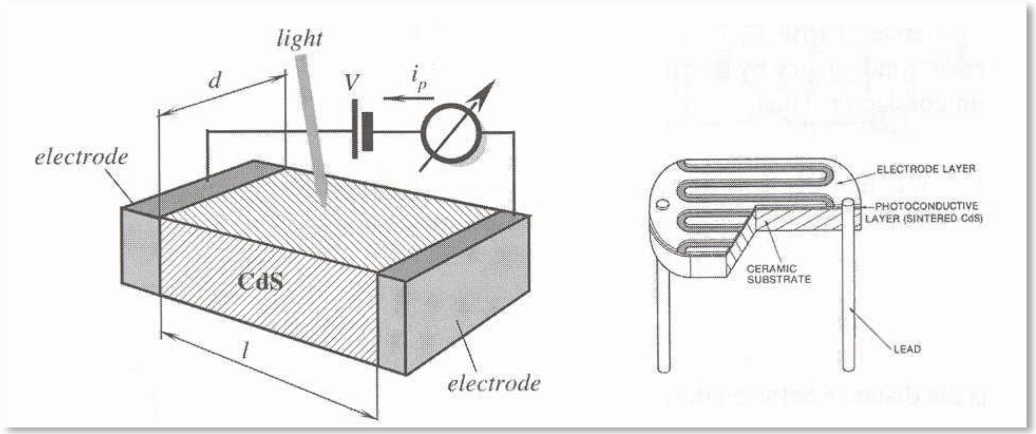
- Conductivity results from the charge, mobilities of electrons and holes and the concentrations of electrons, n and p from whatever source.
- In the absence of light, the material exhibits what is called dark conductivity, which in turn results in a dark current.
- Depending on construction and materials, the resistance of the device may be very high (a few MegaOhms (MΩ) or a few kΩ.
- When the sensor is illuminated, its conductivity changes depending on the change in carrier concentrations (excess carrier concentrations).

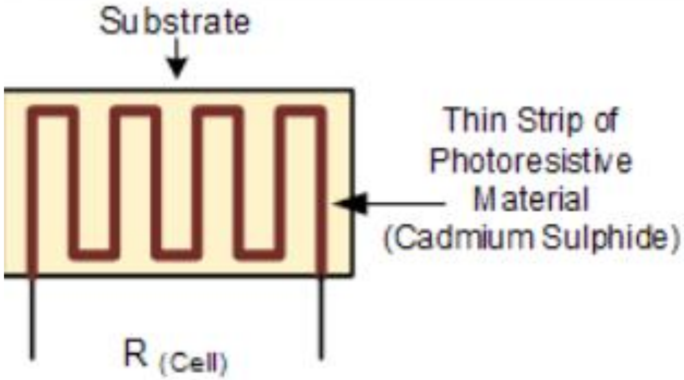
Light Sensors/Detectors

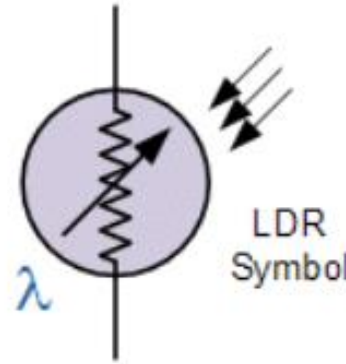
- Simplest light sensor is an LDR (Light-Dependent Resistor).
- Optical characteristics close to human eye.
- Common material is CdS (Cadmium Sulphide)
- Sensitivity:

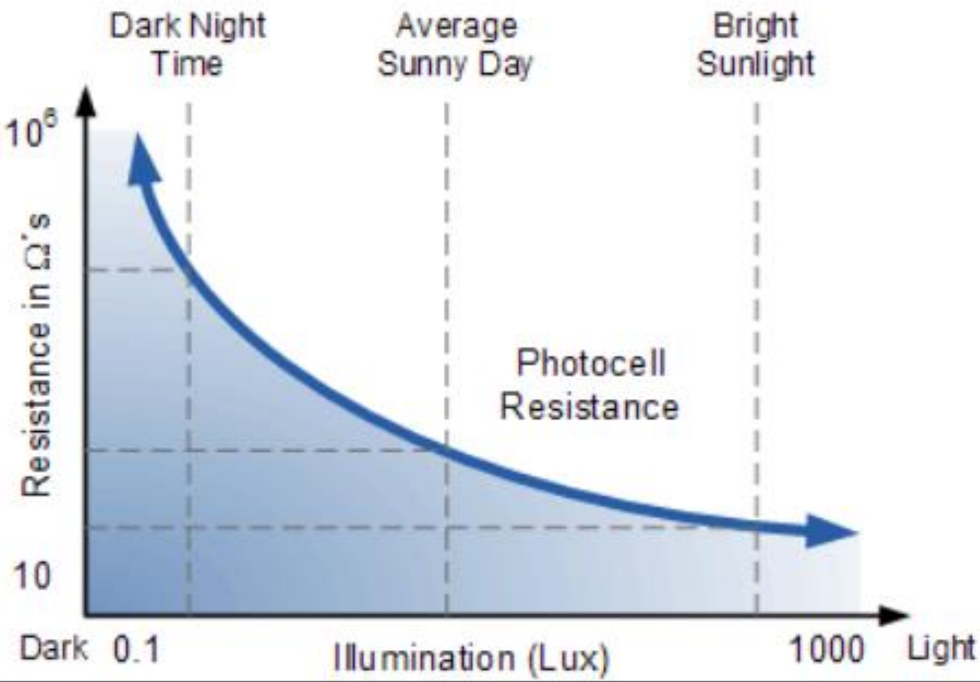
Typical

dark 1 MΩ,
10 lux 40 kΩ,
1000 lux 400 Ω.




Substrate
Thin Strip of
Photoresistive
Material
(Cadmium Sulphide)
R (Cell)


λ
LDR
Symbol

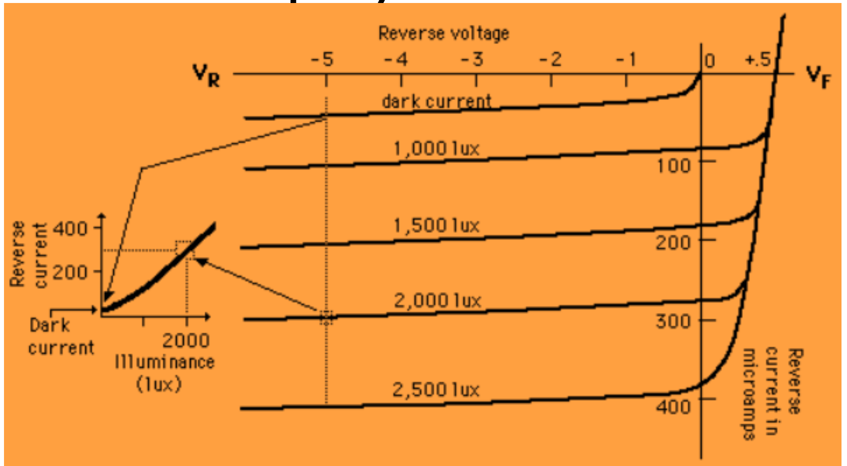

Dark Night
Time
Average
Sunny Day
Bright
Sunlight
10^6
10
Resistance in Ω's
Photocell
Resistance
Dark
0.1
Illumination (Lux)
1000
Light

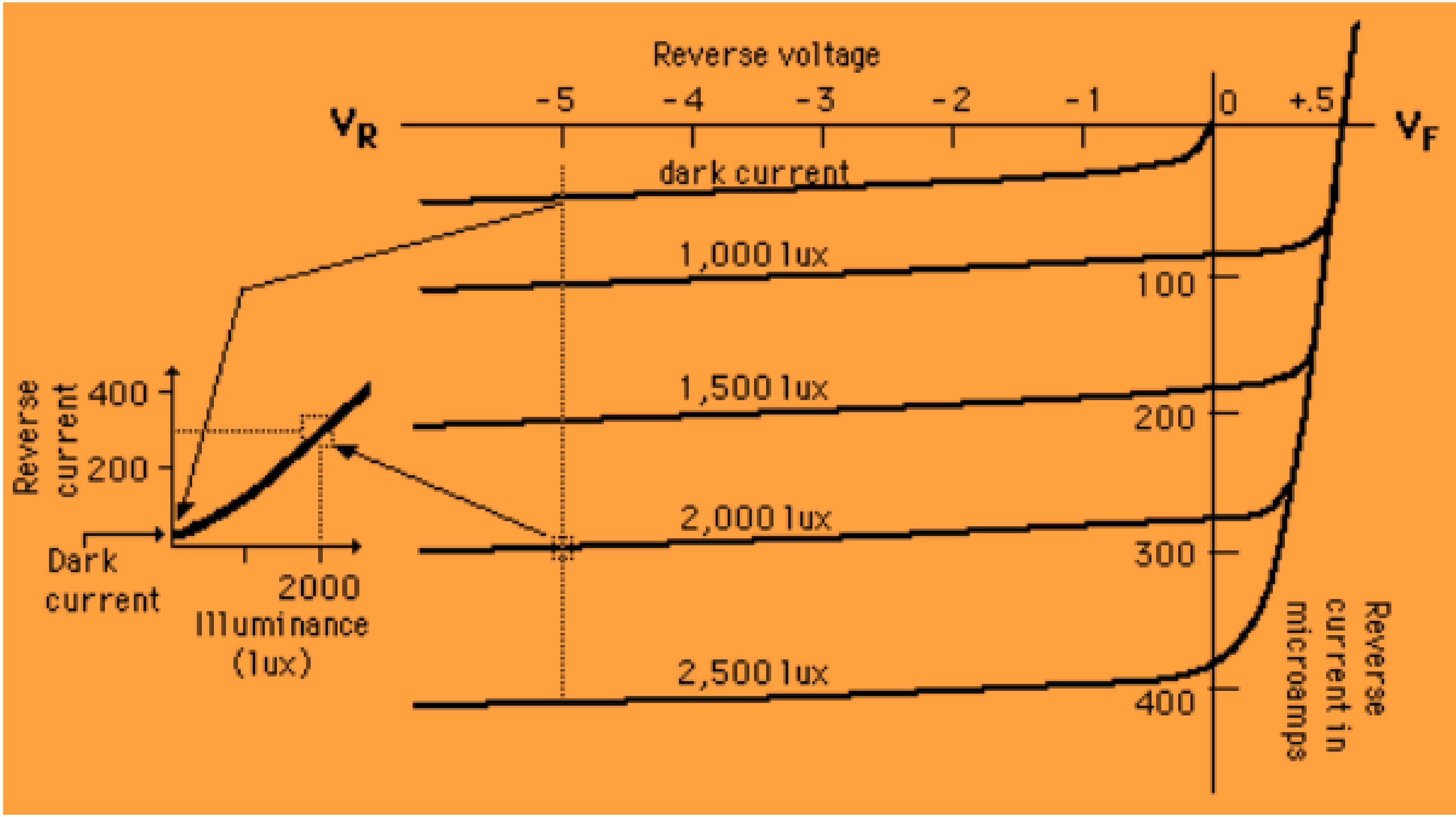
Photodiodes

- **Semiconductor diode exposed to radiation**
- Excess carriers due to photons add to the existing charges in the conduction band exactly in the same fashion as for a pure semiconductor.
- The diode itself may be reverse biased, forward biased or unbiased
- **Forward biased mode is** not useful as a photo-sensor
  - Number of carrier in conducting mode is large
  - Number of carrier added by radiation small
  - Sensitivity is very low

Photodiode - two modes

- 1. Photoconductive mode
  - Diode is reverse biased
  - Operates similarly to a photoconductor
  - The reverse voltage application will increase the depletion layer’s width, which in turn decreases the response time & the junction capacitance. This mode is fast and displays electronic noise
- 2. Photovoltaic mode
  - Diode is not biased
  - Operates as a source (solar cell for example)
- It gives a very small dynamic range & non-linear characteristic




Reverse voltage
-5
-4
-3
-2
-1
0
+.5
V_R
V_F
dark current
1,000 lux
1,500 lux
2,000 lux
2,500 lux
100
200
300
400
Reverse current in microamps
Reverse current
400
200
Dark current
2000
Illuminance (lux)

Photodiode - construction

- Any diode can serve as a photodiode if:
  - n region, p region or pn junction are exposed to radiation
  - Usually exposure is through a transparent window or a lens
  - Sometimes opaque materials are used (IR, UV)
- Specific structures have been developed to improve one or more of the characteristics
    - PIN diode: Addition of the intrinsic p layer increases resistance
    - Reduces dark current
- Phototransistors and photo-Darlington transistors are also available.
- Photocells and phototransistors are particularly sensitive in the infrared region, and so are ideal partners for infrared LED and laser diode sources.

Photodiodes - construction

- Available in various packages and for various applications
    - Individual diodes in cans with lenses
    - Surface mount diodes used in infrared remote controls
    - Arrays (linear) of various sizes for scanners
    - Infrared and UV diodes for sensing and control

- Photodiode as used in in a CD player

Photodiode array used a scanner

Photovoltaic diodes

- The diode is not biased
- Serves as a generator
  - Carriers generated by radiation create a potential difference across the junction
  - Any photodiode can operate in this mode
  - Solar cells are especially large-surface photodiodes

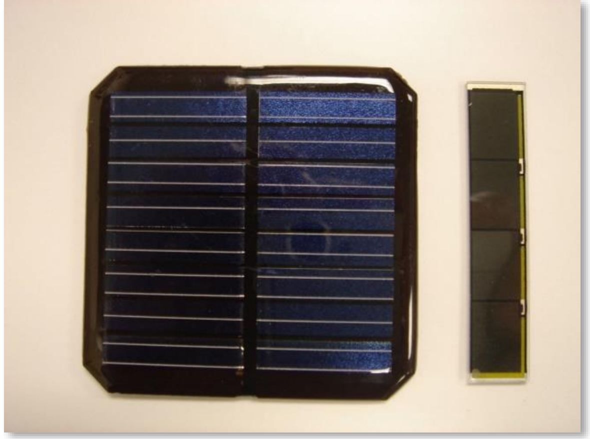


Photo Interrupt

- Uses emitter and detector photo diode pair
- With no obstruction detector is high
- When an object blocks the light the detector is low

- Advantages
  - Simple to interface
  - Inexpensive
  - Reliable

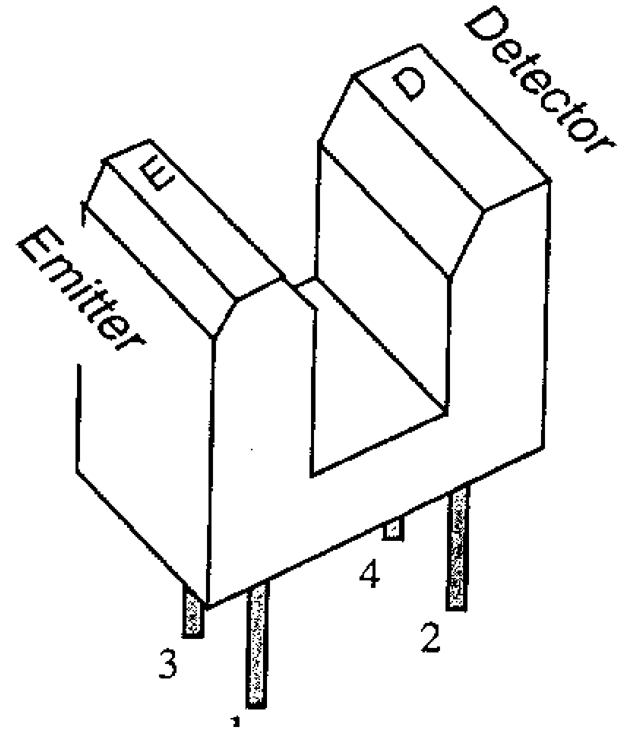
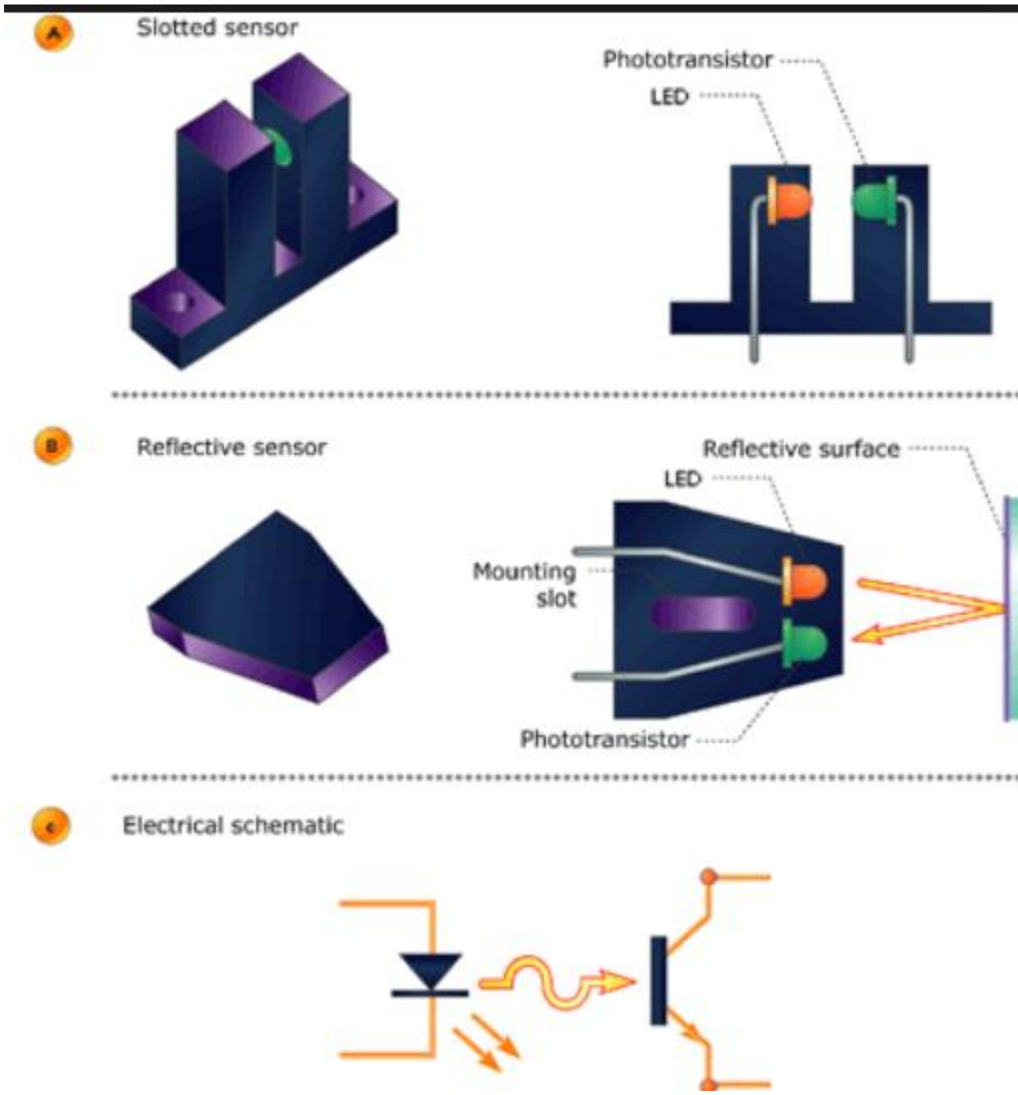


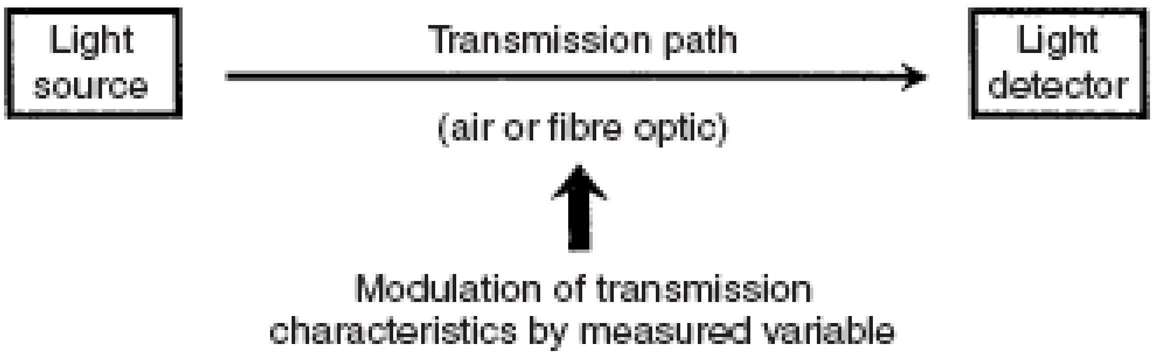
Photo Interrupt
Types

- Wide variety of packages and orientations
- Types
  - Logic (digital ±5 volts)
  - Transistor/diode (analog)
- Manufacturers
  - Fairchild
  - Honeywell



Optical sensors

- Optical sensors are based on the modulation of light travelling between a light source and a light detector.
- The transmitted light can travel along either an **air path or a fibre-optic cable.**
- Either form of transmission gives immunity to electromagnetically induced noise, and also provides greater safety than electrical sensors when used in **hazardous environments.**



Optical Sensors: Advantages and applications

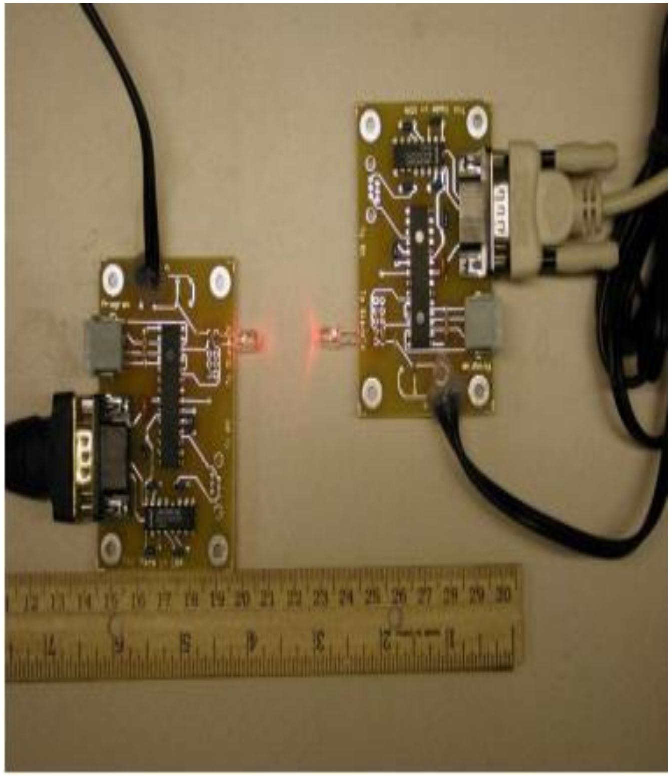
- ELECTROMAGNETIC IMMUNITY
- ELECTRICAL ISOLATION
- COMPACT AND LIGHT
- WIDE DYNAMIC RANGE

- Example Apps:

Temperature; Pressure; Flow; Liquid Level; Displacement; Vibration; Rotation; Acceleration; Magnetic Field; Humidity; Strain;

Optical sensors

- **Light sources suitable for transmission across an air path include tungsten-filament lamps, laser diodes and light-emitting diodes (LEDs).**
- However, as the light from tungsten lamps is usually in the visible part of the light frequency spectrum, it is prone to interference from the sun and other sources.
- Hence, **infrared LEDs or infrared laser diodes are usually preferred**.
- These emit light in a narrow frequency band in the infrared region **and are not affected by sunlight**



- Air-path optical sensors are commonly used to measure proximity, translational motion, rotational motion and gas concentration

Fibre-Optic Sensors

- **As an alternative to using air as the transmission medium, optical sensors can use fibre-optic cable instead to transmit light between a source and a detector**.
- In such sensors, the variable being measured causes some **measurable change in the characteristics of the light transmitted by the cable**. The proportion of light entering the cable must be maximized
- The basis of operation of fibre-optic sensors is the translation of the physical quantity measured into a change in one or more parameters of a light beam.

Fibre-optic sensors characteristic

- Fibre-optic sensors characteristically

1) Long life.

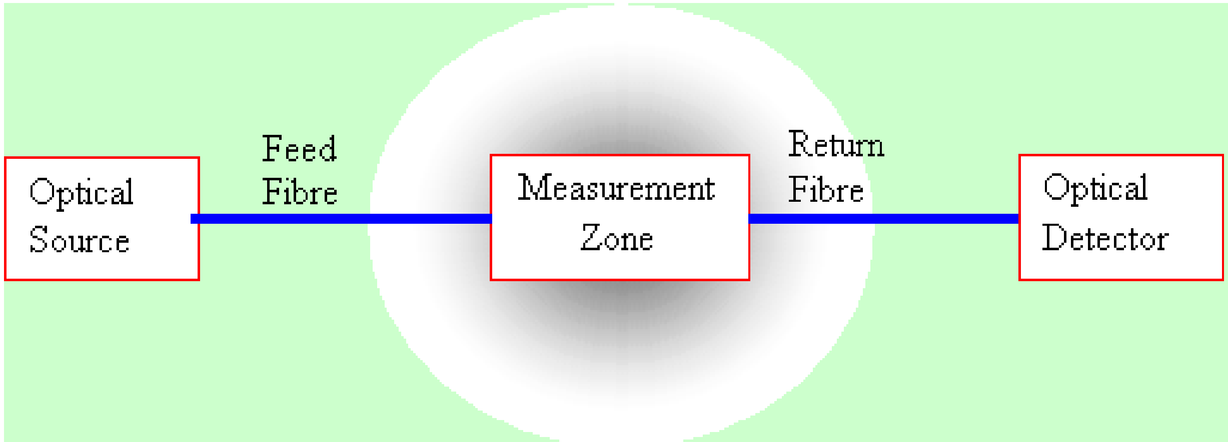
2) Good accuracy : +/- 1%

(for a fibre-optic pressure sensors)

3) Simple, low cost, small size, high reliability

4) Capability of working in many kinds of hostile environment.

WORKING PRINCIPLE

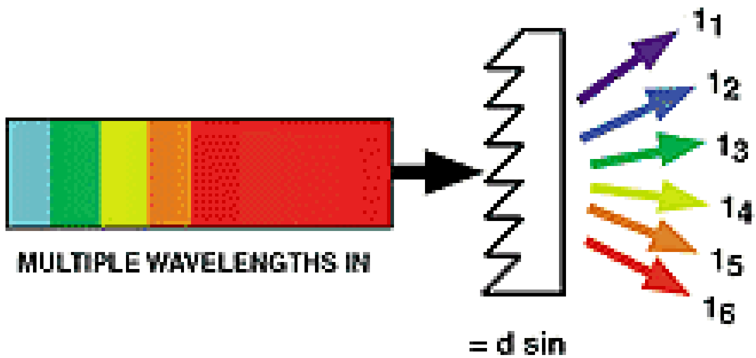


- **Light beam changes by the phenomena that is being measured**
- **Light may change in its five optical properties i.e intensity, phase, polarization , wavelength and spectral distribution**

SENSING DETAILS

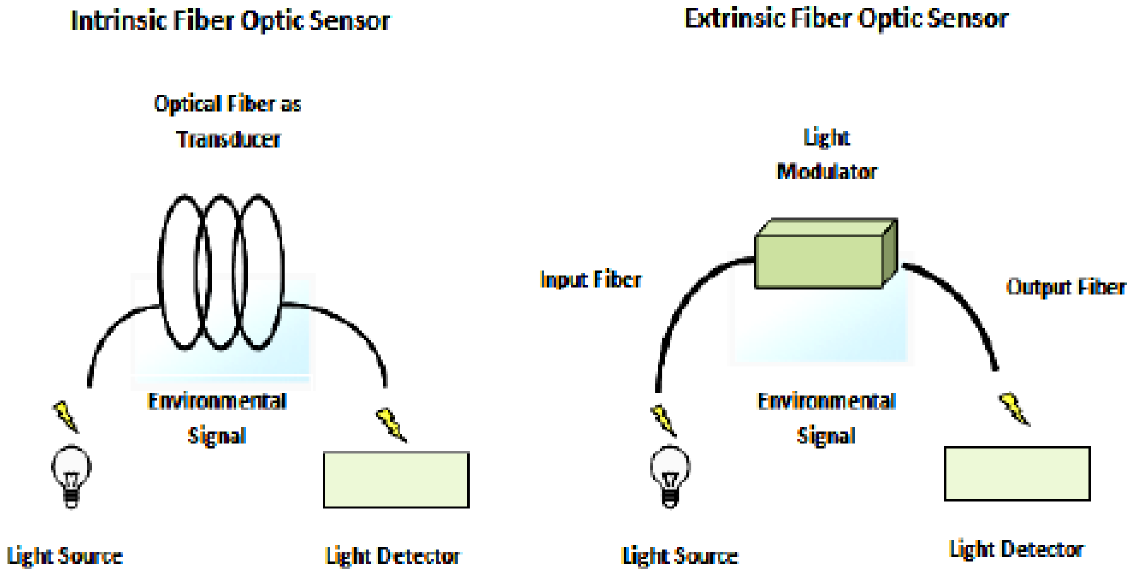
$$E_p(t)\cos[\omega t+\theta(t)]$$

- Intensity based sensors – E_p (t)
- Frequency varying sensors - $\omega_p(t)$
- Phase modulating sensing- $\theta(t)$
- Polarization modulating fiber sensing



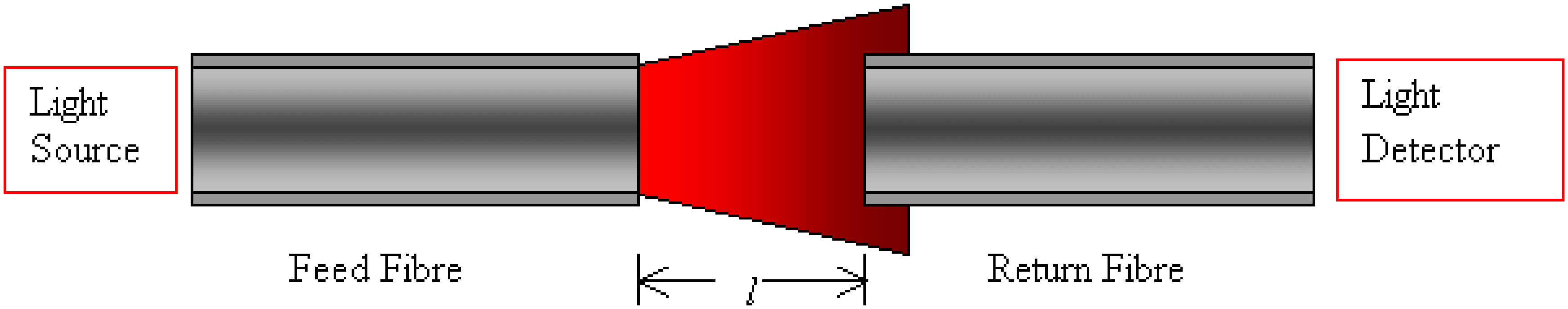
Fibre-optic sensors Classification

- Two major classes of fibre-optic sensor exist, **intrinsic** sensors and **extrinsic** sensors.
- In *intrinsic sensors*, the fibre-optic cable itself is the sensor,
- whereas in *extrinsic sensors*, the fibre-optic cable is only used to guide light to/from a conventional sensor.

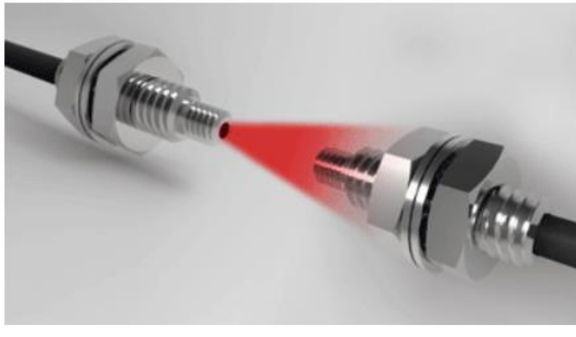


CLASSIFICATION

- Extrinsic sensors

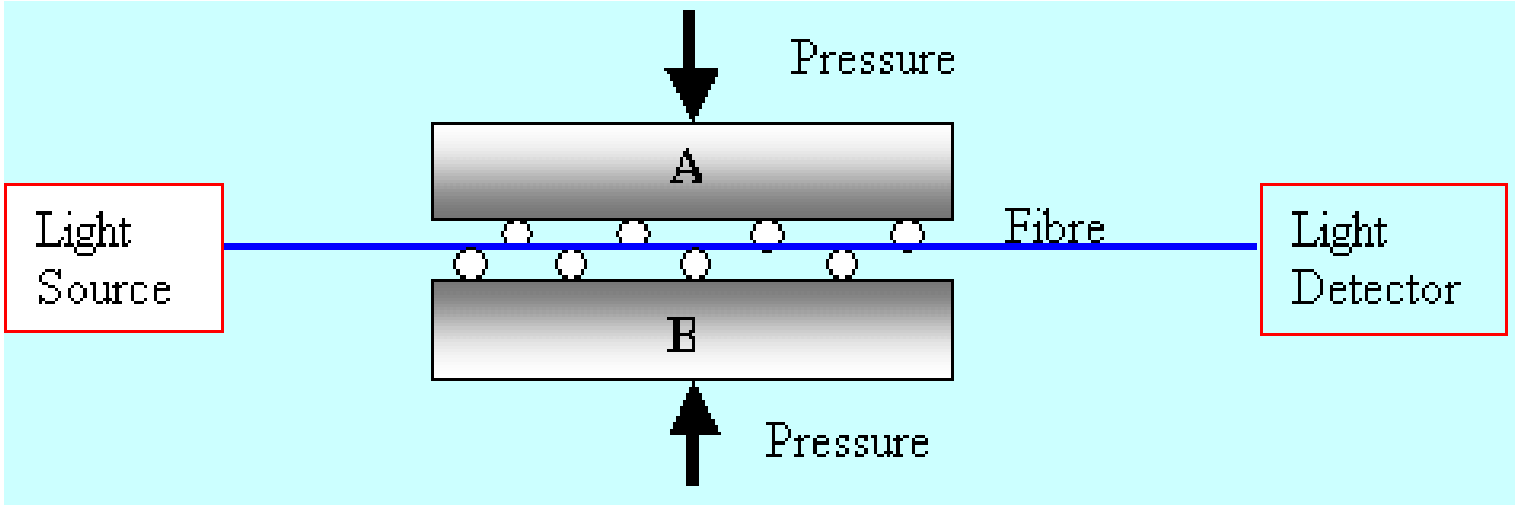


where the light leaves the feed or transmitting fiber to be changed before it continues to the detector by means of the return or receiving fiber



CLASSIFICATION (contd.)

- INTRINSIC SENSORS

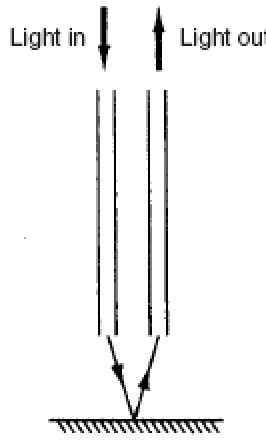


intrinsic sensors are different in that the light beam **does not leave the optical fiber** but is changed whilst still contained within it.

Fibre-optic sensors

- Proximity sensor

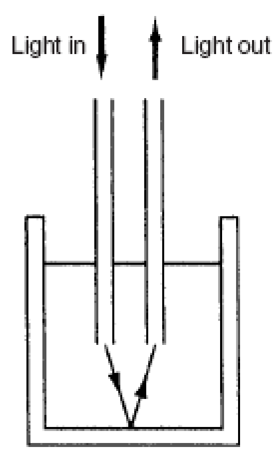
The amount of light reflected varies with the distance between the fibre ends and a boundary



(c)

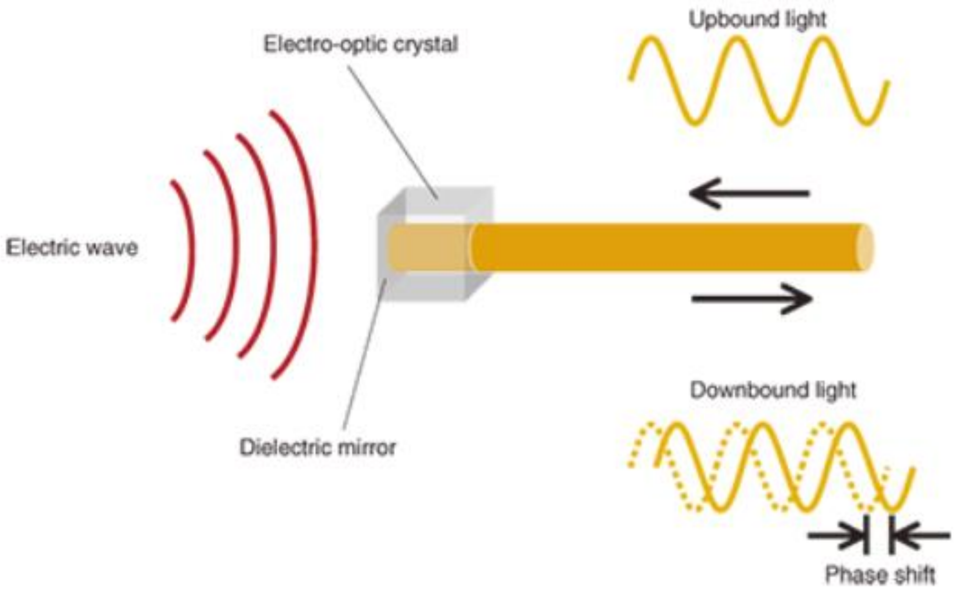
- pH sensor

The amount of light reflected back into the fibers depend on the pH-dependant color of the chemical indicator in the solution around the probe tip

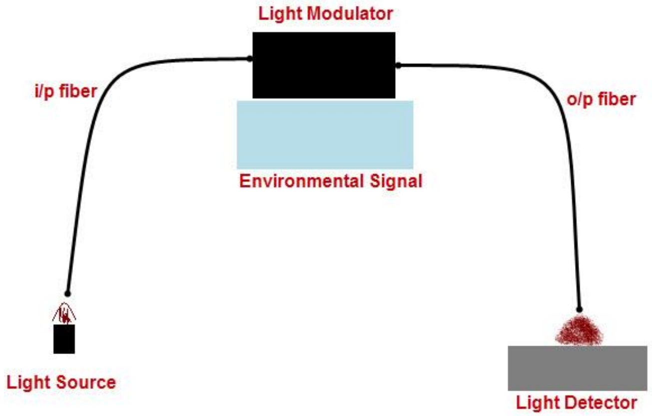


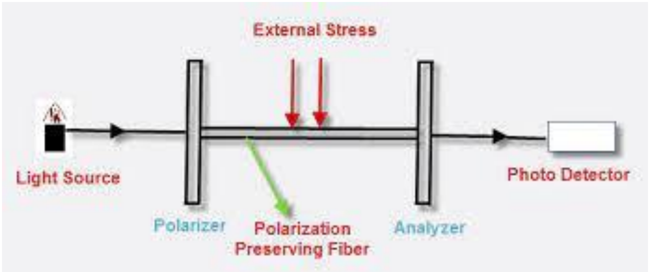
(d)

- **Optical Fiber Electric Field Sensor for Antenna Measurement**



- **Phase Shift is the key output**





Infrared Sensors

- An infrared sensor is an electronic instrument that is used to sense certain characteristics of its surroundings by either emitting and/or detecting infrared radiation.
- It is also capable of measuring heat of an object and detecting motion.
- **Infrared waves are not visible to the human eye**.
- In the electromagnetic spectrum, infrared radiation is the region having wavelengths longer than visible light wavelengths, but shorter than microwaves.
- The infrared region is approximately demarcated from 0.75 to 1000µm.
- The wavelength region from **0.75 to 3µm** is termed as **near infrared**, the region from **3 to 6µm** is termed **mid-infrared**, and the region **higher than 6µm** is termed as **far infrared**.

Infrared Sensor

- Infrared technology is found in many of our everyday products.
- For example, **TV has an IR** detector for interpreting the signal from the remote control.
- **Key benefits of infrared sensors include low power requirements, simple circuitry, and their portable feature.**

Types of Infra-Red Sensors

- Infra-red sensors are broadly classified into two types:
- **Thermal infrared sensors** – These use infrared energy as heat. Their photo sensitivity is independent of wavelength. Thermal detectors do not require cooling; however, they have slow response times and low detection capability.
- **Quantum infrared sensors** – These provide higher detection performance and faster response speed. Their photo sensitivity is dependent on wavelength. Quantum detectors have to be cooled so as to obtain accurate measurements.

Working Principle

- A typical system for detecting infrared radiation using infrared sensors includes; **First**: the **infrared source** such as blackbody radiators, tungsten lamps, and silicon carbide.
- In case of active IR sensors, the sources are infrared lasers and LEDs of specific IR wavelengths.
- **Second:** is the transmission medium used for infrared transmission, which includes **vacuum**, the **atmosphere**, and **optical fibers**.

Working Principle

- **Thirdly:** optical components such as optical lenses made from quartz, CaF_2, Ge and Si, polyethylene
- Fresnel lenses, and Al or Au mirrors, are used to converge or focus infrared radiation. Likewise, to limit spectral response, band-pass filters are ideal.
- **Finally**, the infrared detector completes the system for detecting infrared radiation.
- The output from the detector is usually **very small**, and hence **pre-amplifiers coupled with circuitry are added to further process the received signals**

Applications

- Tracking and art history
- Climatology, meteorology, and astronomy
- Thermography, communications, and alcohol testing
- Heating, hyper-spectral imaging, and night vision
- Biological systems, photo-bio-modulation, and plant health
- Gas detectors/gas leak detection
- Water and steel analysis, flame detection
- Anesthesiology testing and spectroscopy
- Petroleum exploration and underground solution
- Rail safety.

What is a Passive/Pyroelectric Infrared (PIR) Sensor?

- Used to detect motion
- Basically made up of pyroelectric sensors
  - Detect levels of infrared radiation
- Does not emit any radiation, only detects, hence passive
- Note: PIR sensors are slow with time constants ~ 1 sec
- Eltec two-element sensor, shown with matching fresnel IR lens and mounting:

- NAIS ultra-compact PIR sensor

Practical Applications

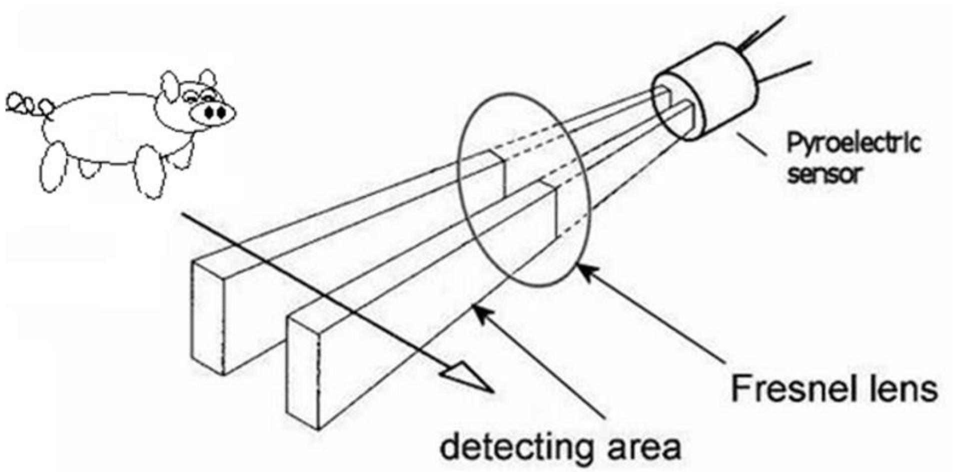
- Motion Detection
  - Automatic doors
  - Interactive Rooms
    - Activate when person enters room
  - Remote triggered cameras
    - Take photos/start recording when person enters room
- Measuring Temperature Differentials
  - Measure temperatures of remote objects

How It Works – Theory

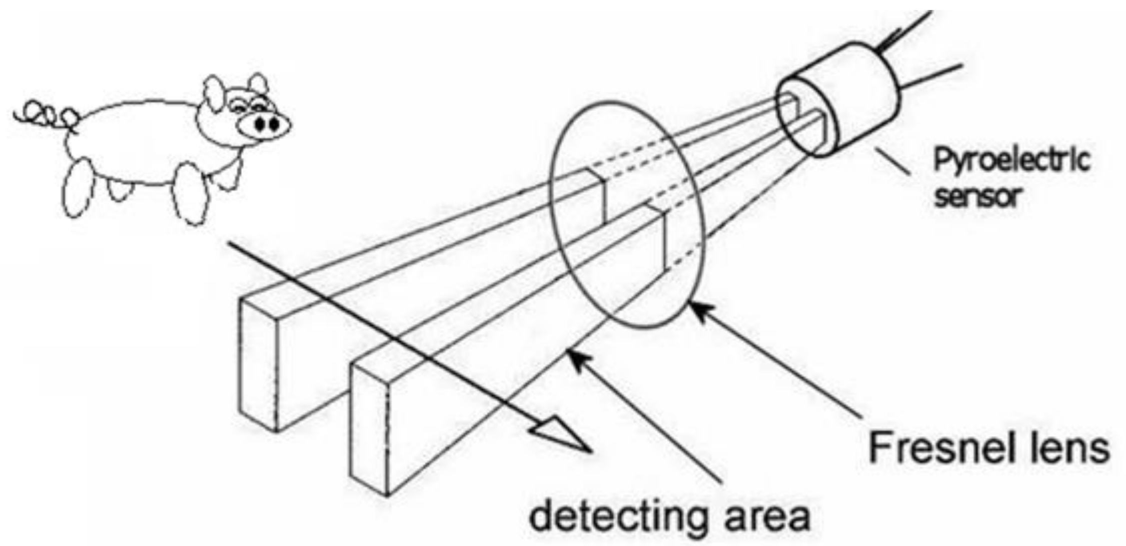
- Infrared radiation exists in the EM spectrum
  - Can’t be seen, but can be detected
- Objects that generate heat also generate IR radiation
- PIR sensor consists of two sensing elements
  - One gives a frame of reference and the other detects the change
  - Can only detect the difference in temperatures between the two sensors

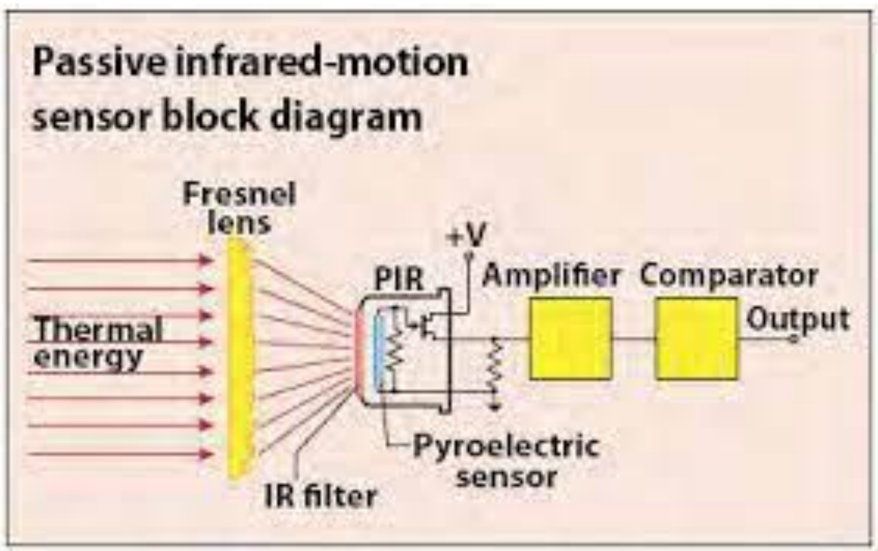
How It Works – Theory (cont.)

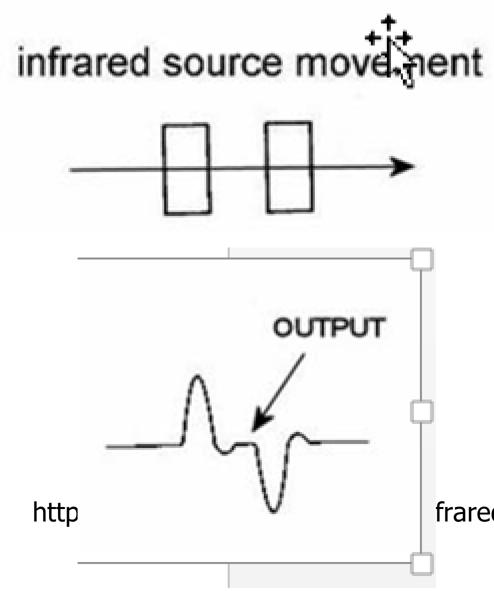
- **For example:** A PIR sensor is pointed into a room. An animal, with a temperature greater than the wall, walks into the room.
- As the animal crosses the first sensor, a positive pulse is produced.
- When the animal is in front of both sensors, there is no sensed change.
- As it crosses the second sensor, a negative pulse is emitted.
- These pulses are what is detected.



How It Works – Theory (cont.)



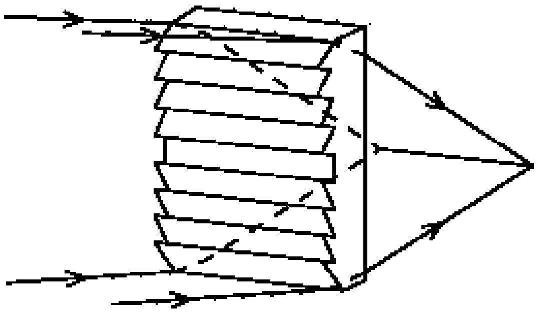


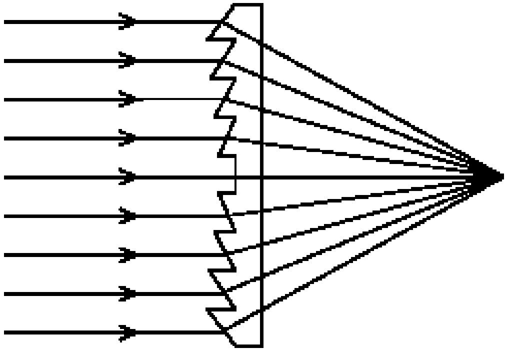


http frared.html

How It Works – Fresnel Lens

- Captures more IR radiation
- Focuses the radiation into a smaller point
- Condenses the light and provides a larger range of IR to the sensor
- Made of material opaque to visible light
- Materials that pass visible light will not pass infrared radiation (e.g. glass, plastic, etc.)





http://www.ladyada.net/learn/sensors/pir.html

Major Specifications

- Power requirements
- Communication (Output):single bit high/low output
- Dimensions
- Operating Temperature
- Range and Detection Angle

Limitations

- Sensing can be confused
  - Motion too close to sensor
  - Motion is not passed through sensor one at a time
  - Cannot detect slow moving or stationary objects
  - Sensor is approached straight on
- Limited range in most sensors
- Temperature sensitive

Temperature Measurement

- Instruments to measure temperature can be divided into separate classes according to the physical principle on which they operate. The main principles used are:
- The thermoelectric effect ➔ Thermocouples
- Resistance change ➔ RTD’s and Thermistors

Other Principles (FYI)

- Sensitivity of semiconductor device
- Radiative heat emission
- Thermography
- Thermal expansion
- Resonant frequency change
- Sensitivity of fibre optic devices
- Acoustic thermometry
- Color change
- Change of state of material.

Temp Sensors

https://www.youtube.com/watch?v=w3Hfj2kMrGo

Thermocouples- important

- Consist of a pair of dissimilar metal wires joined together at one end (sensing, hot junction) and terminated at the other end (reference, cold junction) which is kept at known constant temperature.
- emf (voltage) is produced when there is a difference in temperature between the two junctions, this is called the **thermocouple effect or Seebeck effect**.
- $$e = a_1 T + a_2 T^2 + a_3 T^3 + \cdots + a_n T^n$$ ← FYI

Which can be approximated for certain pairs of metals by

$$e \approx a_1 T$$

- Thermal emf magnitude depends on the materials used and on temperature difference .
- Remember how to convert from degrees C to degrees F
- Many types of thermocouples exist which differ in the metals used to construct them,
- among these are type E,J,K and S which differ in the combination of the used materials and their temperature range and application

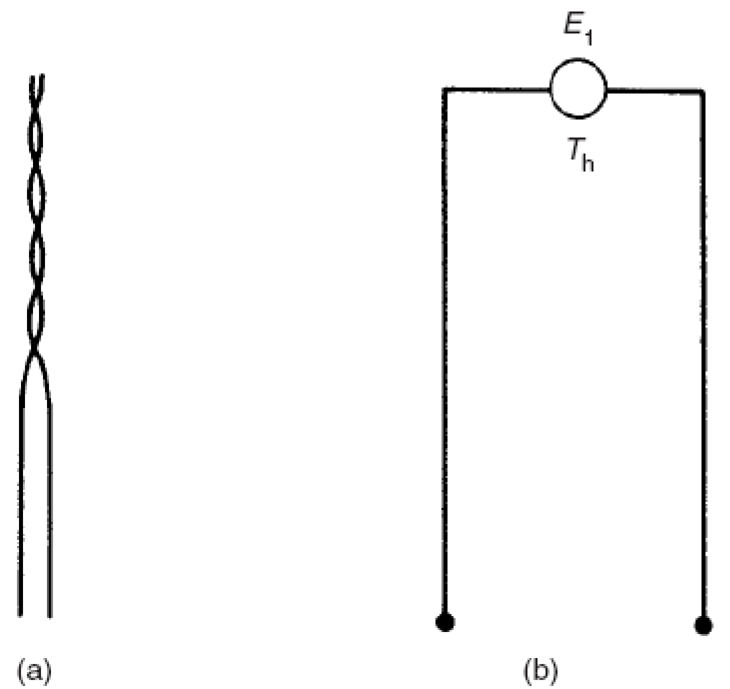
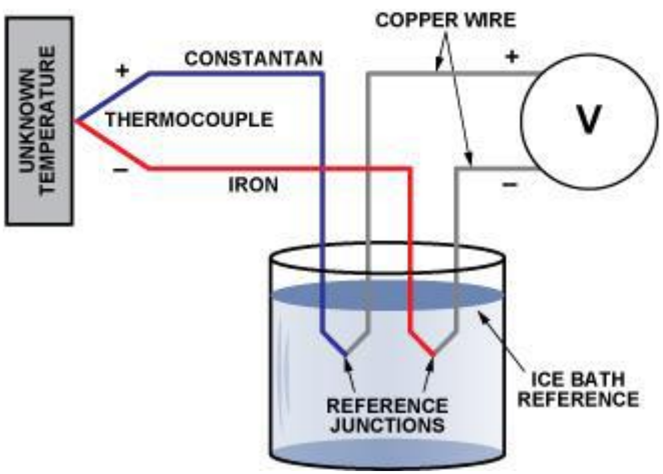
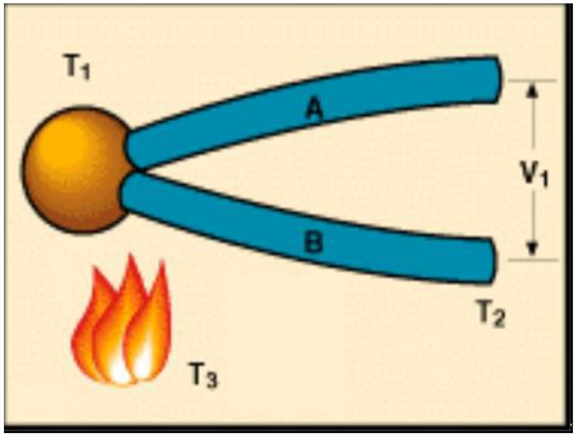


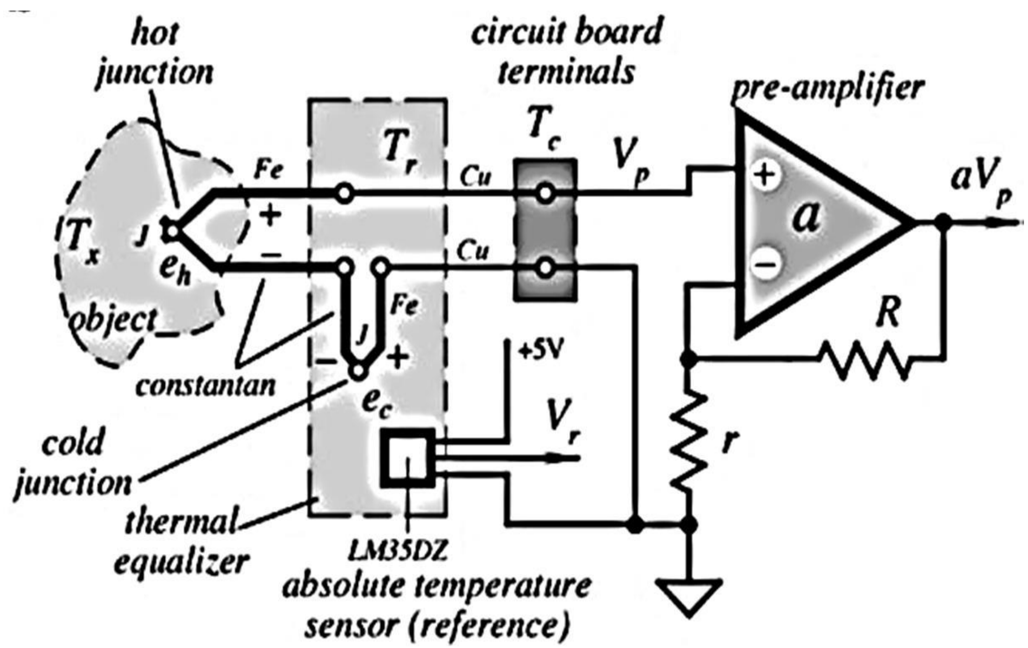
Fig. 14.2 (a) Thermocouple; (b) equivalent circuit.

- The emf generated at the hot junction is presented by E1 and temperature is known as Th
- E1 is measured at the open ends of the thermocouple (known as reference junction)





Zero Temp reference



Temp reference measured by LM35 temp sensor

Thermocouple Types

- Type E ➔ Chromel-Constantan
- Type J ➔ Iron-Constantan
- Type K ➔ Chromel-Alumel
- Type S ➔ Platinum-Platinum/Rhodium

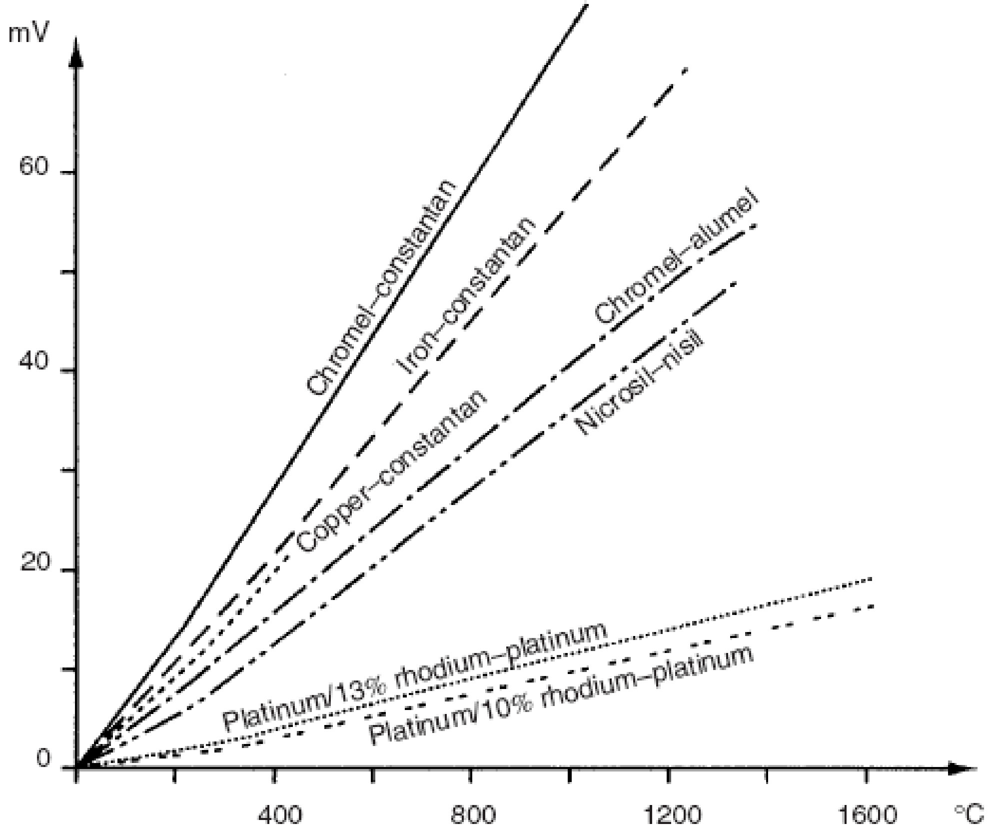
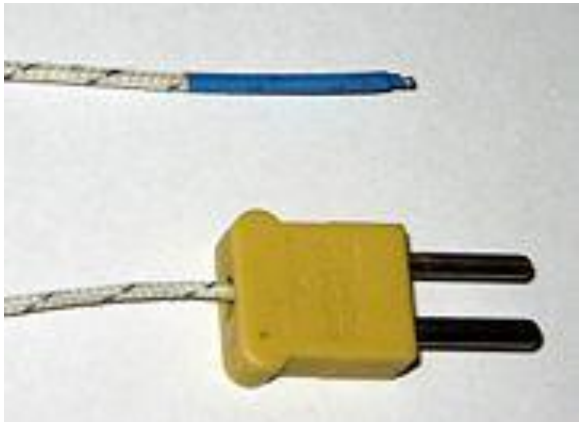
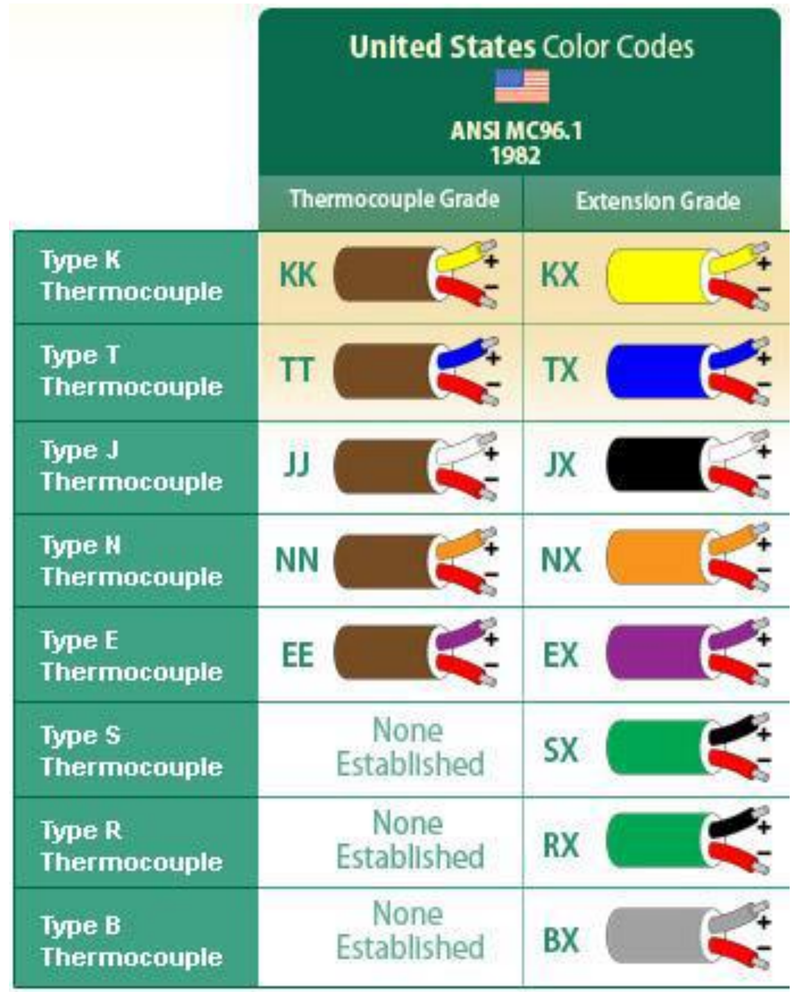


Fig. 14.1 E.m.f. temperature characteristics for some standard thermocouple materials.

FYI





	United States Color Codes ANSI MC96.1 1982 Thermocouple Grade	Extension Grade
Type K Thermocouple	KK	KX
Type T Thermocouple	TT	TX
Type J Thermocouple	JJ	JX
Type N Thermocouple	NN	NX
Type E Thermocouple	EE	EX
Type S Thermocouple	None Established	SX
Type R Thermocouple	None Established	RX
Type B Thermocouple	None Established	BX

Thermistors / Important

- A **thermistor** is a type of resistor with resistance varying according to its temperature. The word is a combination of *thermal* and *resistor*.
- Thermistors are widely used as **inrush current limiters**, **temperature sensors**, **self-resetting overcurrent protectors**, **and self-regulating heating elements.**
- Assuming, as a first-order approximation, that the relationship between resistance and temperature is linear, then:

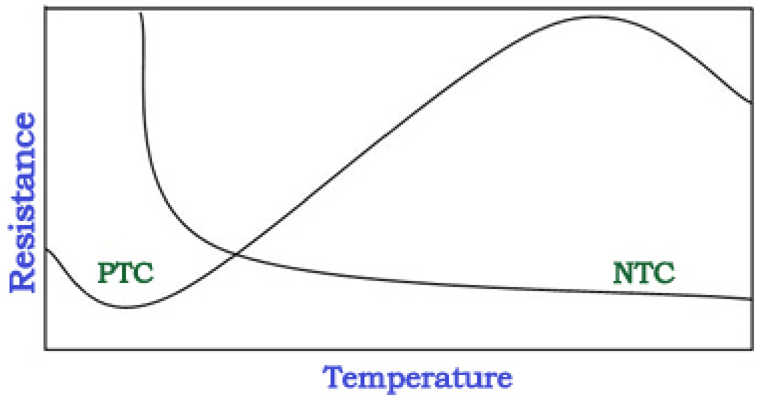
$$\Delta R = k\Delta T$$

where

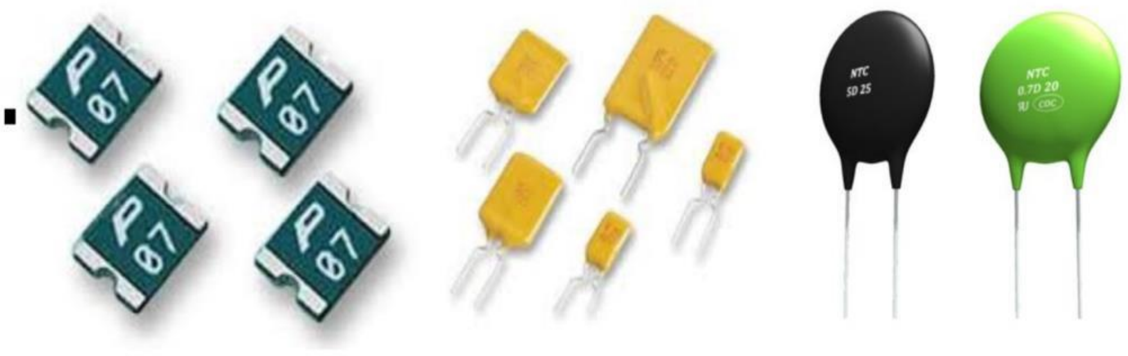
ΔR = change in resistance

ΔT = change in temperature

k = first-order temperature coefficient of resistance



Thermistors



Thermistors / Important

- Thermistors can be classified into two types depending on the sign of *k*. If *k* is positive, the resistance increases with increasing temperature, and the device is called a positive temperature coefficient (**PTC**) thermistor, or **posistor**.
- If *k* is negative, the resistance decreases with increasing temperature, and the device is called a negative temperature coefficient (**NTC**) thermistor.
- Resistors that are not thermistors are designed to have the smallest possible *k*, so that their resistance remains nearly constant over a wide temperature range
- Thermistors differ from resistance temperature detectors (RTD) in that the material used in a thermistor is generally a ceramic or polymer, while RTDs use pure metals. The temperature response is also different; RTDs are useful over larger temperature ranges.

RTD's / Important

Resistance thermometers, which are alternatively known as *resistance temperature devices* (or RTDs), rely on the principle that the resistance of a metal varies with temperature according to the relationship:

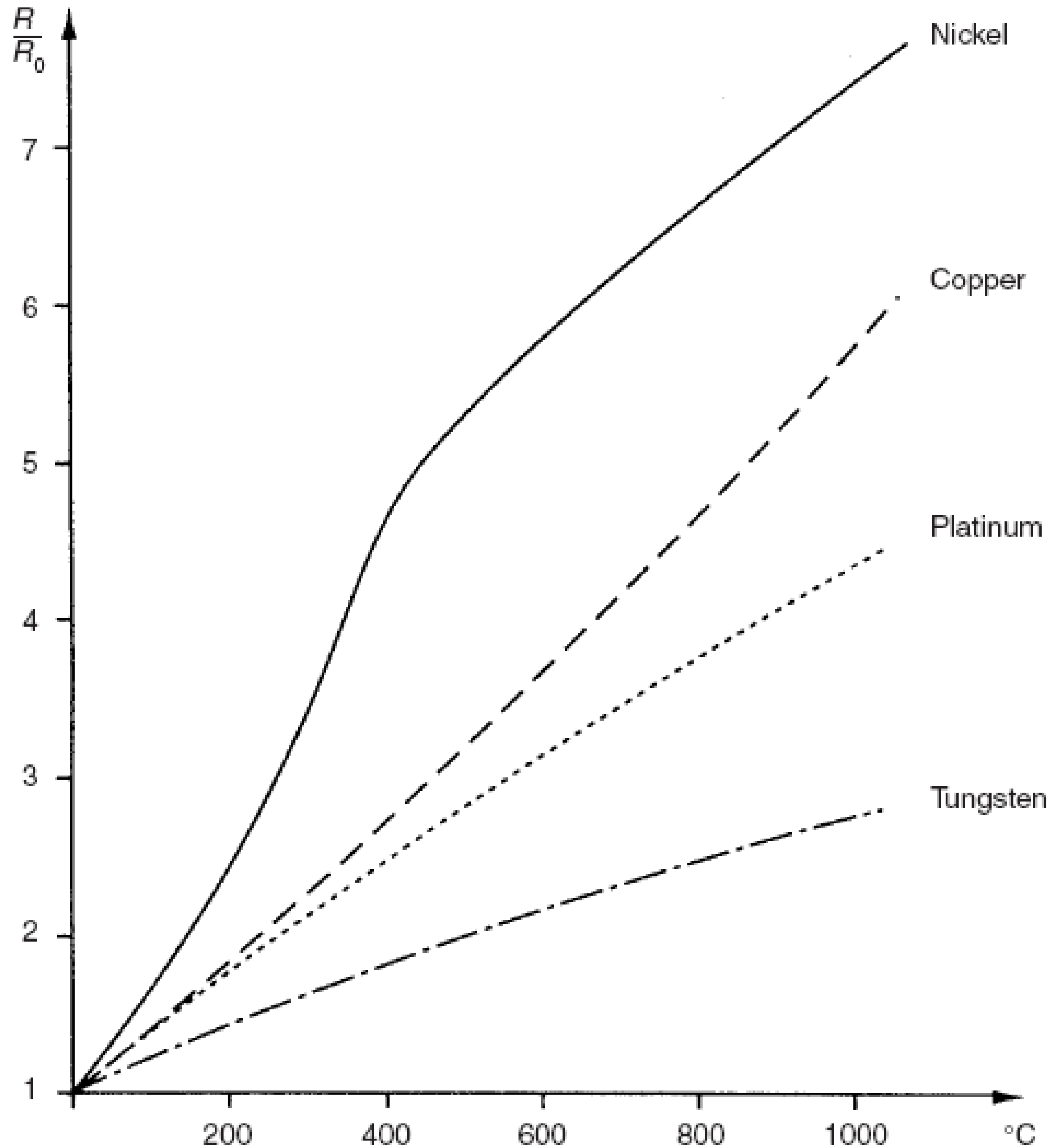
$$R = R_0 \left(1 + a_1 T + a_2 T^2 + a_3 T^3 + \cdots + a_n T^n\right) \tag{14.7}$$

This equation is non-linear and so is inconvenient for measurement purposes. The equation becomes linear if all the terms in $a_2 T^2$ and higher powers of T are negligible such that the resistance and temperature are related according to:

$$R \approx R_0 (1 + a_1 T)$$

This equation is approximately true over a limited temperature range for some metals, notably platinum, copper and nickel, whose characteristics are summarized in Figure 14.8. Platinum has the most linear resistance–temperature characteristic, and it also has good chemical inertness, making it the preferred type of resistance thermometer

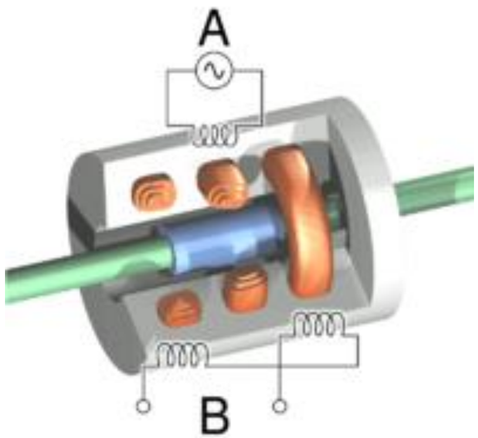
FYI



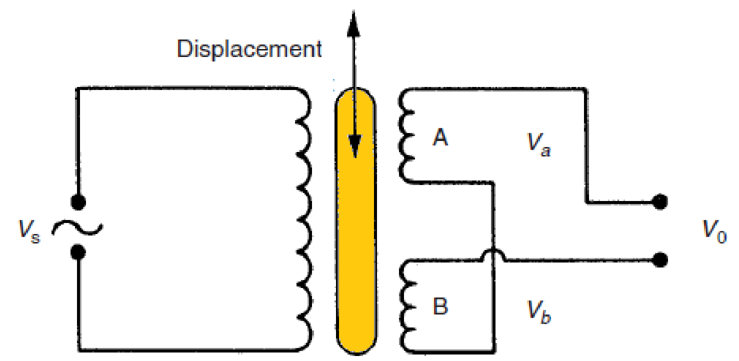
Typical resistance–temperature characteristics of metals.

Translational Motion Transducers

- Translational displacement is movement in a straight line between two points
- Translational Displacement transducers can be used as primary or secondary transducers
- Simple type as resistive potentiometer
- LVDT: linear variable differential transformer



Cutaway view of an LVDT. Current is driven through the primary coil at *A*, causing an induction current to be generated through the secondary coils at *B*.



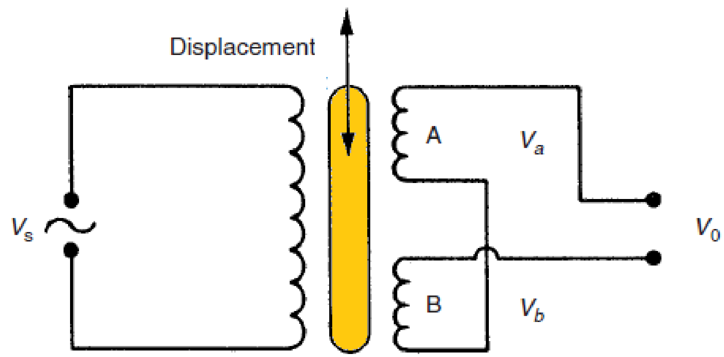
Linear Variable Differential Transformer

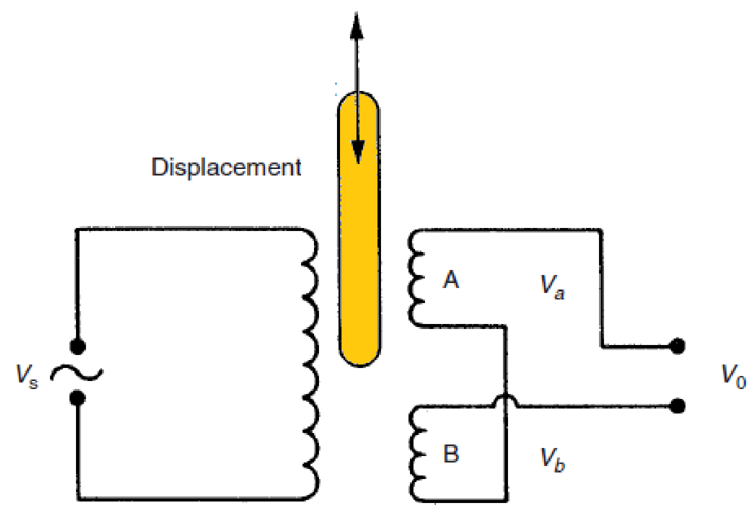
- LVDT has one primary and two secondary's (A and B) connected in series in opposing manner.
- The object moves the central iron core of the transformer.
- For an excitation voltage Vs given by

$V_s = V_p \sin(\omega t)$, the e.m.f.s induced in the secondary windings V_a and V_b are given by:

$$V_a = K_a \sin(\omega t - \varphi), V_b = K_b \sin(\omega t - \varphi)$$

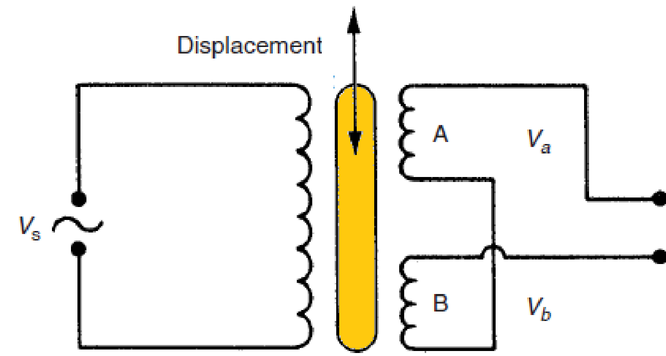
- Parameters K_a and K_b depend on the amount of coupling between the respective secondary and primary windings and hence on the position of the iron core.

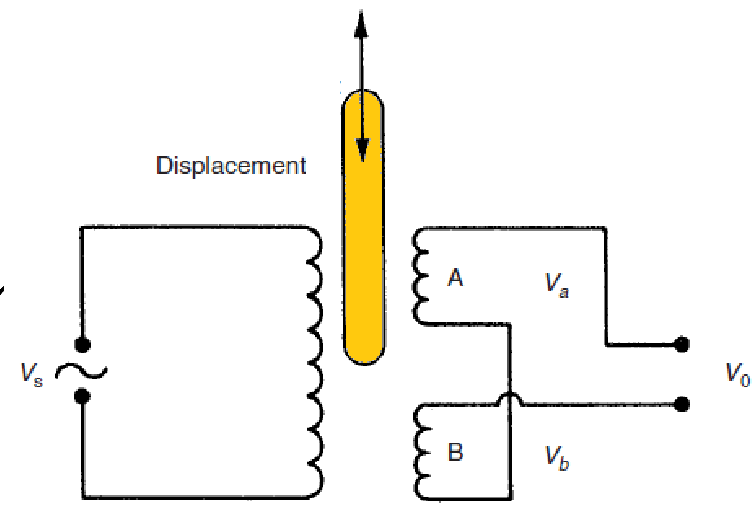




Linear Variable Differential Transformer

- Because of the series opposition mode of connection of the secondary windings, the output voltage, V_0 is the difference between V_a and V_b,
- With the core in the central position, $K_a = K_b$, and $V_0 = 0$.
- The relationship between the magnitude of V_0 and the core position is approximately linear over a reasonable range of movement of the core on either side of the null position.



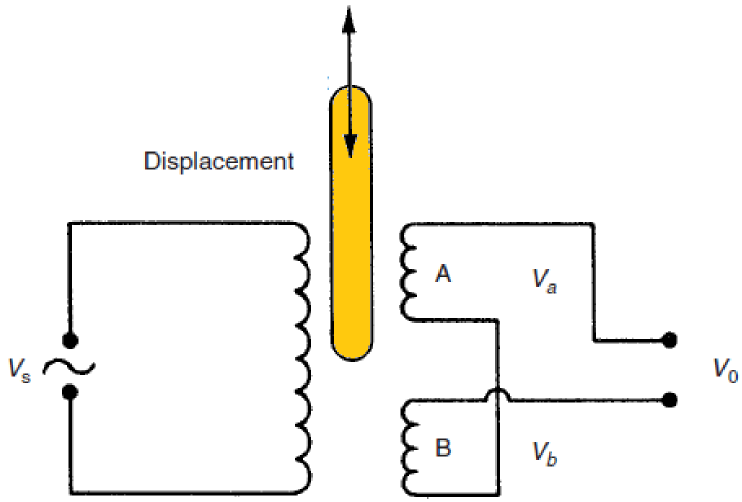


$$V_o = V_a - V_b = (K_a - K_b)\sin(\omega t - \varphi)$$

Linear Variable Differential Transformer

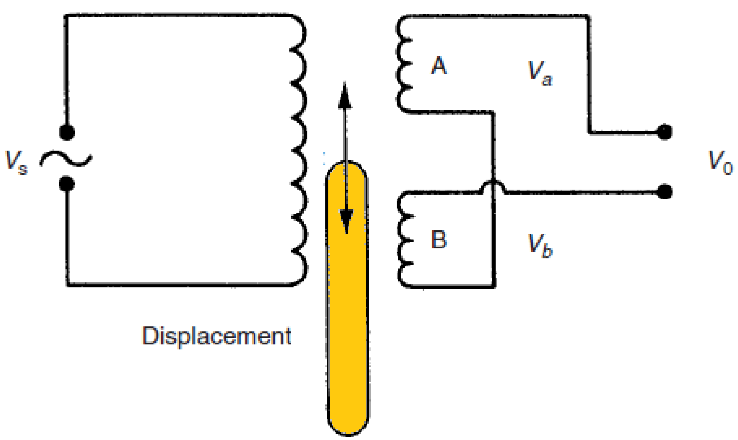
- Suppose that the core is displaced upwards (i.e. towards winding A) by a distance *x*. then K_a increases to become K_L and K_b decreases to become K_S. We thus have:

$$V_o = V_a - V_b = (K_L - K_S)\sin(\omega t - \varphi)$$



- If, alternatively, the core were displaced downwards from the null position (i.e. towards winding B) by a distance *x*, then K_a decreases to become K_S and K_b increases to become K_L, and we would have:

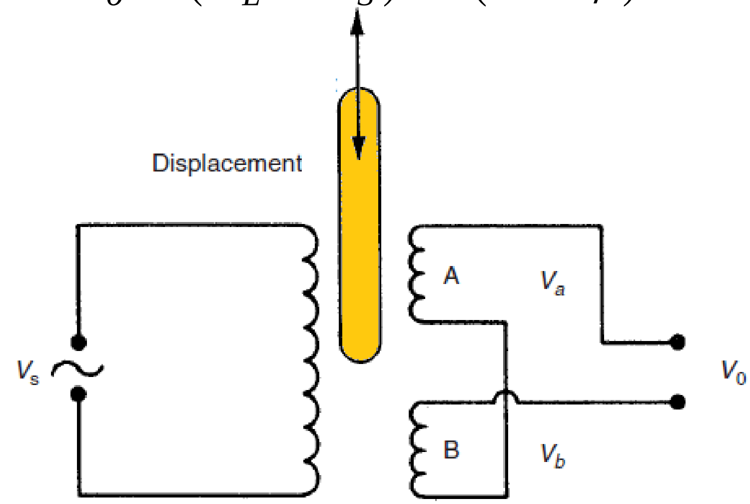
$$V_o = V_a - V_b = (K_S - K_L)\sin(\omega t - \varphi)$$
$$V_o = V_a - V_b = (K_L - K_S)\sin(\omega t - \varphi + \pi)$$

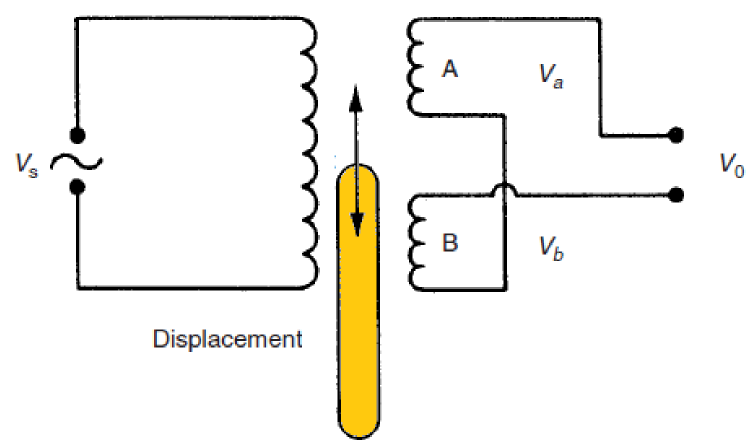


Linear Variable Differential Transformer

- Thus for equal magnitude displacements *+x* and *-x* of the core away from the central (null) position, the magnitude of the output voltage V_0 is the same in both cases. The only information about the direction of movement of the core is contained in the phase of the output voltage, which differs between the two cases by 180°.
- If, therefore, measurements of core position on both sides of the null position are required, it is necessary to measure the phase as well as the magnitude of the output voltage.

$$V_o = (K_L - K_S)\sin(\omega t - \varphi)$$

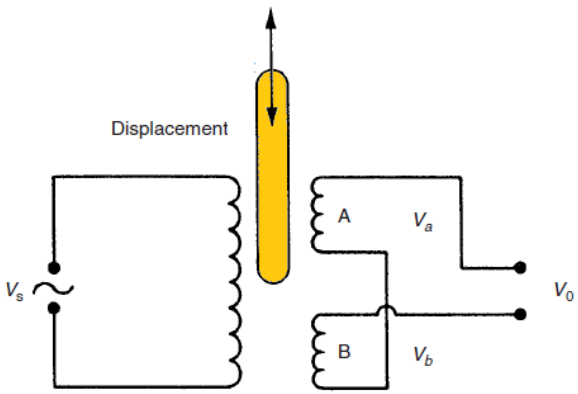




$$V_o = (K_L - K_S)\sin(\omega t - \varphi + \pi)$$

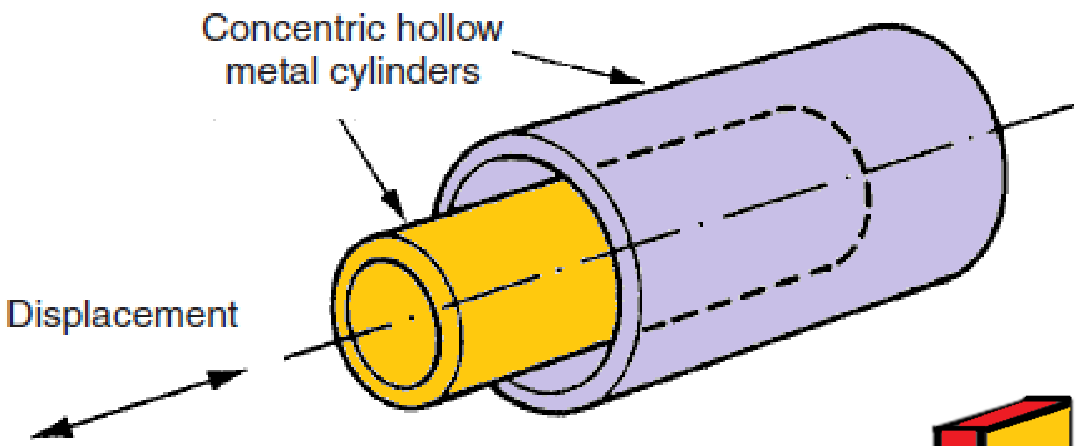
Linear Variable Differential Transformer

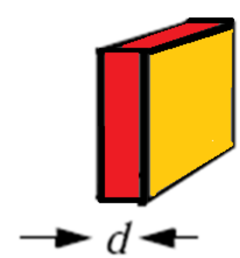
- Some problems that affect the accuracy of the LVDT are the presence of harmonics in the excitation voltage and stray capacitances, both of which cause a non-zero output of low magnitude when the core is in the null position.
- It is also impossible in practice to produce two identical secondary windings, and the small asymmetry that invariably exists between the secondary windings adds to this non-zero null output. The magnitude of this is always less than 1% of the full-scale output and in many measurement situations is of little consequence.
- Where necessary, the magnitude of these effects can be measured by applying known displacements to the instrument. Following this, appropriate compensation can be applied to subsequent measurements.



Variable Capacitance Transducers

- In the concentric cylinders variable capacitance transducer, capacitance plates are formed by two concentric, hollow, metal cylinders.
- The displacement to be measured is applied to the inner cylinder, which alters the capacitance

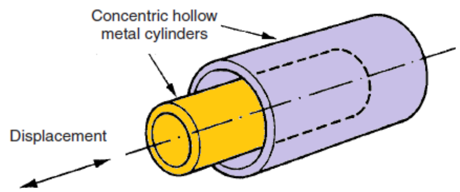


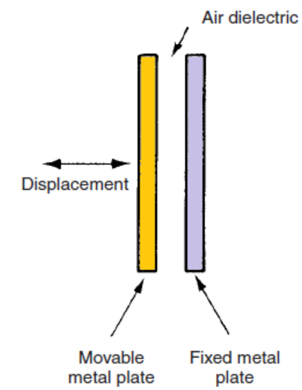


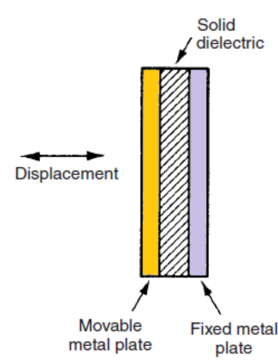
$$C = \varepsilon_o \varepsilon_r \frac{A}{d}$$

Variable Capacitance Transducers

- Inaccuracies as low as ±0.01% are possible with these instruments, with measurement resolutions of 1 micron. Individual devices can be selected from manufacturers' ranges that measure displacements as small as 10-11 m or as large as 1m.
- The fact that such instruments consist only of two simple conducting plates means that it is possible to fabricate devices that are tolerant to a wide range of environmental hazards such as extreme temperatures, radiation and corrosive atmospheres.
- As there are no contacting moving parts, there is no friction or wear in operation and the life expectancy quoted is 200 years.

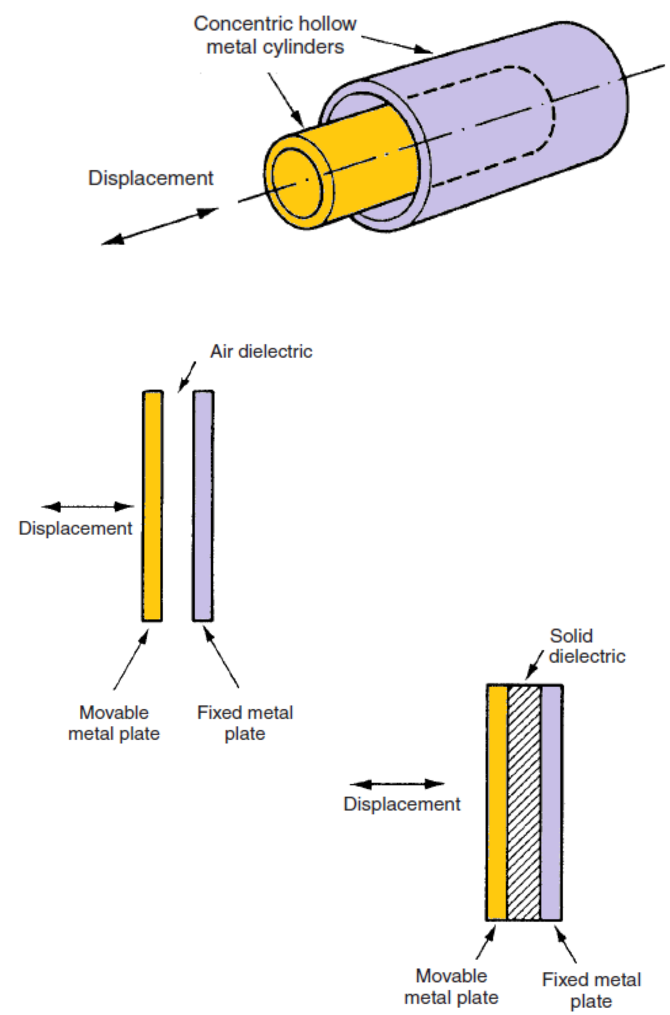




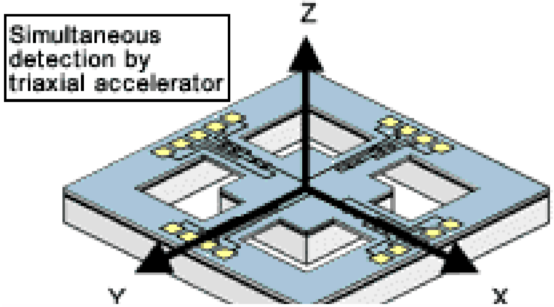


Variable Capacitance Transducers

- The major problem with variable capacitance transducers is their high impedance. This makes them very susceptible to noise and means that the length and position of connecting cables need to be chosen very carefully.
- In addition, very high impedance instruments need to be used to measure the value of the capacitance.
- Because of these difficulties, use of these devices tends to be limited to those few applications where the high accuracy and measurement resolution of the instrument are required.



Accelerometers



- Because of earth's gravity, the sensor will read 1 to 0 g as the sensor is rotated from being vertical to horizontal.
  - This can be used to measure angle of tilt
- Most have analog outputs that need amplification
  - Some have built-in amplifiers for direct connection into microcontroller

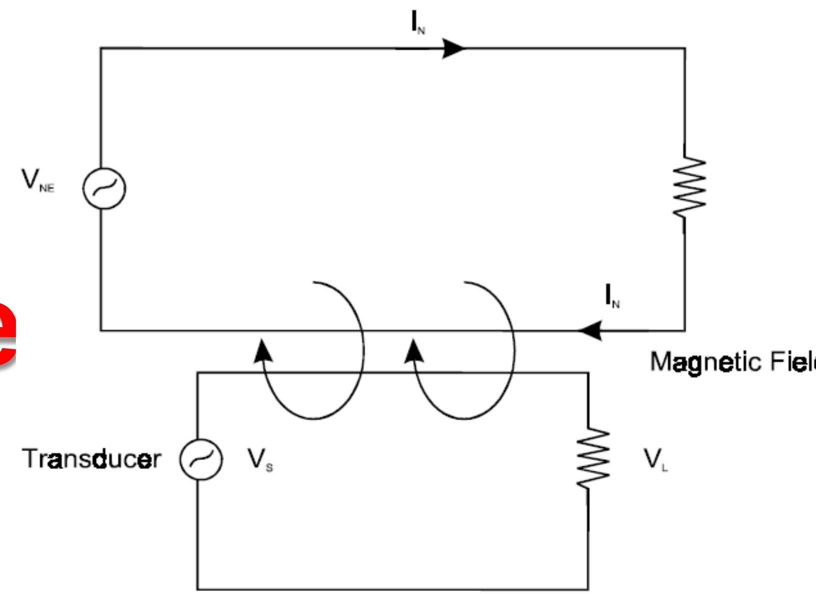
Accelerometers
Applications

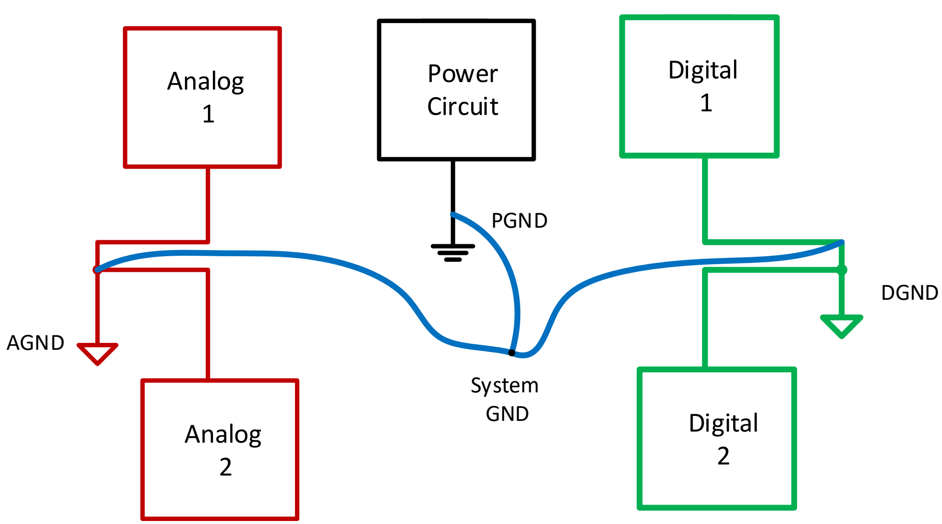
- Can be used to sense orientation, vibration and shocks.
- Used in electronics like the Wii and iPhone for user input.
- Acceleration integrated once gives velocity, integrated a second time gives position.
  - The integration process is not precise and introduces error into the velocity and position.

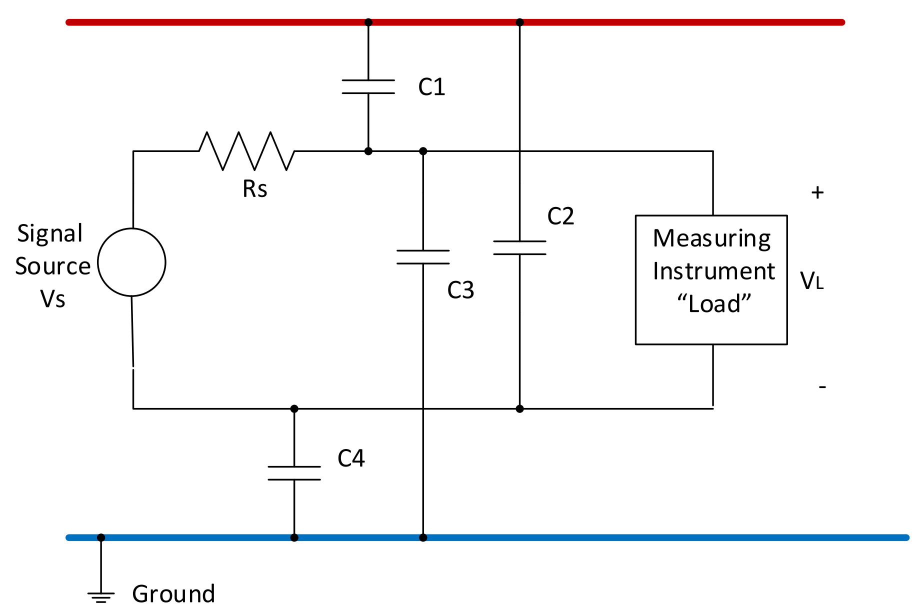
ENEE4304

Lec-notesG7-2021

Measurement Noise and Signal Conditioning







Noise and Interference

- Noise, by definition, is the presence of an unwanted electrical signal in a circuit.
- Interference is the undesirable effect of noise.
- Where a noise voltage causes improper operation of a circuit, or its relative magnitude is of the same order as the desired electrical signal, then it is interference.
- Noise itself cannot be totally eliminated but only reduced in magnitude until it no longer causes interference.
- This is especially true in data acquisition systems where the analog signal levels from transducers measuring a physical quantity can be very small.
- Compounding this in many instances is the physical cable distance over which these signals must be transmitted and the effect that noise may have on this extended circuitry.

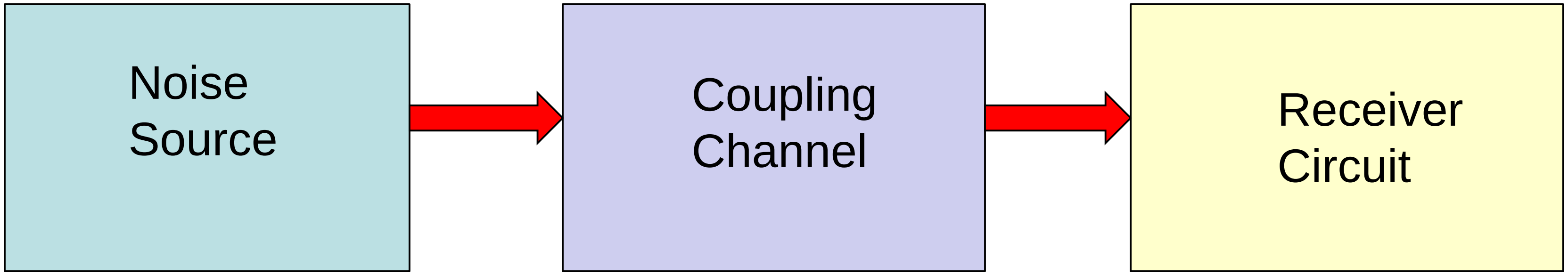
Noise and Interference

- Noise itself cannot be totally eliminated but only reduced in magnitude until it no longer causes interference.
- Noise is reduced by proper design practices and whatever noise that remain is treated by signal conditioning circuits
- Types of Noise :
  - Serial (differential type) which acts in series with useful output voltages of sensors and transducers and can cause significant errors
  - Common Mode noise which affects both lines in the same manner, it is dangerous since it can become differential in certain circumstances

Classification of Noise Sources

- External Sources such as motors, fluorescent lamps, monitors, mains cables, RF and audio-frequency circuits
- Internal Sources such as thermoelectric noise, shot noise and electrochemical action

Components of Noise induced Problem



Noise Source

- AC power Cables
- High voltage or high current circuits (motors etc)
- Switching power supplies
- Computer monitors
- Fluorescent lamps

Coupling Channel

- Common Impedance (Conductive coupling)
- Electric Field (Capacitive coupling)
- Magnetic Field (Inductive coupling)

Receiver Circuit

- Transducer
- Transducer to signal conditioning cable
- Signal conditioning
- Signal conditioning to measurement system cable

Coupling Mechanisms

- The mechanisms for coupling noise most common to data acquisition and control applications are as follows:
  - ➢ Conductive coupling
  - ➢ Capacitive coupling
  - ➢ Inductive coupling
  - ➢ Other Coupling Mechanisms

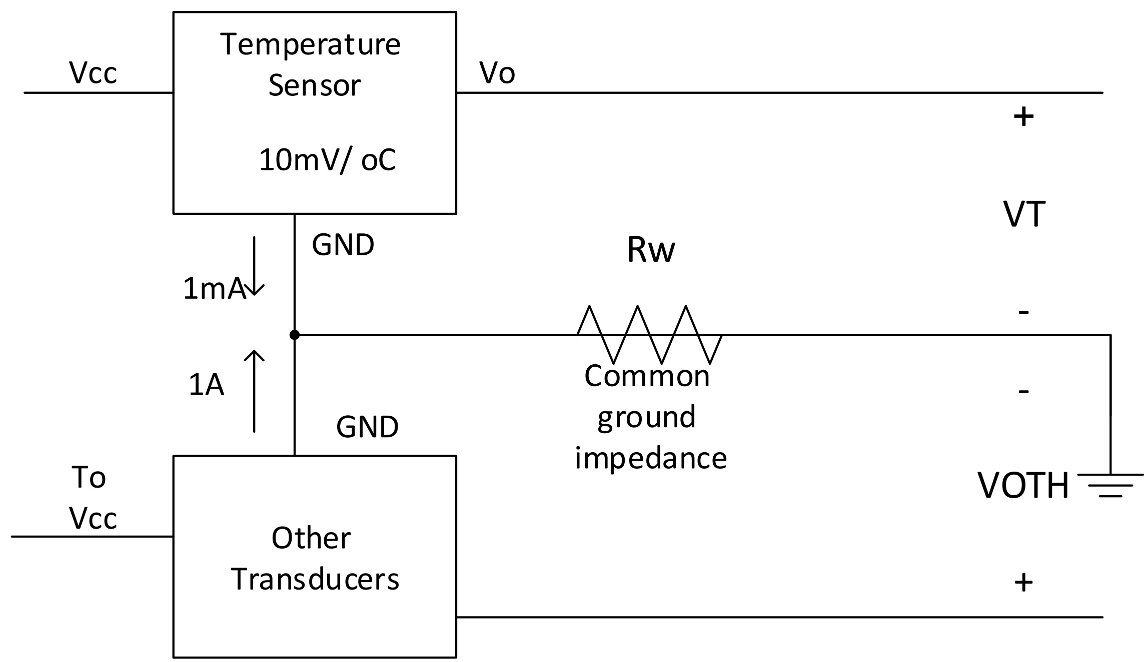
Conductive Coupling

- Conductive coupling occurs where two or more circuits share a common signal return.
- In such cases, return current from one circuit, flowing through the finite impedance of the common signal return, results in variations in the ground potential seen by the other circuits.

Conductive Coupling

- A series ground connection scheme resulting in conductive coupling is shown in Figure below.
- If the resistance of the common return lead is 0.1 Ω and the return current from all other circuits is 1 A, then the voltage measured from the temperature sensor, (V_T), would vary by 0.1 Ω × l A = 100 mV, corresponding to 10 degrees error in the temperature measured.

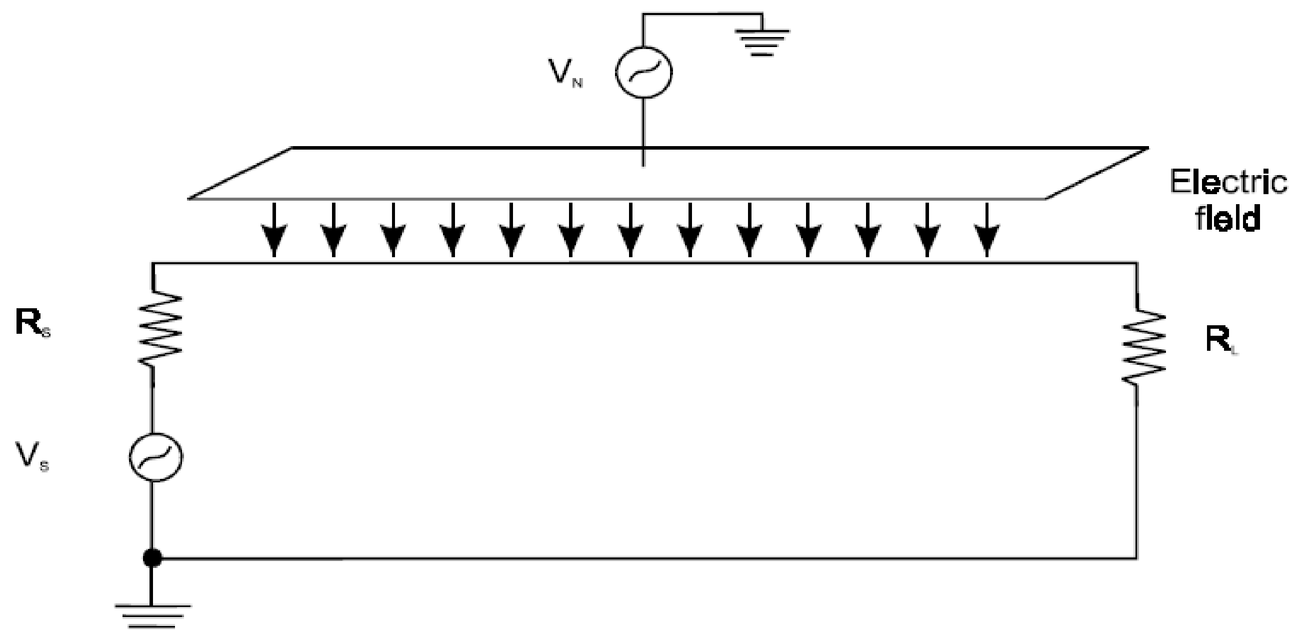
Series ground connections resulting in conductive coupling



Capacitive Coupling

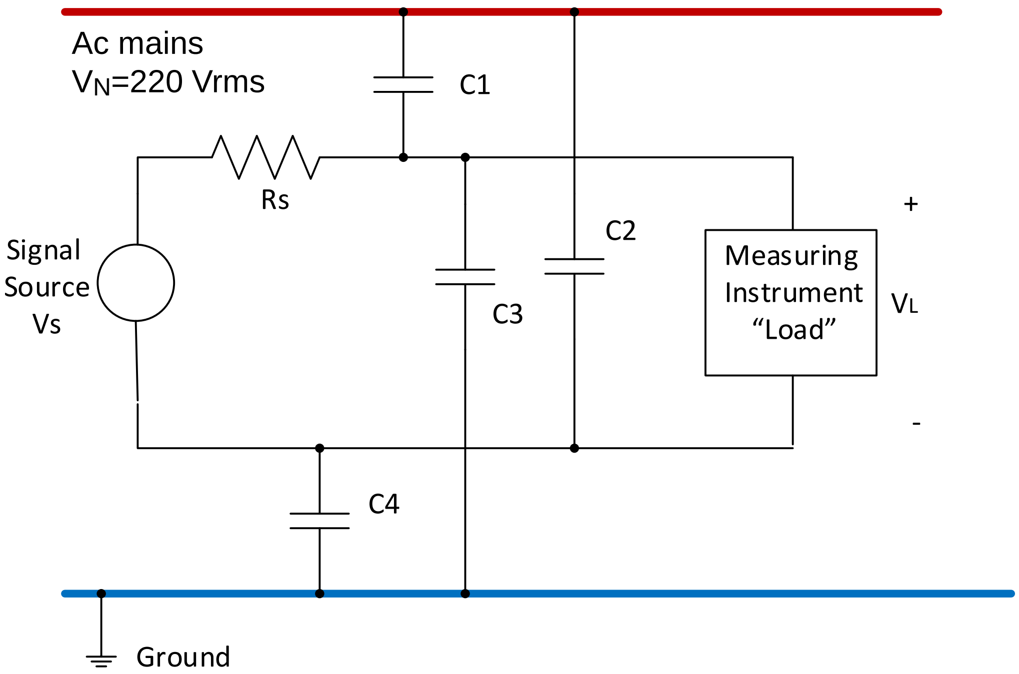
- Due to electric fields
- Electric fields occur in the vicinity of voltage-varying sources.
- Capacitive coupling ***is the transmission of external noise through mutual and stray capacitances between a noise source and receiving circuit.***
- This is sometimes referred to as electrostatic coupling, although this is a misnomer, since the electrical fields are not static.
- Since cables tend to be the longest circuit elements, capacitive coupling is best demonstrated by considering a signal circuit connecting a signal source to a measurement system by a pair of long signal-carrying conductors.

- The physical representation of electric field coupling between a noise source and such a signal circuit is shown in Figure below.



Physical representation of an electrical field coupling into a signal circuit

- Noise voltage $V_n = \omega R_S C_n V_N$
- where Cn is any of the parasitic/ stray capacitors C1,C2, C3, C4
- If we make C1=C2 and C3=C4 then the noise voltage caused by these caps will be equal and opposite in sign and cancel each other
- Any unbalance in capacitor values will result in net noise voltage added or subtracted from V_L
- Also Rs must be smaller than load resistance and stray capacitance impedance

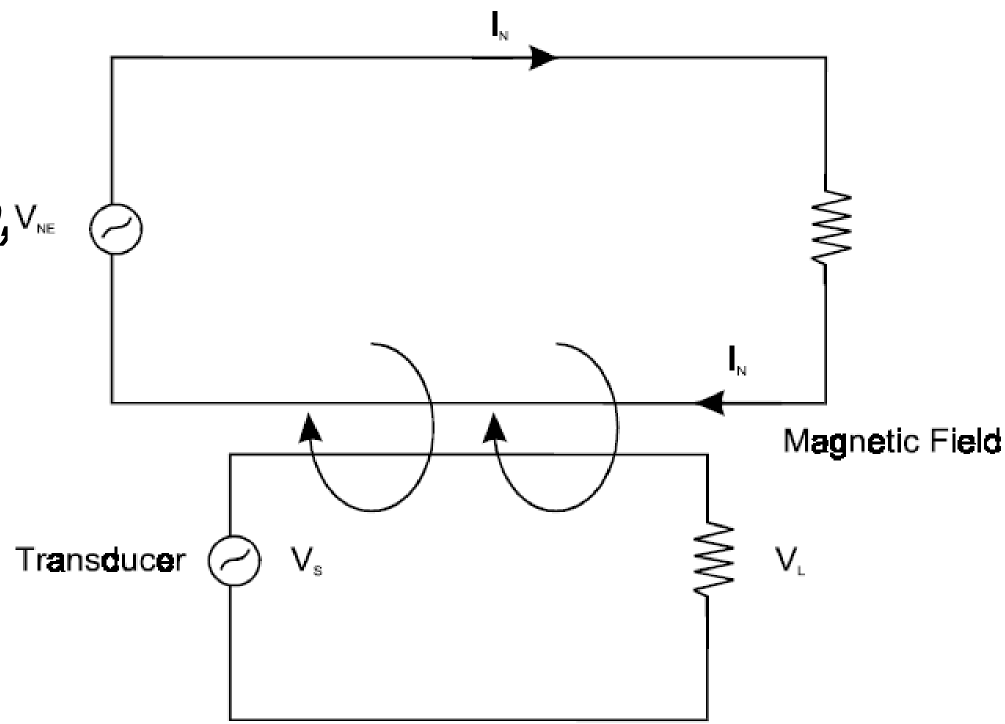


- The amplitude and the frequency of the noise source cannot be altered, the only means for reducing capacitive coupling into the signal circuit is to reduce the equivalent **signal circuit resistance to ground or reduce the mutual stray capacita**nce.

$$V_n = \sim \omega R_S C_n V_N$$

Magnetic field coupling “Inductive Coupling”

- Magnetic field coupling or inductive coupling ***is the mechanism by which time-varying magnetic fields produced by changing currents in a noise source, link with current loops of receiving circuits.***
- The physical representation of magnetic field coupling between a noise source and a signal circuit is shown in Figure



- Lenz’s law states that the voltage, Vn induced into a closed loop signal circuit of area A is proportional to the rate of change of the magnetic field coupling the circuit loop, the flux density (B) of the magnetic field and the area of the loop.
- This is represented by the formula:

$$Vn = 2\pi f BA \cos\varphi (10^{-4})$$

$$V_n = 2\pi f BA \cos\varphi \,(10^{-4})$$

- where
  - f = the frequency of the sinusoidal varying flux density
  - B = the rms value of the flux density (gauss)
  - A = the area of the signal circuit loop (m^2)
  - φ = the angle between the flux density (B) and the area (A).
- This equation indicates that the noise voltage can be reduced by reducing *B*, *A*, or $\cos\varphi$.
- The flux density (*B*) can be reduced by increasing the distance from the source of the field or if the field is caused by currents flowing through nearby pairs of wires, twisting those wires to reduce the net magnetic field effect to zero and or by alternating its direction.

Inductive Coupling

- The signal circuit loop area (*A*) can be reduced by placing the signal wires of the receiving circuit current loop closer together.
- For example, consider a signal circuit whose current carrying wires are 1 meter long and 1 centimeter apart, lying within a 10 gauss 60 Hz magnetic field, typical of fans, power wiring and transformers.
- The maximum voltage induced in the wires occurs for $\varphi = 0^\circ$.
- Vn = (2**π x** 60)(10)(1 × 10^–2)(10^–4) = 3.7 mV.
- If the distance between the wires is reduced to 1 mm the noise voltage is reduced ten fold to 0.37 mV.

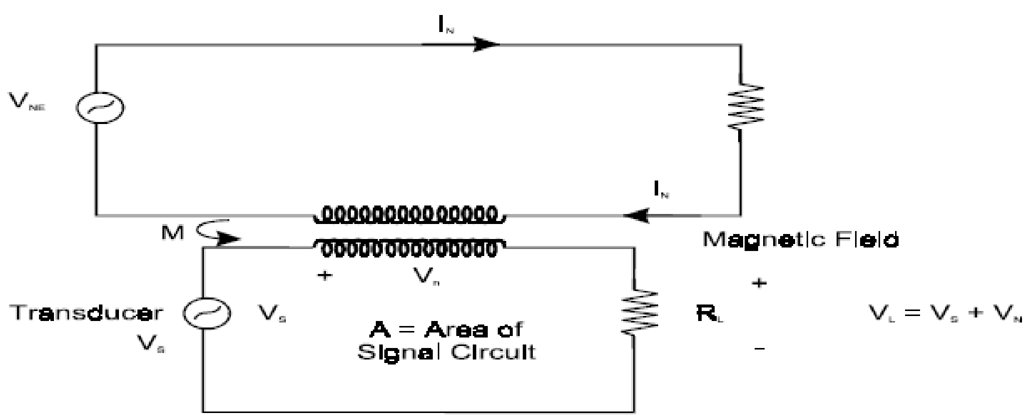
Inductive Coupling

- The cosφ, term can be reduced by correctly orienting the wires of the signal circuit in the magnetic field.
- For example, if the signal wires were perpendicular to the magnetic field ($\varphi = 90°$) the induced voltage could be reduced to zero, although practically this would not be possible.
- Running the signal wires together in the same cable as the wires carrying the noise current source would maximize the induced noise voltage

- The equivalent circuit model of magnetic coupling between a noise source and a signal circuit is shown in Figure below.
- In terms of the mutual inductance (M), Vn is given by:

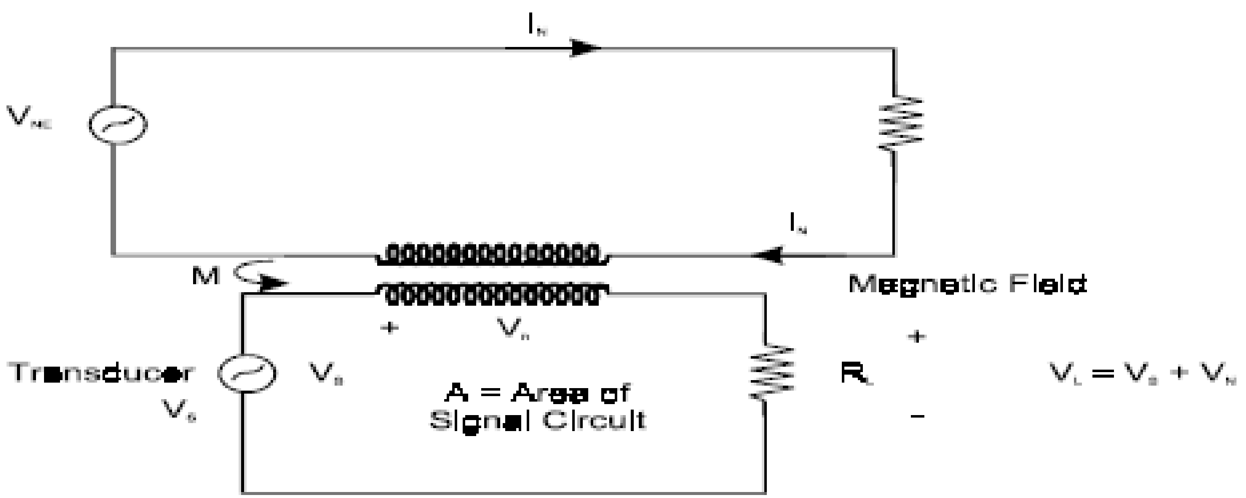
$$V_n = 2 \pi f M I_N$$

- I_N - is the rms value of the sinusoidal current in the noise circuit and f is its frequency.
- The mutual inductance (M) is directly proportional to the area (A) of the signal circuit current loop and the flux density, (B).



Inductive Coupling

- The physical geometry of the current loop of the receiving signal circuit, specifically its area, is the key to why it is susceptible to magnetic fields and how to minimize the effect.
- Cables provide the longest and largest current loop.
- The effect of magnetic coupling is best demonstrated by considering the circuit of Figure below, in which the signal cable current loop is coupled by a sinusoidal changing magnetic field with a peak flux density of $B\varphi$.



- Ideally, the only voltage appearing across the load should be V_S – the source signal voltage.
- However, the magnetic flux induces a voltage in the loop that appears in series with the receiver signal circuit.
- The voltage appearing across the load is the sum of the source voltage and the unwanted magnetic field induced voltage (V_N).

Techniques for Reduction of Noise

- 1. Location of signal wires:
  - Both mutual inductance and capacitance between signal wires are inversely proportional to the distance between them
  - It is recommended to place signal wires as far as possible from noise sources (at least 0.3 m)
- 2. Design of wires: Use twisted wires
- 3. Proper grounding
- 4.Shielding

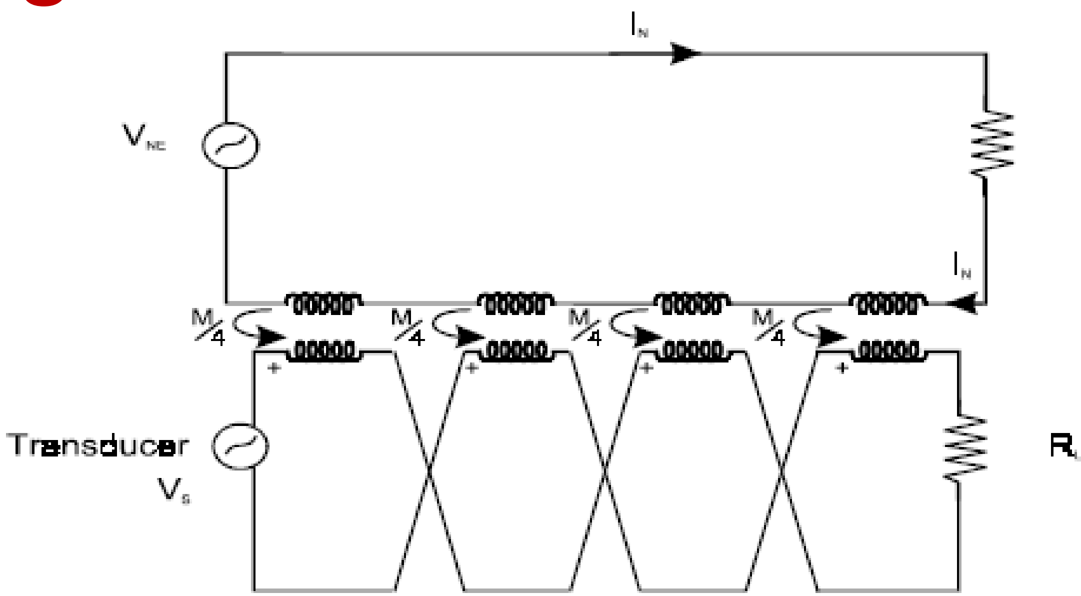
Location of signal wires:

- Both mutual inductance and capacitance between signal wires are inversely proportional to the distance between them
- It is recommended to place signal wires as far as possible from noise sources (at least 0.3 m)
- The mutual stray capacitance can be reduced by
  - **increasing the relative distance of the signal wires from the noise source,**
  - **correct orientation of the conductors,**

Design of Wires: Use twisted wires

- Twisting the insulated conductors together, can greatly reduce the amount of magnetic coupling into the signal lines.

Design of Wires: Use twisted wires



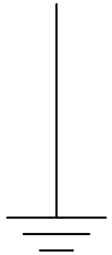
- The voltage induced in each section of the loop now alternates phases; its magnitude reduced by the reduction in area of each twisted loop (i.e. 1/4).
- Provided there is an even number of twists in the signal conductors, the voltages due to the magnetic field cancel out and only the desired signal voltage appears across the load.

Grounding Techniques

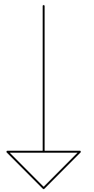
- The word ground has a historical origin that is , perhaps, the cause of the different meanings in use today.
- Originally , it referred to a point that was actually connected to earth in order to obtain zero potential
- In electronic systems, the ground point is the reference potential
- The confusion between earth and ground can be avoided if we consider that the electrical system on aircraft has aground point for voltage reference , a point that is not connected to earth
- We will use earth for connection to the earth and ground as a central reference connection

Grounding Techniques

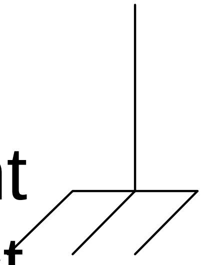
- Usually we use the following Ground symbols:
- Power Ground PGND : provides path for current faults



- Digital Ground- DGND: common for all digital and logic circuits

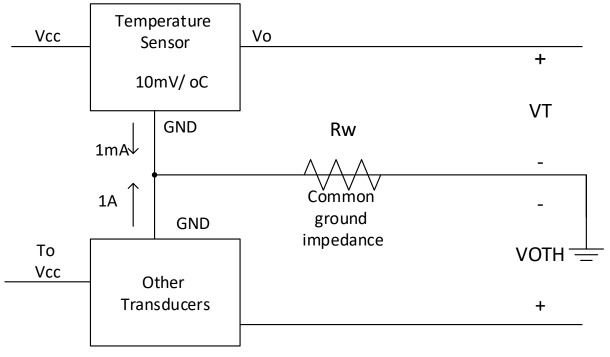


- Analog Ground –AGND : common for all analog signals
- Safety Ground = Chassis Ground (Earth) : connected to all metallic parts of the equipment to protect people if power lines come in contact with metal enclosure



Solution to previous problem

- Don't allow the 1A current affect the output temperature sensor V_T

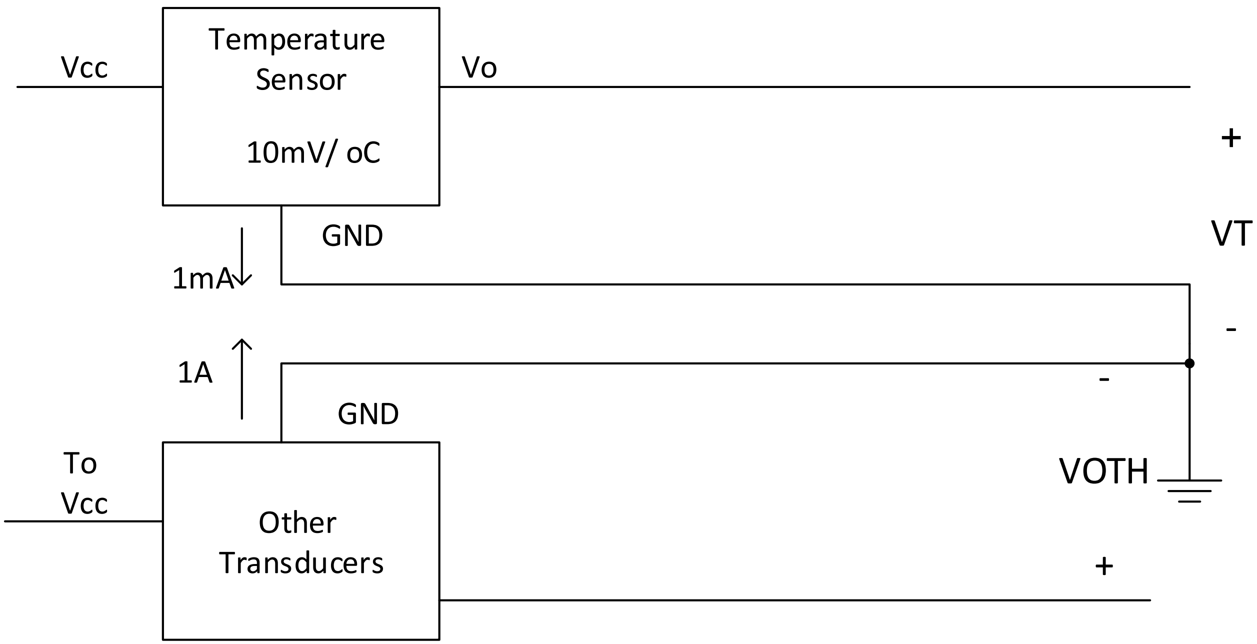


Wrong

Solution to previous problem

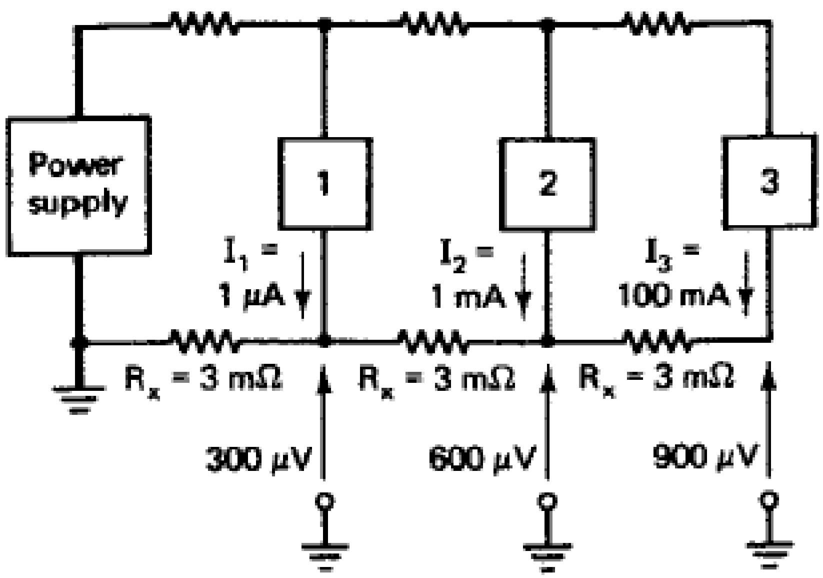
- Don't allow the 1A current affect the output temperature sensor V_T

Correct



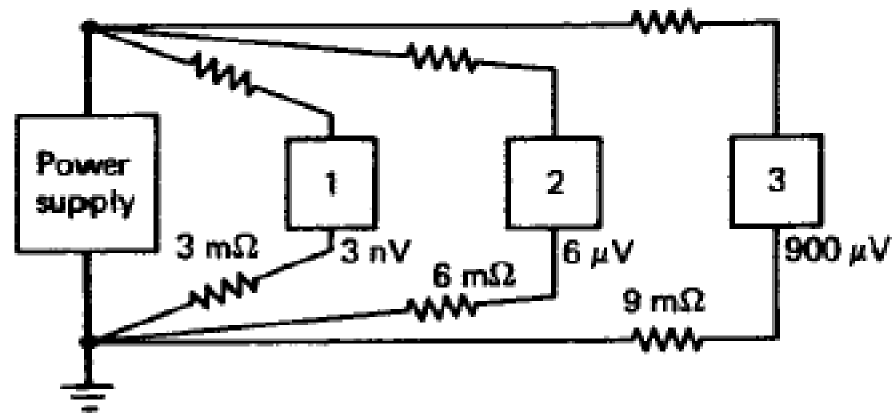
Ground Star Connection

Parallel distribution of power

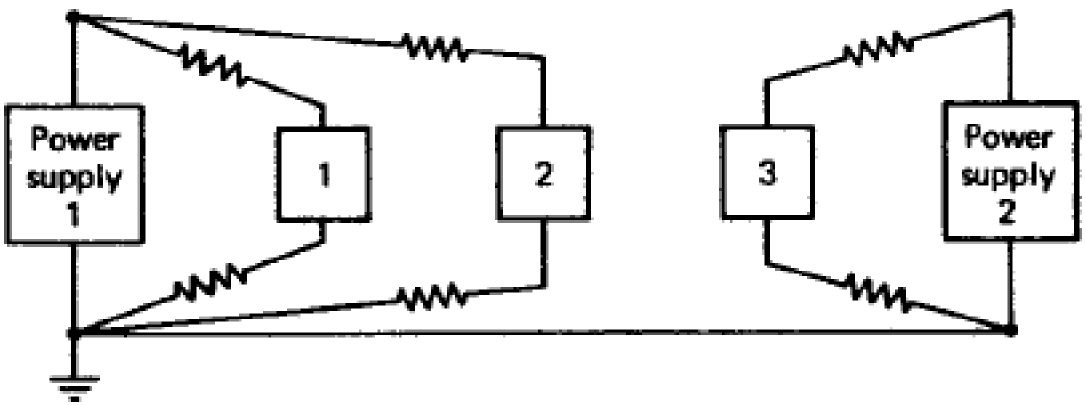


3 mohm is the resistance of 15 cm of AWG#18 wire

Radial (Star) distribution of power



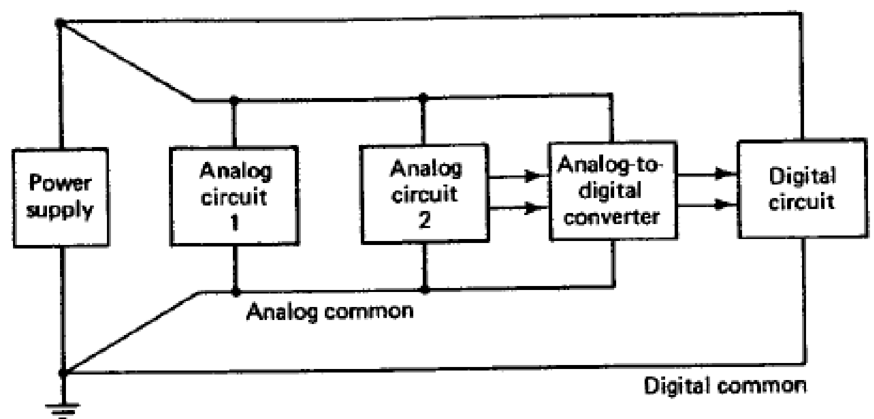
Two Power supplies can be used such that long wires are avoided for circuit 3



- If the voltage drop on power supply path does not affect the operation of the circuits, a combination of parallel and radial distribution could be used.
- The star connection will then be used for ground wire

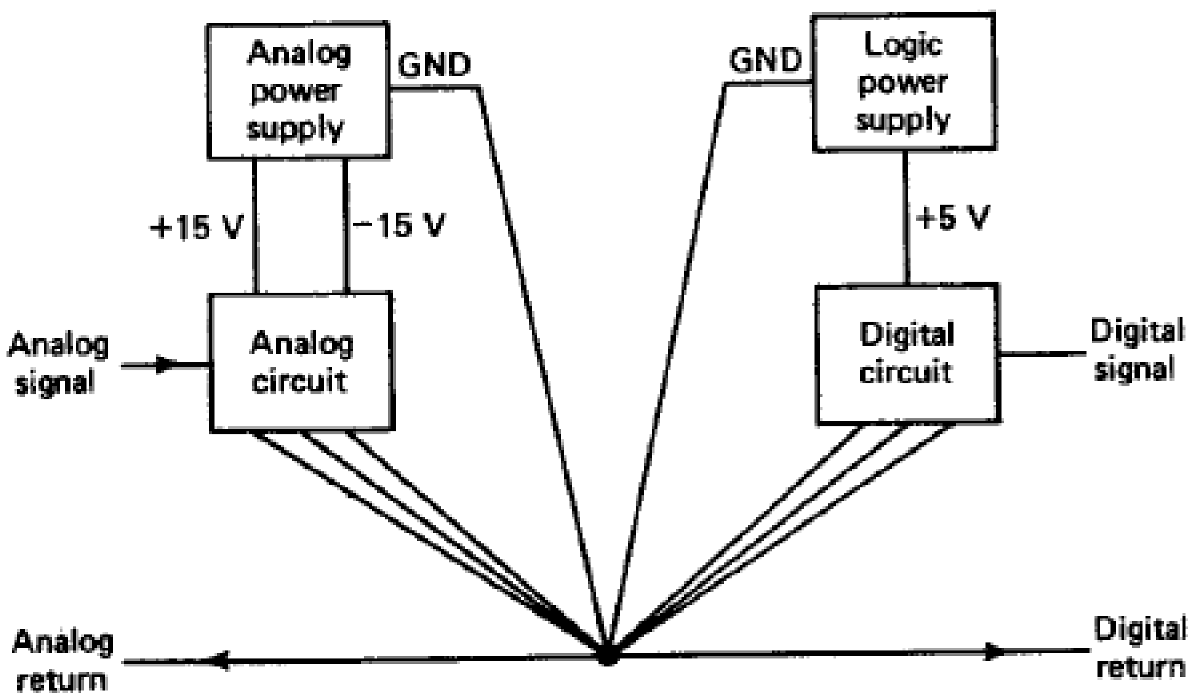
Grounding of Analog-Digital Circuits

- Consider the case when analog and digital circuits are used together
- Digital signals, create large current spikes in the ground paths due to switching
- These currents can cause much interference in analog circuits
- Even if they both share the same power supply, their ground wires must be different with only one common point as shown in the figure , this minimizes common impedances between digital and analog circuit



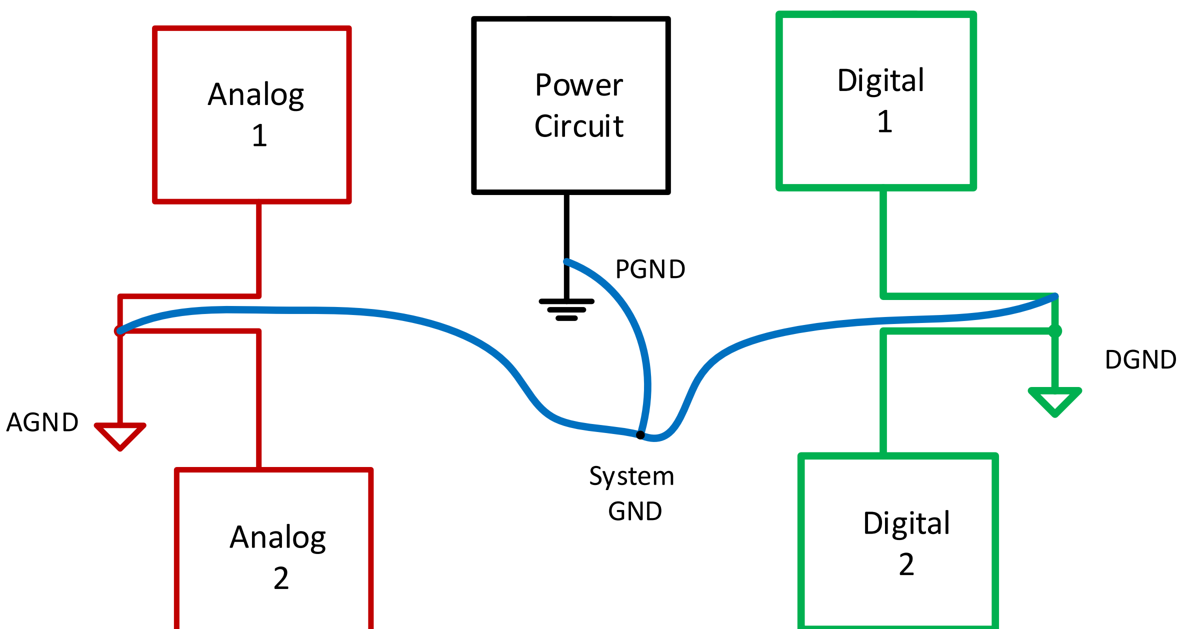
Analog-Digital Circuits

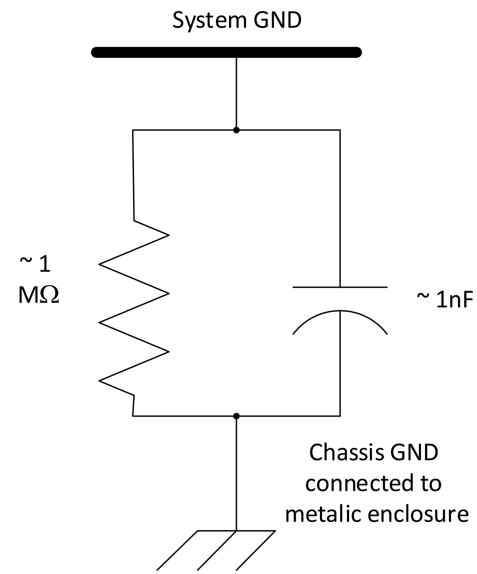
- When digital and analog circuits are powered by separate sources, each circuit must be connected to ground of its power supply.
- Then both grounds are connected to a single point ground that is called "star GND" or "system GND"



In schematic Capture (Board physical layout)

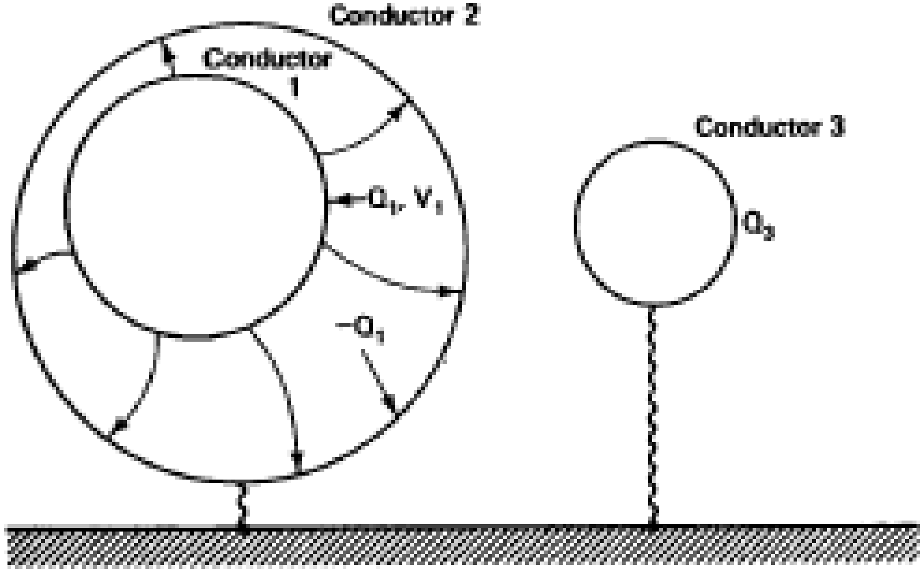
- Use Multiple grounds (with different symbols) according to type of circuit and then connect to the star point or system ground
- Connection of system ground to chassis (safety) ground can be done through a filter since system ground can act as a huge antenna that picks extra noise if connected to chassis directly, so a filter might be used





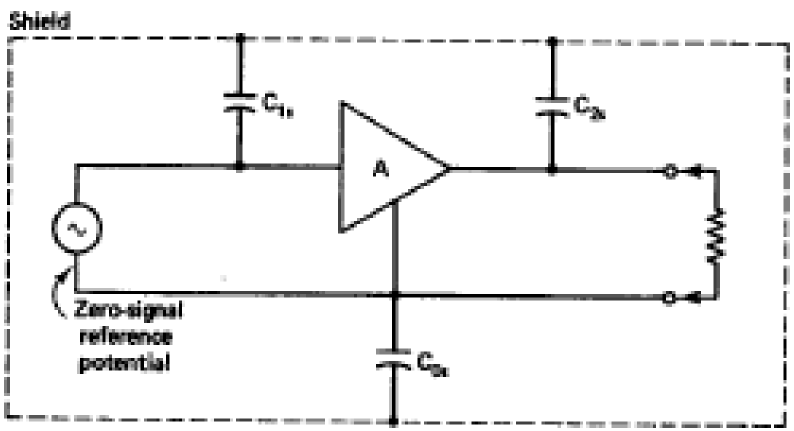
Electrical Shielding

- ***Shielding: adding a complete metallic enclosure or screen to remove capacitive coupling.***
- Conductor 2 is the shield to prevent mutual capacitance between 1 and 3

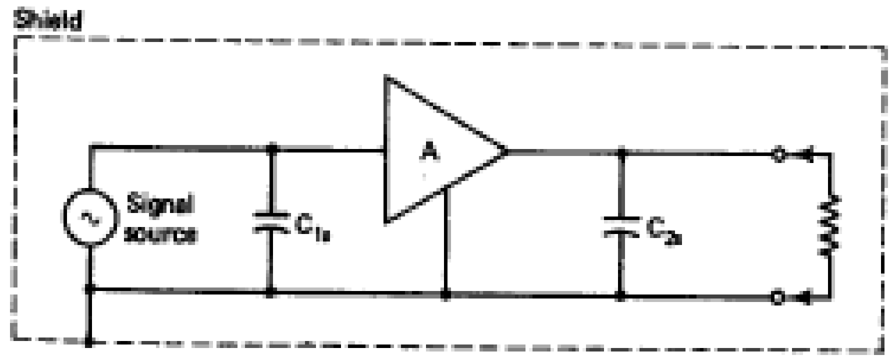


Rules of Shielding

- **Rule 1:** Connect the shield to low potential such as ground or earth , if not stray caps can appear as feedback caps affecting operation



Shield Floating
C1s and C2s appear as Feedback Caps that can affect frequency response of amplifier



Shield Grounded
C1s and C2s appear as input and output caps

- **Rule 2:** Shield conductor should be connected to zero-signal reference potential at the point the signal is earthed (point 1).
- Fig a shows an earthed signal source and **an incorrect connection between the shield and the signal reference lead at some other point (3)**. There is no connection between the shield and zero reference at point 1
- Ground 1 and 2 usually at different potentials, or in other words, there is a ground voltage V12

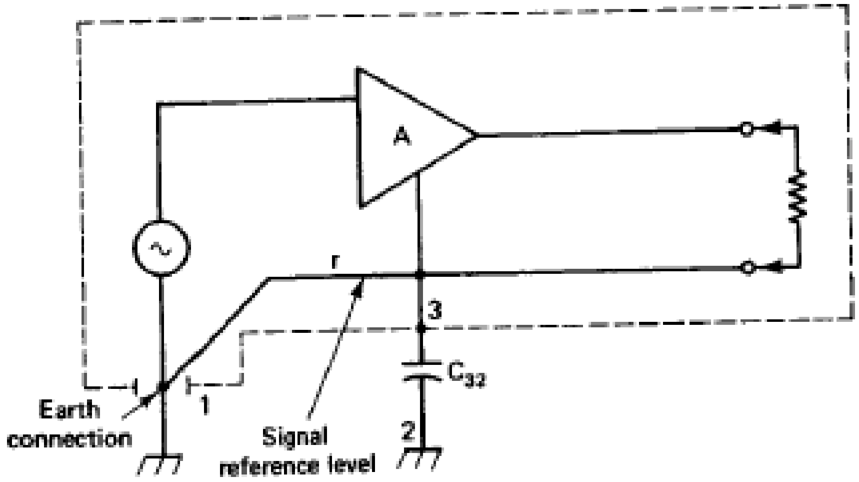


Fig a

- Fig b shows equivalent circuit of this case,
- The current due to V12 circulates through r, the reference signal wire, creating interference
- However if 1 and 3 , besides being at the same potential, coincide in a single physical point, no current passes through r, and interference is eliminated (Fig c)

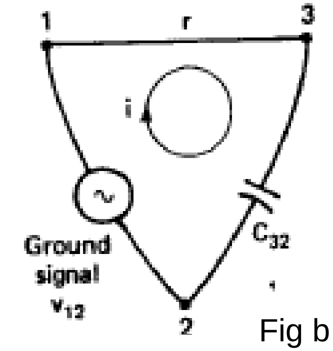


Fig b

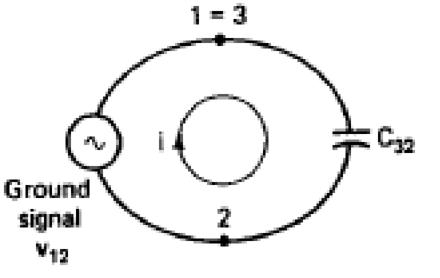


Fig c

Note that from electrical point of view Fig b and Fig c represent exactly the same circuit. However physical paths are different for the current

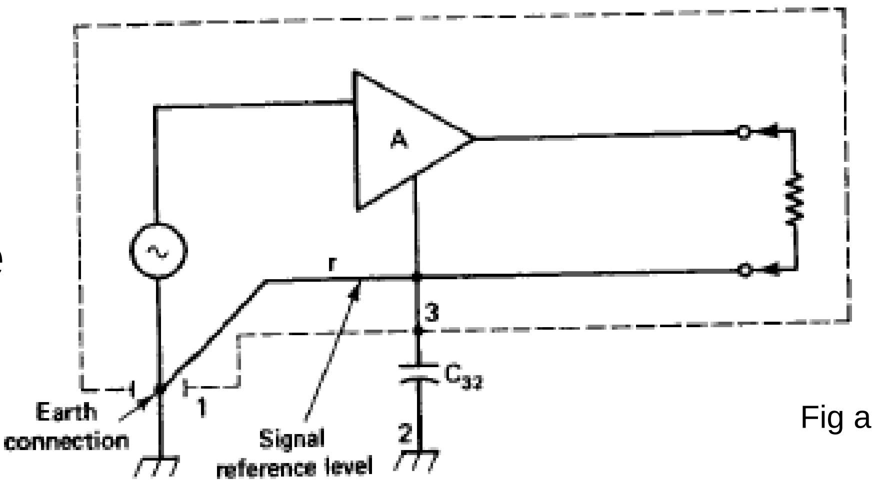


Fig a

ENEE4304
Instrumentation and Measurements

Signal Conditioning

Signal Conditioning Functions

- Isolation
- Filtering
- Amplification
- Linearization (bias removal)
- Excitation
- Other Functions

What is Electrical Isolation?

- Electrical isolation is a protective design feature of many data loggers and data acquisition systems.
- Isolation is implemented to separate measurement signals from each other in order to keep them from interacting and causing electrical issues.
- Isolation, separates different sections in the system to cut off the flow of current among them. This protects the system’s electrical components while still allowing for communication and data exchange as usual between electric circuits.
- For example, you can use Hall effect sensors which incorporate magnetism to transfer data across isolated system components.
- By allowing no DC paths, isolation keeps unintended current from flowing between the system segments.

Why Isolate Your Systems?

- Isolation is often required in real-time data acquisition applications such as:
- Medical Devices
- Automotive manufacturing
- Machine monitoring (turbines, motors, etc.)
- Food processing operations
- Many other heavy industrial uses

Why Isolate Your Systems?

- One excellent reason to use isolated data acquisition systems is to protect yourself or your personnel from electrical accidents.
- In particular, galvanically-isolated systems protect operators from being exposed to unsafe currents and high voltage.
- Otherwise, current flowing between the system's units can cause serious harm.
- Electrical isolation also ensures that your system's circuits are safe from damage from excessive current and voltage levels.
- Isolated measurement systems ensure that your measurements are free (as much as possible) from signal noise.

- While it’s true that all measurements have a certain amount of inaccuracy, if you’re working in a high-accuracy application then you’ll need to reduce this inaccuracy as much as possible.
- An isolated design helps to prevent signal noise by likewise preventing ground loop feedback. Galvanic isolation offers an additional benefit in the form of common-mode voltage rejection, which reduces signal noise by ignoring those signals (voltages) which are common to both inputs.
- This is especially useful if you’re trying to record accurate measurements in areas with high levels of electromagnetic interference.

- For the average user of a data acquisition system, the most likely risk is that the analog/digital signals will be corrupted or that the system will be damaged as a result of unintended ground current flow.
- Ground loops pose one of the greatest threats, both to measurement signals and to users themselves:
- • Data Loss: Networked data systems lacking isolation are at great risk of losing data through signal degradation.
- Isolation safeguards data from signal degradation while also helping to protect your initial investment in your data acquisition system.

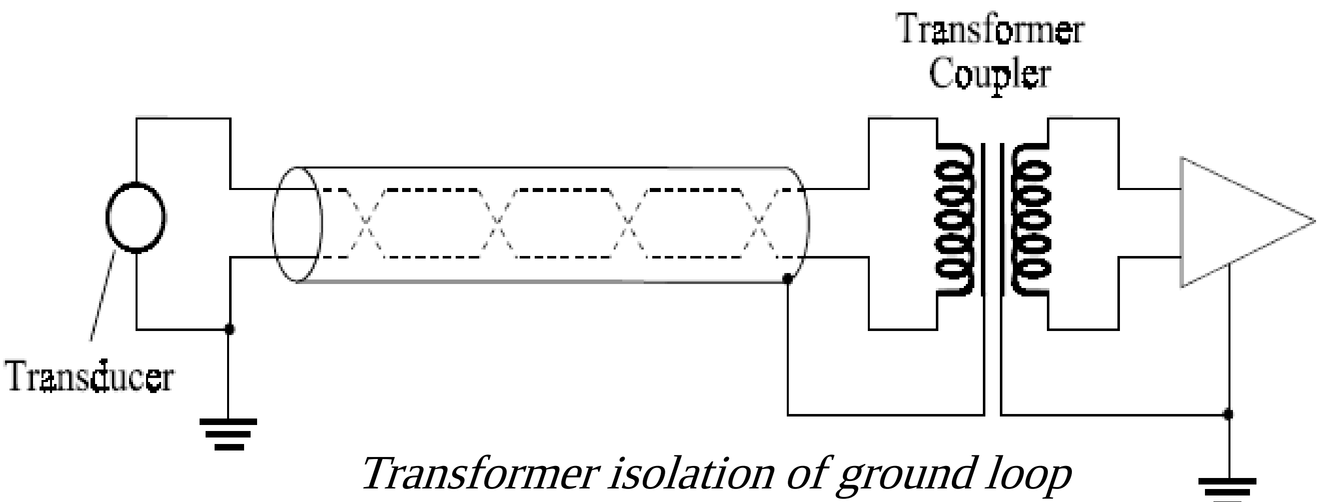
- Physical harm: Users of non-isolated systems face a real risk of harm caused by high current or voltage. Isolation prevents these ground loops from forming, thereby protecting the system and measurement signals.
- If you need to take additional precaution, galvanic isolation prevents ground loops by preventing the current paths which cause current to flow between units in the first place (i.e. by breaking the loop).

Signal circuit isolation

- Where a signal conductor is required to be earthed/grounded at both ends and additional noise immunity is required, the ground loop should be broken by isolating the signal source from the measuring equipment.
- Isolation by the use of transformers, opto-couplers and common mode chokes, is shown next
- When a transformer is used to isolate the signal source from the measurement system the common mode voltage appears between the windings of the transformer and not at the input to the measurement circuit.

Transformer isolation of ground loop

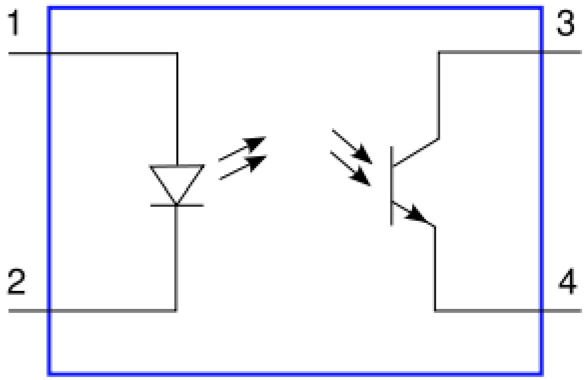
- Noise coupling between the circuits is very small and dependent on any stray capacitance between the transformer windings.
- Disadvantages with using transformers are that they are quite large and costly, especially where several signal circuits have to be isolated.
- In addition, transformers have limited frequency response and provide no DC continuity from the signal source to the measurement system.



Transformer isolation of ground loop

Optocouplers

It consists of a light emitting diode and photo transistor pair



The opto-coupler are typically used **more** for digital signals because of their non-linearity to analog signals.

Optocouplers

- LED for emitter
- Air as barrier for isolation
- Phototransistor for detector

- Opto-coupler can be used for DC and AC

When to Use?

- There are many situations where signals and data need to be transferred from one subsystem to another without making a direct electrical connection.
- Often this is because the **source** and **destination** are at very **different voltage levels**, like a microprocessor which is operating from 5V DC but being used to control a triac which is switching 240V AC.
- In such situations the link between the two must be an isolated one, to protect the microprocessor from overvoltage damage.
- Opto-couplers have advantages: small size, higher speed and greater reliability
- They use a beam of light to transmit the signals or data across an electrical barrier, and achieve excellent isolation

Opto-Coupler Parameters

- The most important parameter for optocouplers are:

1. **Isolation.**
2. **Transfer efficiency**, measured as the current transfer ratio or CTR.

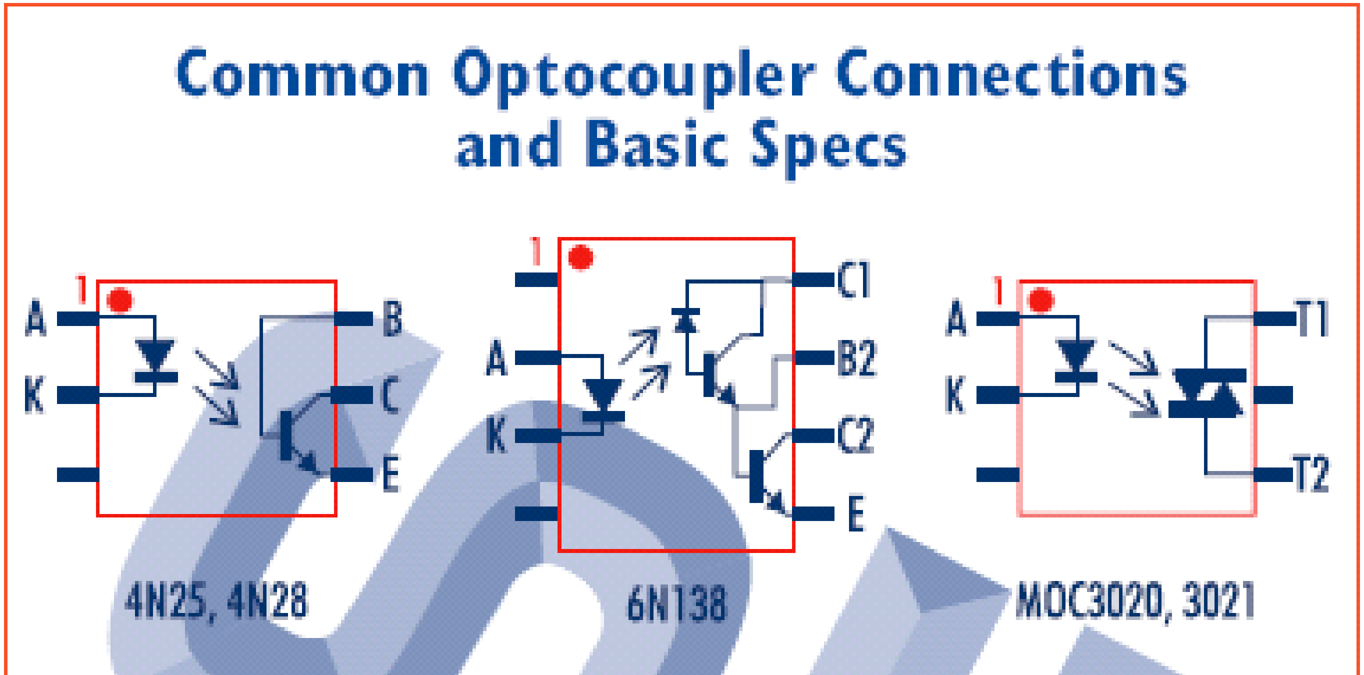
- CTR is simply the ratio between a current change in the output transistor and the current change in the input LED which produced it.

- Typical values for CTR range from 10% to 50% for devices with an output phototransistor and up to 2000% or so for those with a Darlington transistor pair in the output.

Parameters

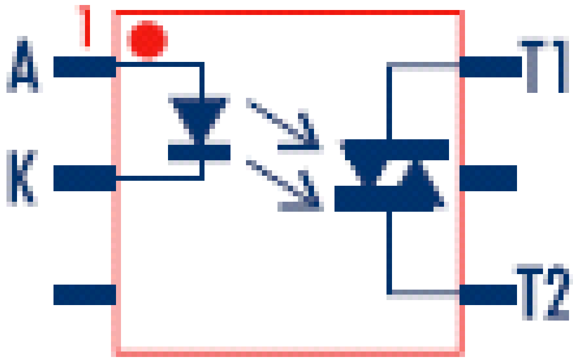
3. Optocoupler's bandwidth - determines the highest signal frequency that can be transferred through it.

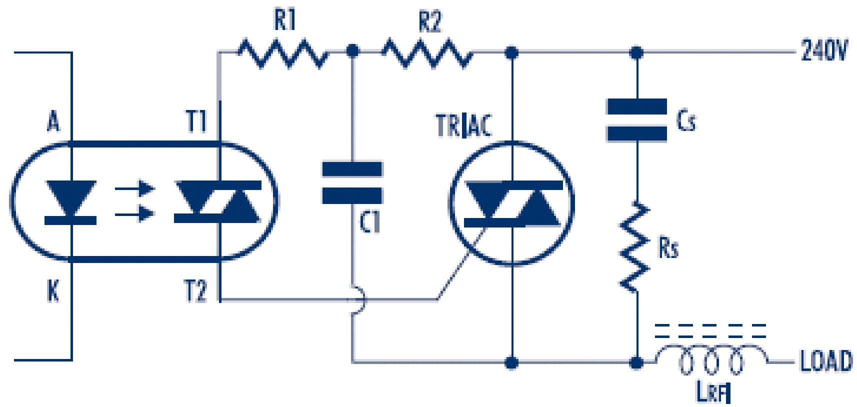
- Typical opto-couplers with a single output phototransistor may have a bandwidth of 200 - 300kHz, while those with a Darlington pair are usually about 10 times lower, at around 20 - 30kHz.



Darlington Pair

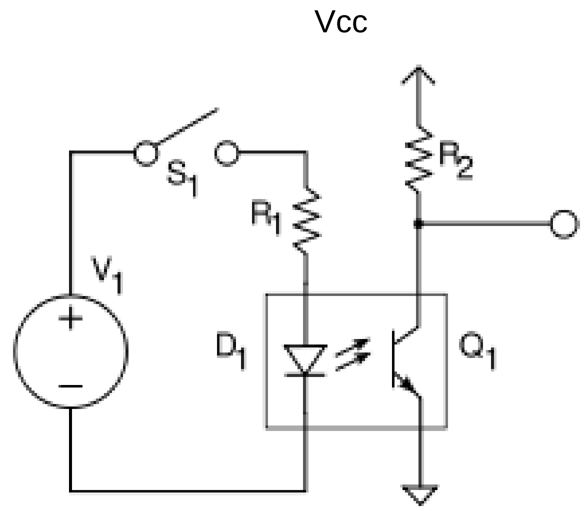
TYPE	ISOLATION (V_{ISO})	INPUT LED $I_{F(max)}$	OUTPUT $V_{CE(max)}$	CTRmin (@ I_F)	BANDWIDTH (kHz)
4N25	5300Vrms	80mA	7V	20% (10mA)	300
4N28	5300Vrms	80mA	7V	10% (10mA)	300
6N138	2500Vrms	20mA	7V	300% (1.6mA)	~20
MOC3020	7500Vpk	50mA	Voff = 400V	(Trig. @ 30mA)	—
MOC3021	7500Vpk	50mA	Voff = 400V	(Trig. @ 15mA)	—





- The other main type of optocoupler is the type having an output Diac or bilateral switch, and intended for use in driving a Triac or SCR.

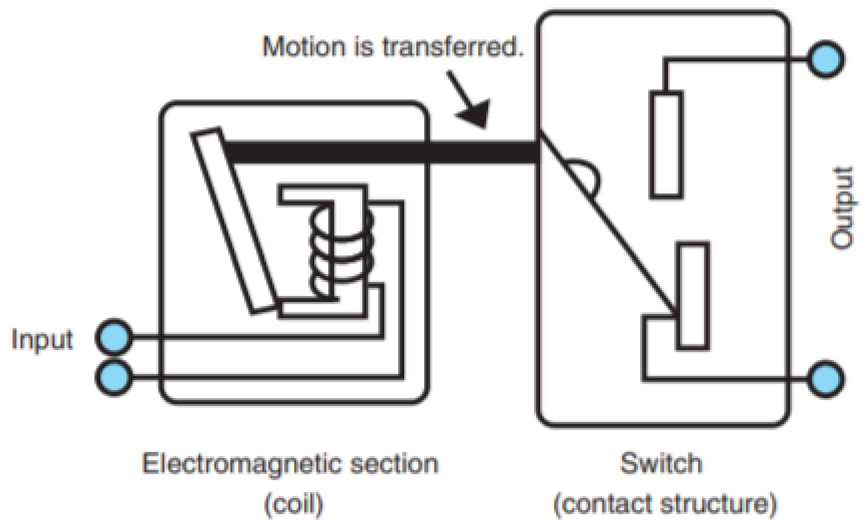
- Examples of these are the MOC3020 and MOC3021.
- Here the output side of the opto-coupler is designed to be connected directly into the triggering circuit of the Triac where it’s operating from and floating at full 120/240 VAC



- A simple circuit with an opto-isolator.
- When switch S1 is open, LED D1 is off, so Q1 is off and no current flows through R2, so Vout = Vcc.
- When switch S1 is closed, LED D1 lights.
- Phototransistor Q1 is now triggered, so current flows through R2
- Vout is then pulled down to low state.
- This circuit, thus, acts as a NOT gate.

Mechanical Relays

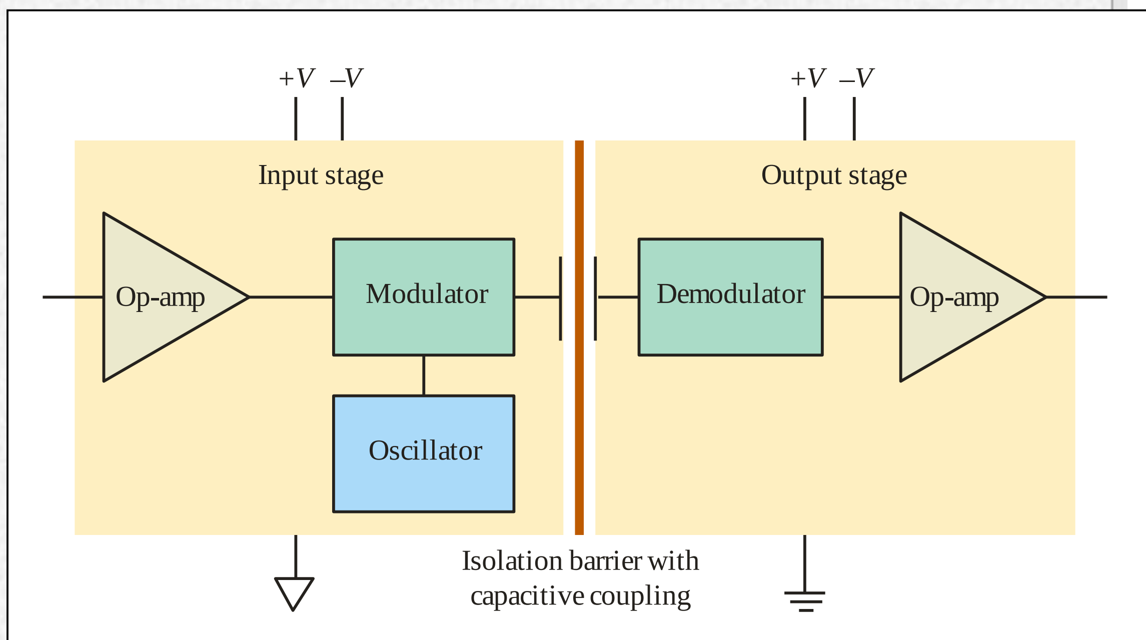
- Mechanical Relays can also provide isolation, but even small relays tend to be fairly bulky compared with ICs.
- Because relays are electro-mechanical, they are not as reliable and are only capable of relatively low speed operation.
- Limited Life since it has moving parts and contacts



Isolation Amplifiers

An **isolation amplifier** is designed to provide an electrical barrier between the input and output in order to provide protection in applications where hazardous conditions exist.

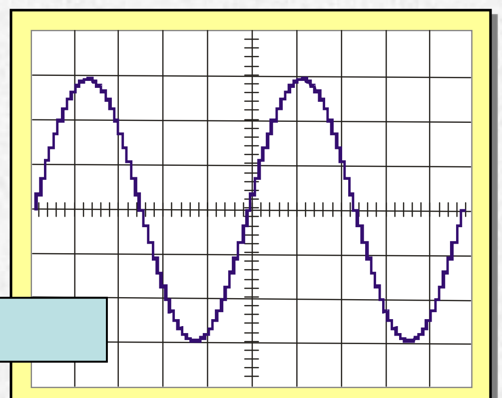
A typical isolation amplifier uses a high frequency modulated carrier frequency to pass a lower frequency signal through the barrier.



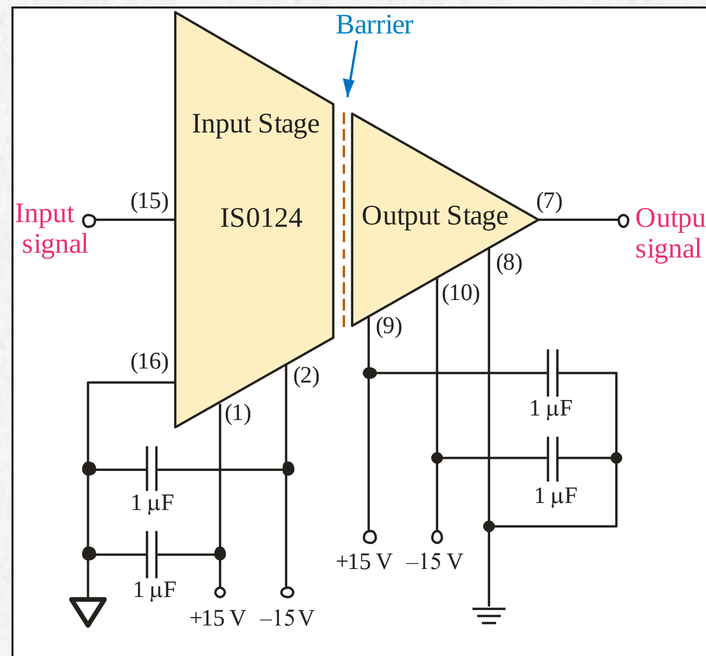
Isolation Amplifiers

The ISO124 is a capacitively-coupled isolation amplifier that uses pulse width modulation to transmit data across the barrier.

The ISO124 has fixed unity gain and is rated to 1500 Vrms of isolation.
The frequency response is specified to 50 kHz, but high-frequency ripple due to the PW modulation may be observed on the output at higher frequencies.



Output waveform

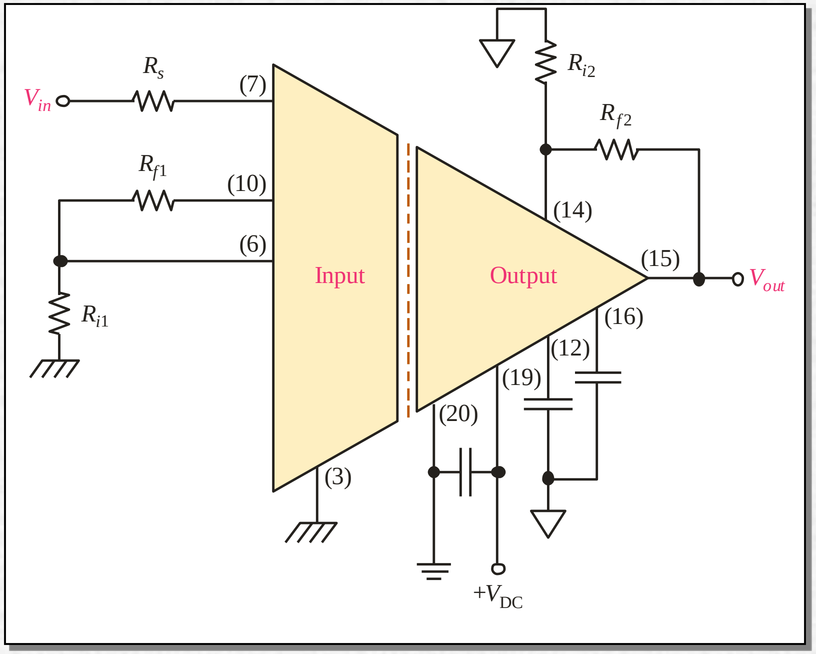


Isolation Amplifiers

The 3656KG is a transformer coupled isolation amplifier that uses pulse width modulation to transmit data across the barrier.

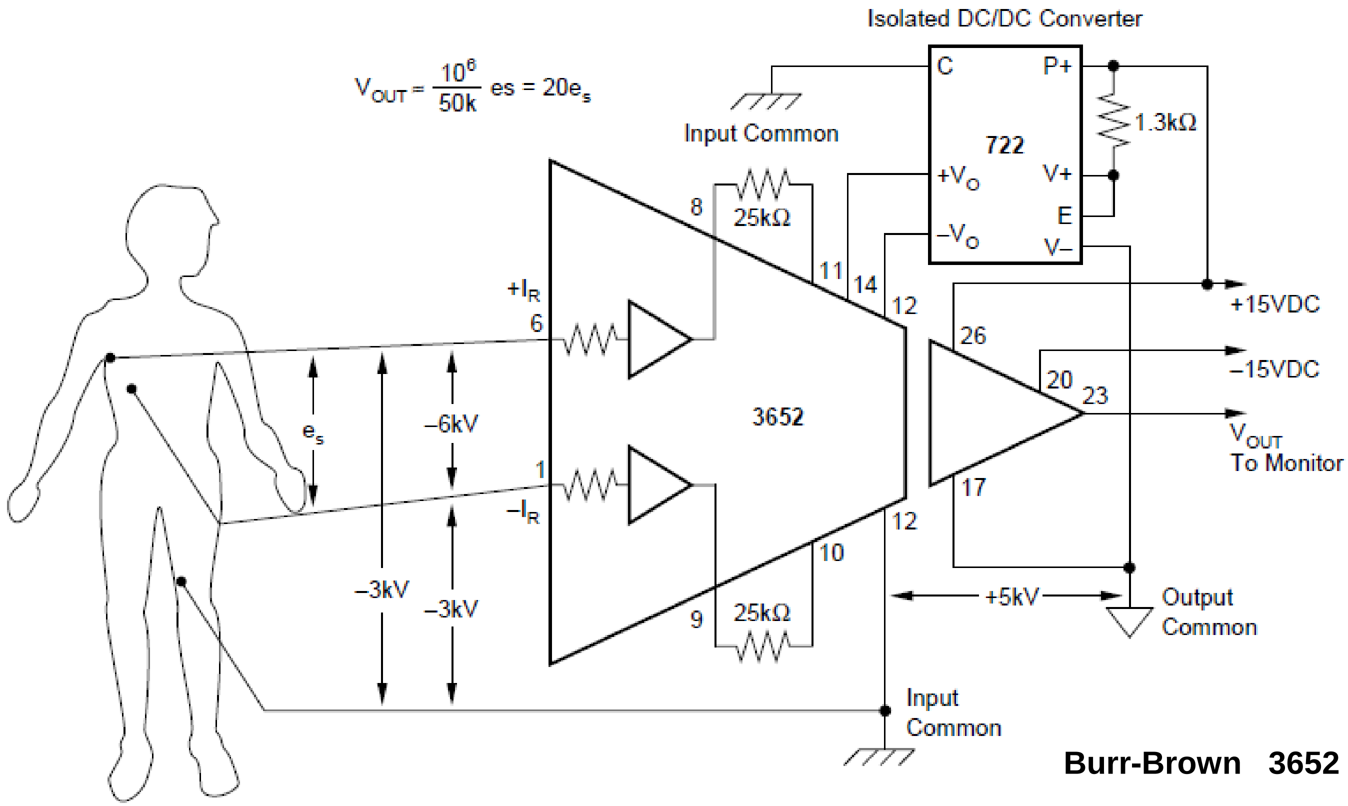
The 3656KG can have gain for **both the input and output** stages. The 3656KG is suited for patient monitoring applications, such as an **ECG** amplifier. The manufacture's data sheet shows detailed connection diagrams for various applications1.

http://focus.ti.com/lit/ds/symlink/3656.pdf



Isolation Amplifier

- Mandatory (اجباري) for use in medical equipment to isolate patients body connected electrodes from the equipment grounds



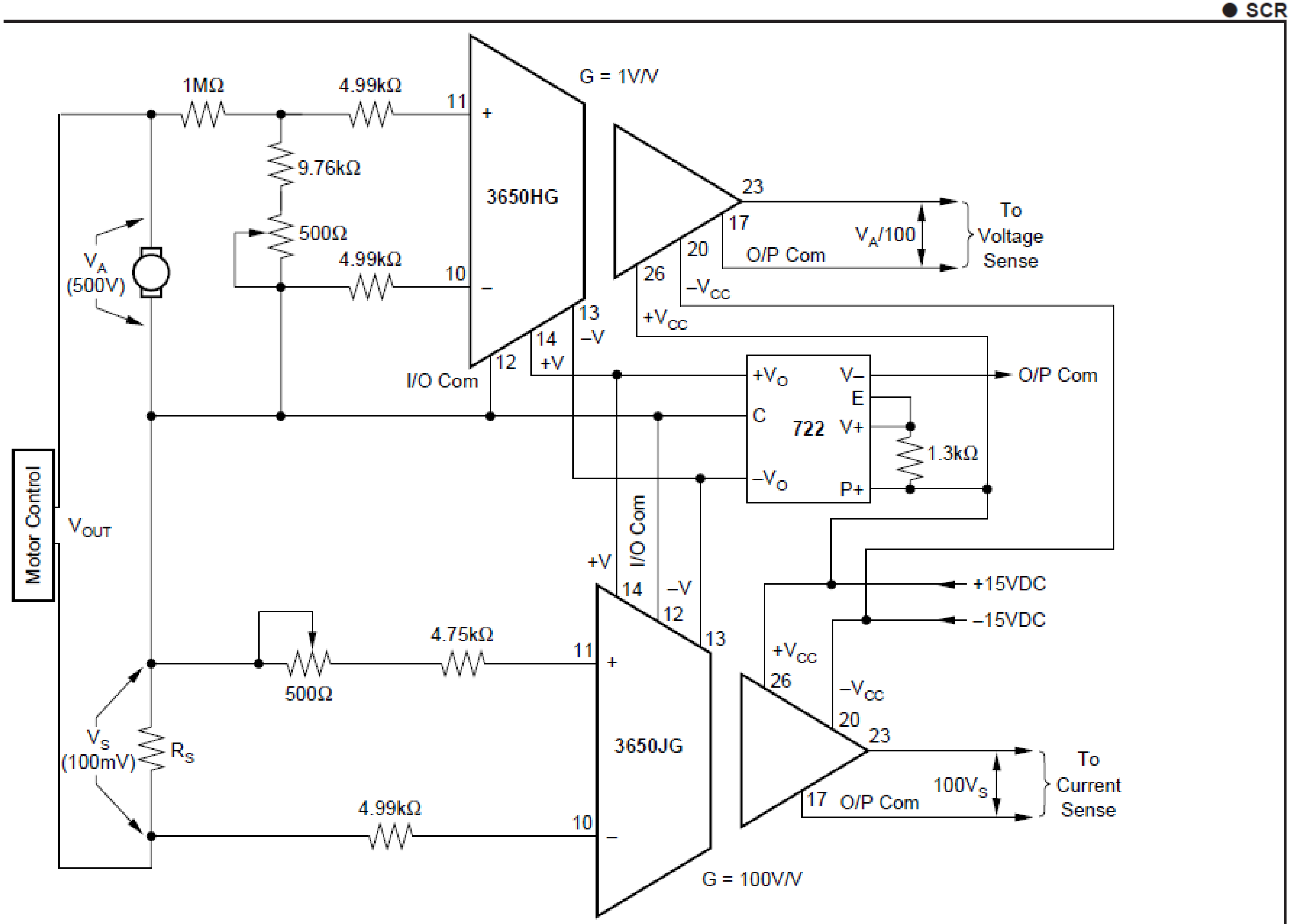
Burr-Brown 3652 amplifier

Isolation Amplifier

- Isolated current & voltage sensor

APPLICATIONS

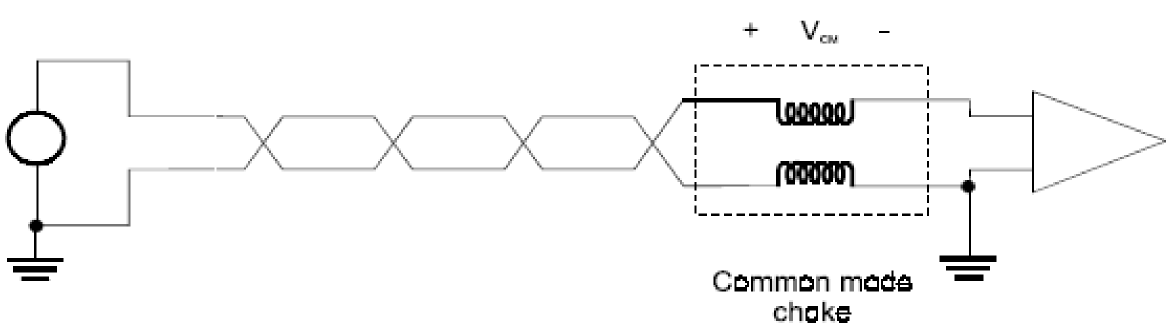
- INDUSTRIAL PROCESS CONTROL
- DATA ACQUISITION
- INTERFACE ELEMENT
- BIOMEDICAL MEASUREMENTS
- PATIENT MONITORING
- TEST EQUIPMENT
- CURRENT SHUNT MEASUREMENT
- GROUND-LOOP ELIMINATION
- SCR CONTROLS

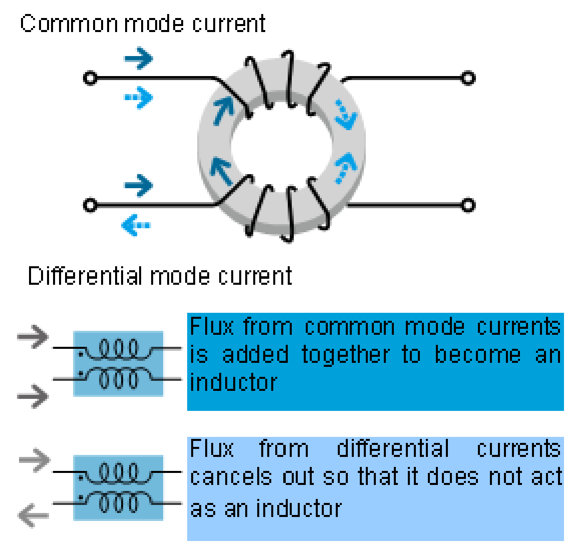


. Isolated Armature Current and Voltage Sensor.

Common Mode Choke

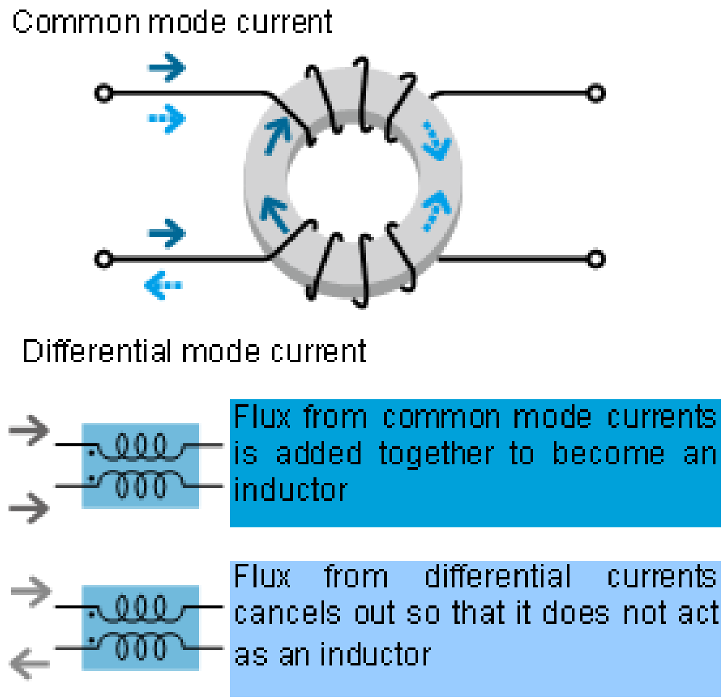
- When a transformer is connected as a common mode choke, as shown below
- DC and differential analog signals are transmitted while common mode AC signals are rejected.
- The common mode noise voltage appears across the windings of the choke.
- One big advantage with this type of isolation circuit is that multiple signal circuits can be wound on a common core without coupling.





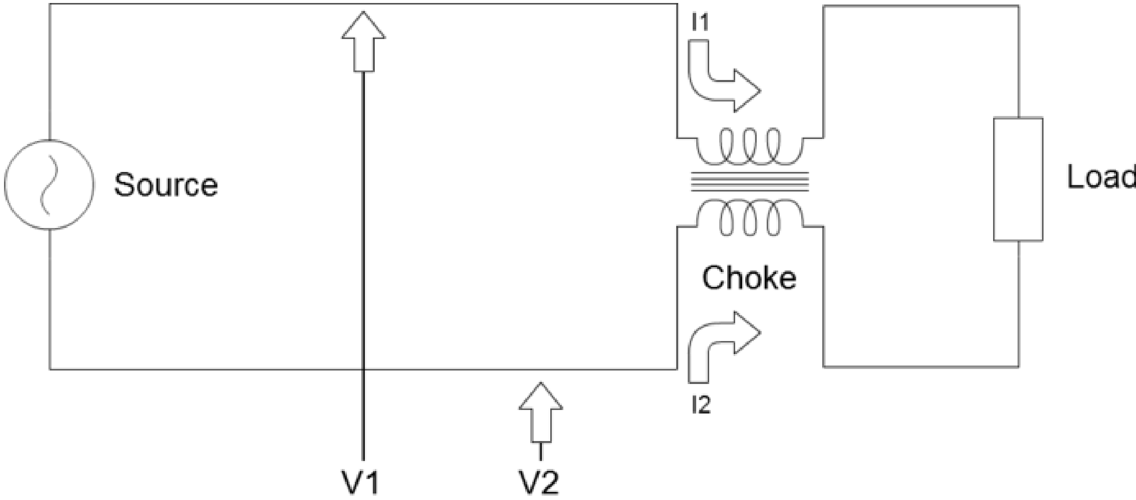
Common-mode choke

- Common-mode chokes, are useful for prevention of electromagnetic interference (EMI) and radio frequency interference (RFI) from power supply lines and for prevention of malfunctioning of electronic equipment.
- They pass differential currents (equal but opposite), while blocking common-mode currents.

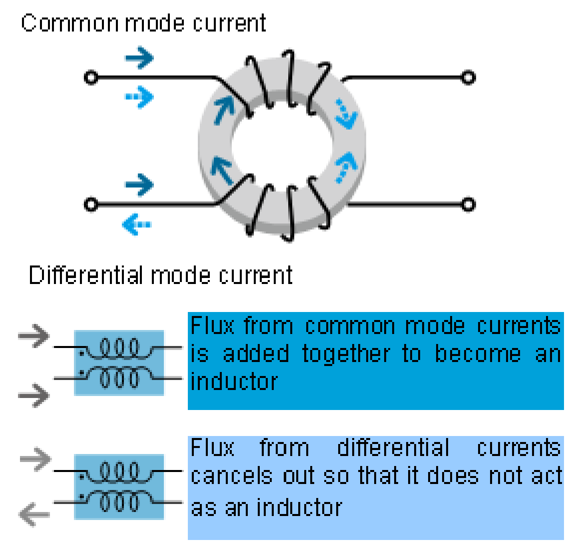


Common-mode choke

- A typical common-mode choke configuration. The common mode currents, I1 and I2, flowing in the same direction through each of the choke windings, creates equal and in-phase magnetic fields which add together. This results in the choke presenting a high impedance to the common mode signal



- Magnetic fields produced by differential-mode currents in the windings tend to cancel each other out; thus the choke presents little inductance or impedance to differential-mode currents.
- This also means the core will not saturate even for large differential-mode currents, and the maximum current rating is instead determined by the heating effect of the winding resistance.
- Common-mode currents, however, see a high impedance due to the combined inductance of the windings.

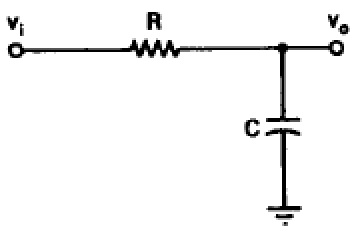


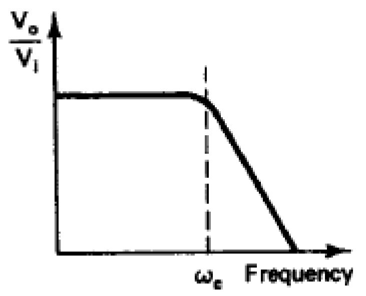
Filtering

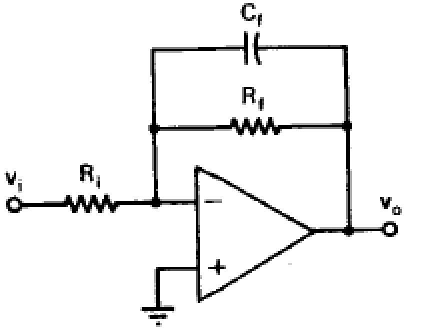
- Processing of signal to remove certain band of frequencies from it
- Filters can be classified as : low pass (LPF), high pass (HPF), band-pass (BPF) , band stop (BSF)
- Also filters can be classifiesd as:
  - passive (contain R,L, C)
  - Active (opamp , R,C)

Reminder

- 1st order LPF







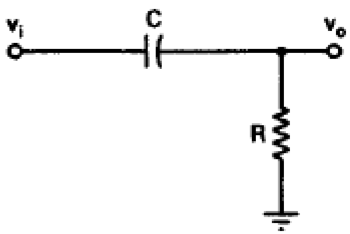
$$\tau = RC$$

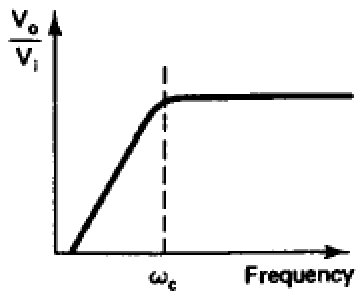
$$\omega_c = 1/\tau$$

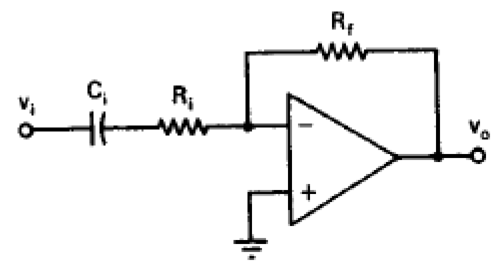
$$\frac{V_o}{V_i} = \frac{1}{1 + j\omega\tau}$$

$$\phi = \tan^{-1}(-\omega\tau)$$

- 1^{st} order HPF



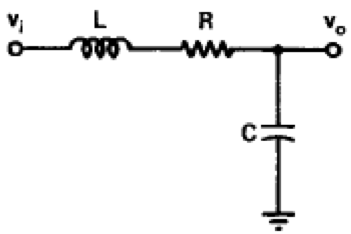




$$\frac{V_o}{V_i} = \frac{j\omega\tau}{1 + j\omega\tau}$$

$$\phi = \tan^{-1}(1/\omega\tau)$$

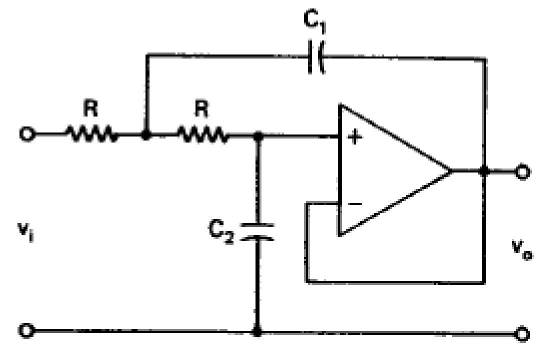
- 2^{nd} order LPF

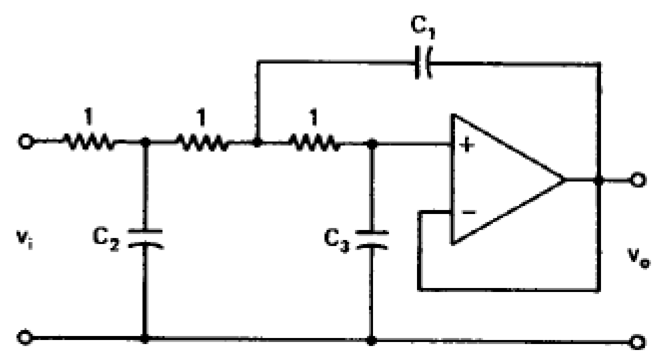


$$\frac{V_o}{V_i} = \frac{1}{(j\omega/\omega_c)^2 + (2\,\zeta\, j\omega/\omega_c) + 1}$$

$$\zeta = (R/2)(C/L)^{1/2}$$

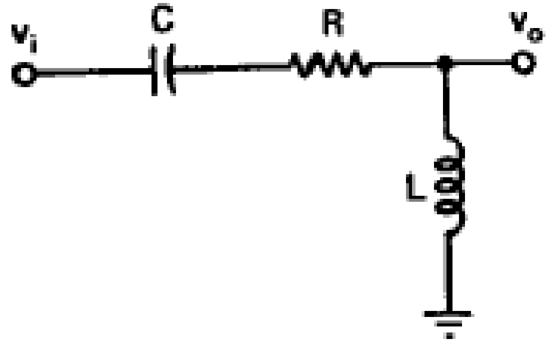
$$Q = 1/(2\zeta) = \omega_c/\Delta\omega,$$

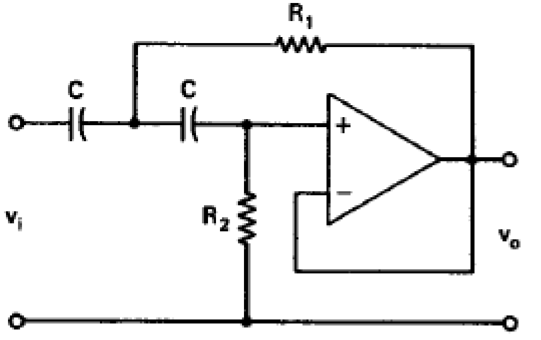




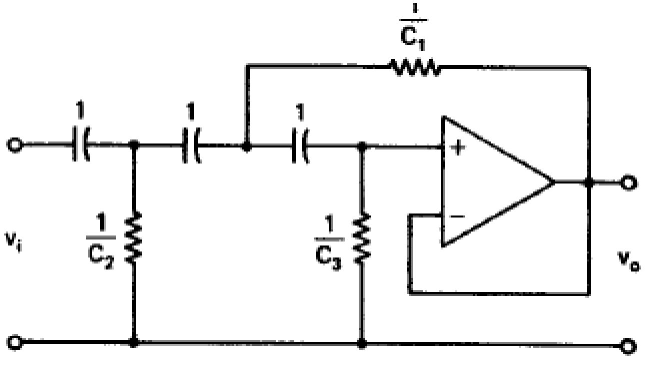
Normalized third order LPF filter

- 2^{nd} order HPF





Second order HPF filter



Normalized third order HPF filter

Op-amp Considerations for active filters (very important)

- In most cases we have assumed **an ideal op-amp**, now we consider some non-ideal characteristics:
- The Gain Bandwidth Product
- Input Offset Voltage
- Slew Rate

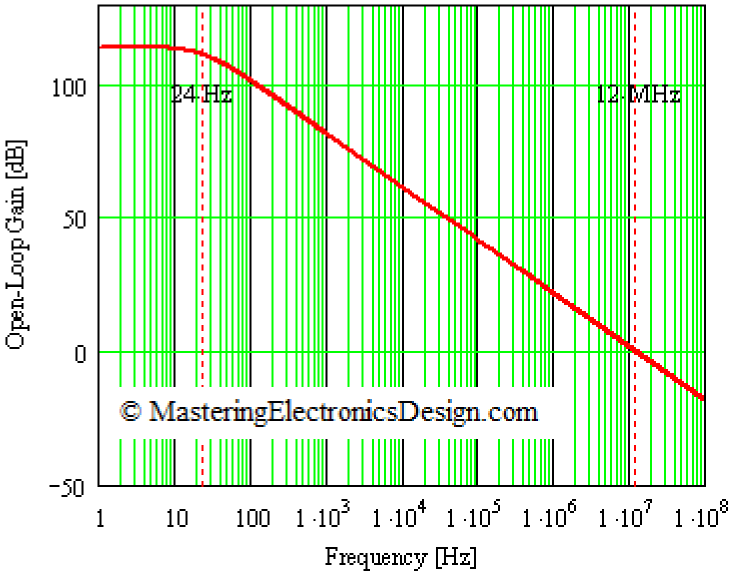
Op-amp Considerations

- The **Gain Bandwidth Product** describes the op amp gain behavior with frequency.
- Manufacturers insert a dominant pole in the op amp frequency response, so that the output voltage versus frequency is predictable.
- Why do they do that?
- Because the operational amplifier, which is grown on a silicon die, has many active components, each one with its own cutoff frequency and frequency response.
- Because of that, the operational amplifier frequency response would be random, with poles and zeros which would differ from op amp to op amp even in the same family.
- As a consequence, manufacturers thought of introducing a dominant pole in the schematic, so that the op amp response becomes more predictable.
- It is a way of “standardizing” the op amp frequency response. At

Gain Bandwidth Product (GBW)

- GBW product of an opamp is equal to the product of gain and bandwidth at a particular frequency.
- **The gain bandwidth product is constant** , thus for a non-inverting amplifier circuit, we obtain the bandwidth by dividing the GBW product by the amplifier circuit gain

$$\text{Bandwidth [Hz]} = \frac{\text{Gain Bandwidth Product [Hz]}}{\text{Closed Loop Gain}}$$

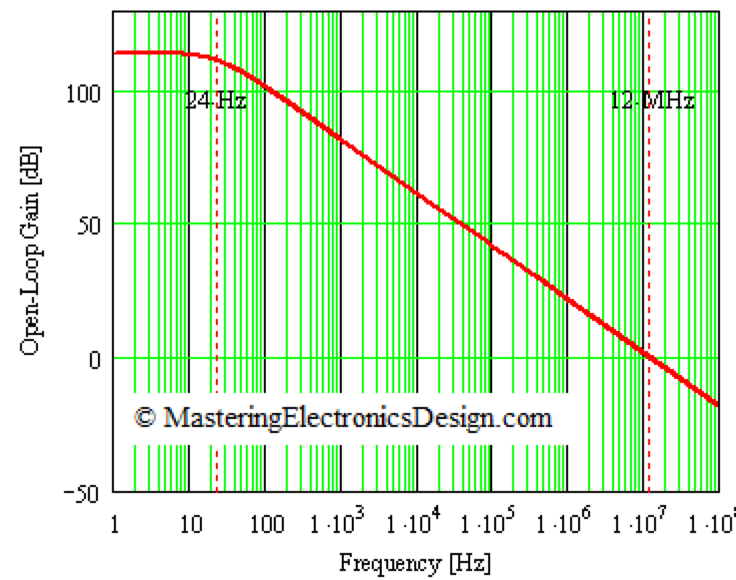


- The dominant pole will make the op amp behave like a single-pole system, which has a **drop of 20 dB** for every decade of frequency, starting with the cutoff frequency

Gain Bandwidth Product (GBW)

- In the case of ADA4004, the gain bandwidth product is 12 MHz.
- This means that, at a gain of one, the bandwidth is 12 MHz, and at the maximum open-loop gain of 500000 (114 dB), the bandwidth is 12 MHz divided by 500000, which is 24 Hz. This is the op amp open-loop cutoff frequency.

$$\text{Bandwidth [Hz]} = \frac{\text{Gain Bandwidth Product [Hz]}}{\text{Closed Loop Gain}}$$



Input Offset Voltage

- Ideal opamp has the property of zero output voltage when the input voltage is zero
- Practical opamps exhibit this feature; they have an input offset voltage.
- **The input offset voltage is the voltage that must be applied between the input terminals to get zero output**
- The offset voltage is not important when dealing with voltages above 1 V
- The offset voltage is nulled by introducing an opposing voltage at one of the opamp terminals according to data sheet of particular opamp.

Input Bias Current

- In practical opamps, the current flowing into the terminals is not zero
- In order to keep the input transistor of the opamp on, a base or gate current called input bias current is required all the time
- When this current flows through the feedback network it causes errors
- To minimize these errors, feedback resistors should be kept low such as below 10K
- **The effect of bias currents is reduced or eliminated by making the impedances seen by each input of the opamp almost equal**

Slew Rate

- **Slew Rate (SR) is the maximum rate of change of amplifier output voltage**
- When rapid changes are demanded in the output, the current available to charge and discharge the compensation cap is limited and slew rate limiting occurs, for example a 741 opamp has SR of 0.5V/uS
- Thus the output cannot change from -5V to +5V in less than 20 us

Slew Rate (SR)

Slew rate (SR) is the maximum rate at which an op-amp can change output without distortion.

$$SR = \frac{\Delta V_o}{\Delta t} \quad (\text{in } V/\mu s)$$

The SR rating is given in the specification sheets as V/μs rating.

Maximum Signal Frequency

The slew rate determines the highest frequency of the op-amp without distortion. assume input and output are sinusoidal

$V_o = V_{op} \sin\omega t$

$$f \leq \frac{SR}{2\pi V_p}$$

where V_{op} is the peak output voltage

Power Supply

Power Supply

The usual supply voltages are ±15 V. When v_o is allowed to exceed the op-amp biasing voltages the op amp will saturate and is said to be out of the amplifier's linear range (typically ±13 V). We may reduce the power-supply voltage, but this also reduces the linear range. When the power supply goes below approximately 4 V the internal biasing voltages of the device are not satisfied.

It would be convenient always to have dual-polarity power supplies available in equipment or circuits using op amps. Unfortunately, this is not possible. There are, however, certain circuitry tactics for using the operational amplifier in single-polarity configurations. One solution is to ground the minus supply terminal, while the positive is connected to V_{cc} in the usual way. Figure 1.17 shows this circuit. The noninverting input is connected to a junction on a voltage-divider network. This effectively raises the operating point above ground.

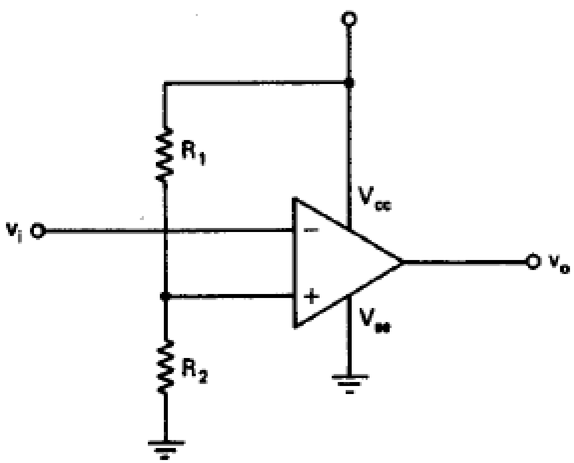


Figure 1.17 Single power-supply circuit.

Different Op Amps

Op amps are bipolar or FET types. The bipolar op amps have a pair of bipolar input transistors. They have good input offset voltage stability but moderate input bias currents and input resistances. FET-input op amps with a pair of input FETs offer very low input bias currents and very high input resistances but have poor input offset voltage stability (Dostal, 1981).

Programmable Op Amps

A programmable op amp such as the UC4250 permits setting the power consumption and dynamic properties of the op amp. By adding the proper external resistor, we can adjust the quiescent supply current [the operating current flowing in a circuit during zero-signal (idle) intervals]. Lower quiescent currents yield lower frequency responses and lower output current capabilities (Dostal, 1981).

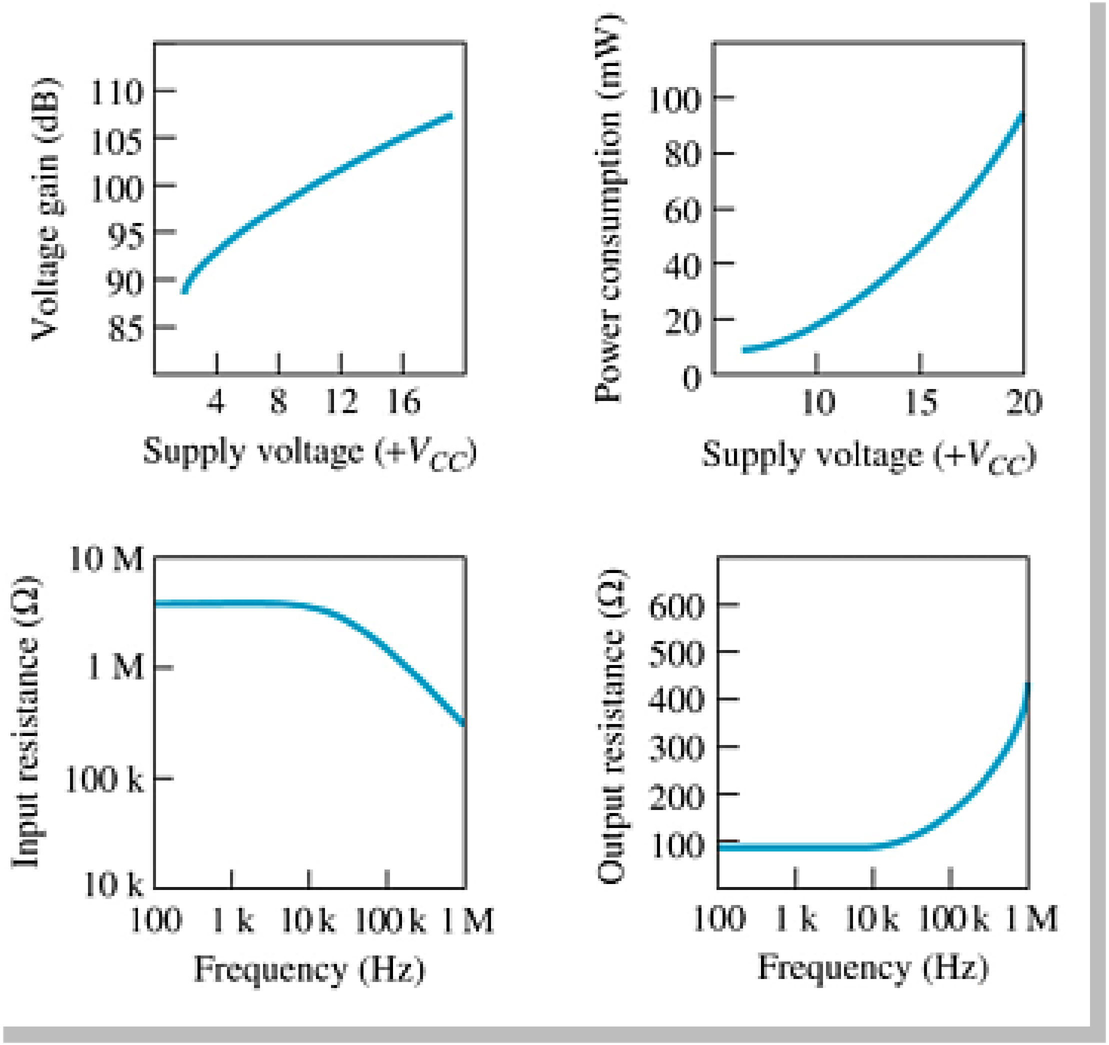
Common opamps

Type	Feature	Input bias current	Offset voltage	GBW	Price
741	Low cost	80 nA	2 mV	1 MHz	$0.35
308	Low bias current	3 nA	2 mV	1 MHz	0.69
ICL8007	FET input	50 pA	50 mV	1 MHz	5.00
CA3130	FET input	6 pA	20 mV	4 MHz	0.89
OP-07	Low offset	1 nA	30 μV	800 kHz	1.99
LH0052	Low offset	0.5 pA	0.1 μV	1 MHz	5.00
LF351	High GBW	50 pA	5 mV	4 MHz	0.62
LM312	Low bias current	3 nA	0.7 mV	1 MHz	2.49
UC4250	Programmable	7.5 nA	4 mV	800 kHz	1.84

	Iomax	funity	slew rate (V/uS)
	mA	MHz	(V/uS)
LF353	20	4	13
LF356	20	5	12
LM318	21	15	70
LM739	1.5	6	1
NE531	20	1	35
TL072	10	3	13
LM741	25	1	0.5
TL074	17	4	13

Op-Amp Performance

The specification sheets will also include graphs that indicate the performance of the op-amp over a wide range of conditions.

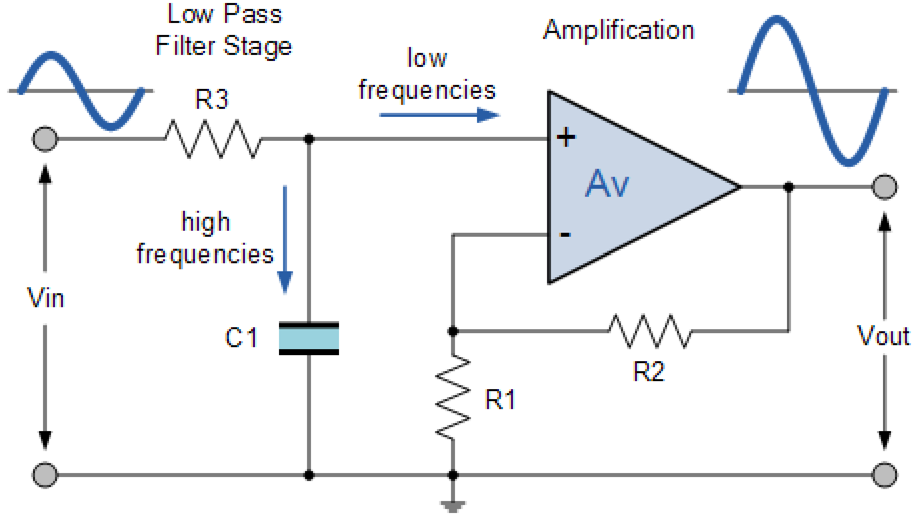


Example

- Design a 1st order LPF for the audio frequency (< 20 kHz) and a dc gain =11 using a LM741C opamp with GBW=1Mhz, SR=0.5 V/us , input impedance 3 Mohm
- What is peak value of output the voltage that can be obtained considering the SR? assume input is sinusoidal.

Example solution

- Dc gain k= 1+R2/R1=11 ==> R2/R1=10
- Choose R1=5kΩ, ==> R2=50 kΩ
- For balance of resistance at both opamp terminals choose R3=R1//R2
- R3=5k//50k=4.55kΩ
- fc=20 kHz=1/(2πR3C1)
- ==> C1=1.75 nF



- Now assuming Vo=Vp sinωt
- And we can find the ΔV/Δt= ωVp cosωt or slow rate as the max value of ΔV/Δt which is equal to : SR= ωVp =2πf Vp
- and the max allowable values of Vi and Vo are

$$V_{op} \le \frac{SR}{2\pi f}$$

$$V_{op} \le \frac{0.5\, V/\mu sec}{2\pi(20000)Hz} = 3.98\, V$$

$$Vi(peak) \le \frac{3.98}{11} = 0.362\, V$$

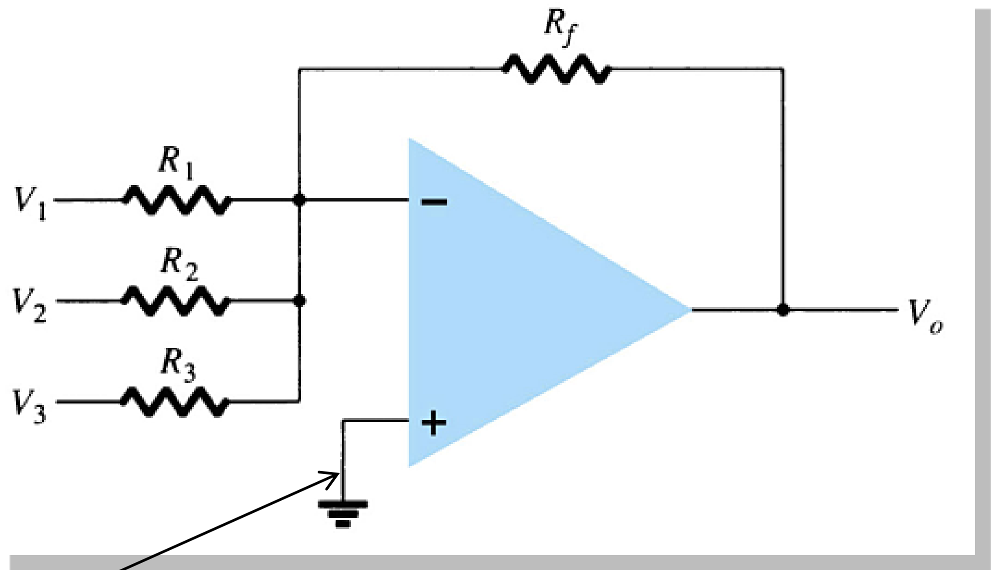
Amplification & other Functions

- Non Inverting amplifier
- Inverting amplifier
- Difference amplifier
- Instrumentation amplifier
- Integrator
- Differentiator
- Log amplifier
- Anti-log amplifier
- Trans-conductance Amplifier
- Rectifiers

Voltage Summing

The output is the sum of individual signals times the gain:

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$



Add resistance of equal

=R1//R2//R3//Rf

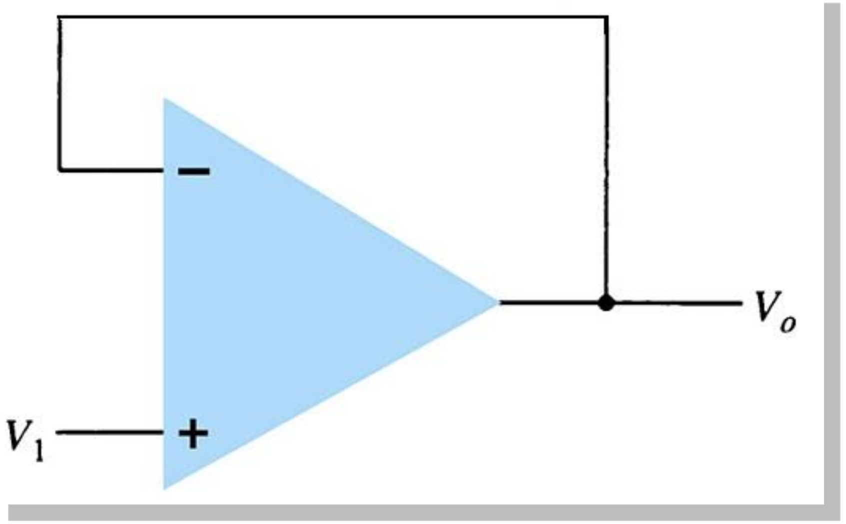
[Formula 14.3]

Voltage Buffer

Any amplifier with no gain or loss is called a **unity gain amplifier**.
The advantages of using a unity gain amplifier:

- Very high input impedance
- Very low output impedance

Realistically these circuits are designed using equal resistors ($R_1 = R_f$) to avoid problems with offset voltages.



Difference Amplifier

$$V_{out} = aV_1 - bV_2$$

$$a = \left(1 + \frac{R_4}{R_2}\right) * \frac{R_3}{R_3 + R_1} = \left(\frac{R_2 + R_4}{R_2}\right) * \frac{R_3}{R_3 + R_1}$$

$$b = \frac{R_4}{R_2}$$

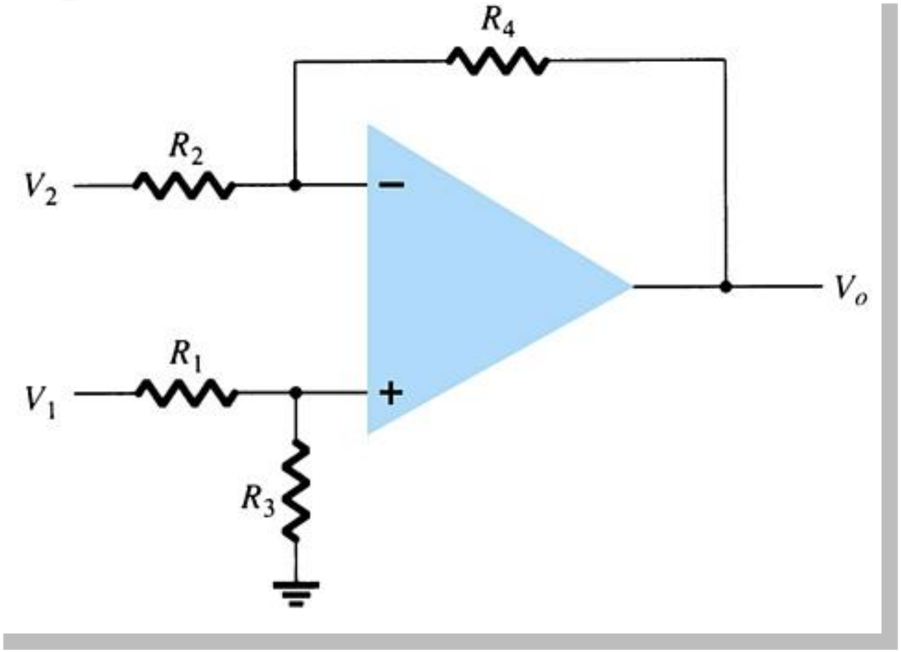
$$for$$

$$R4 = R3 = mR$$

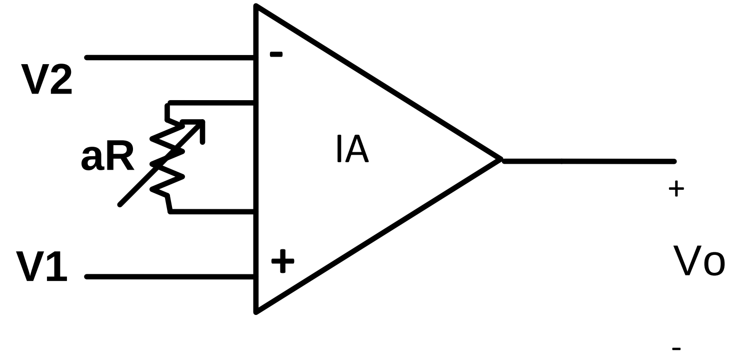
$$R1 = R2 = R$$

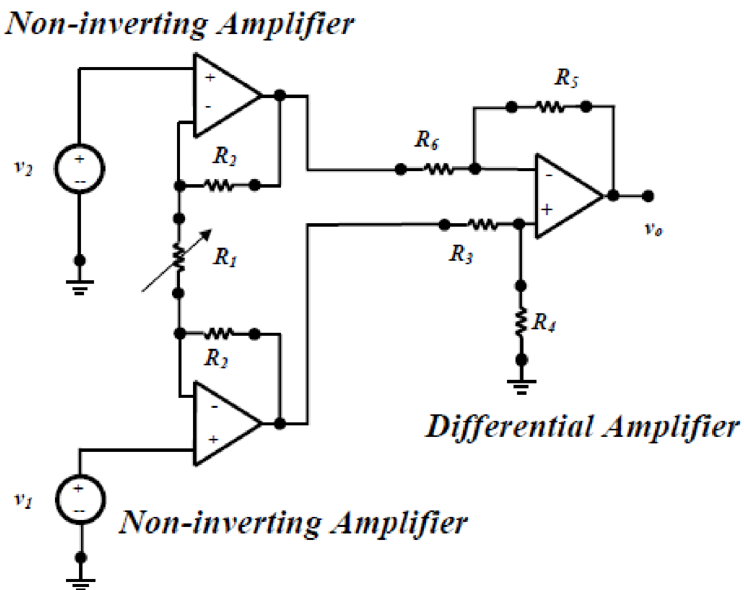
$$\& \, a = b = m$$

$$V_{out} = m(V_1 - V_2)$$

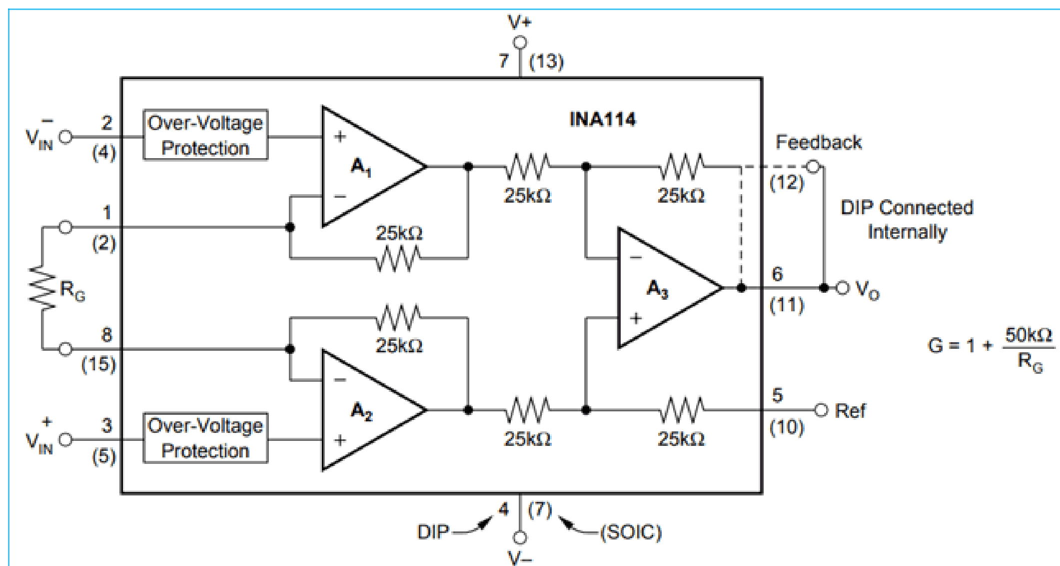


IA





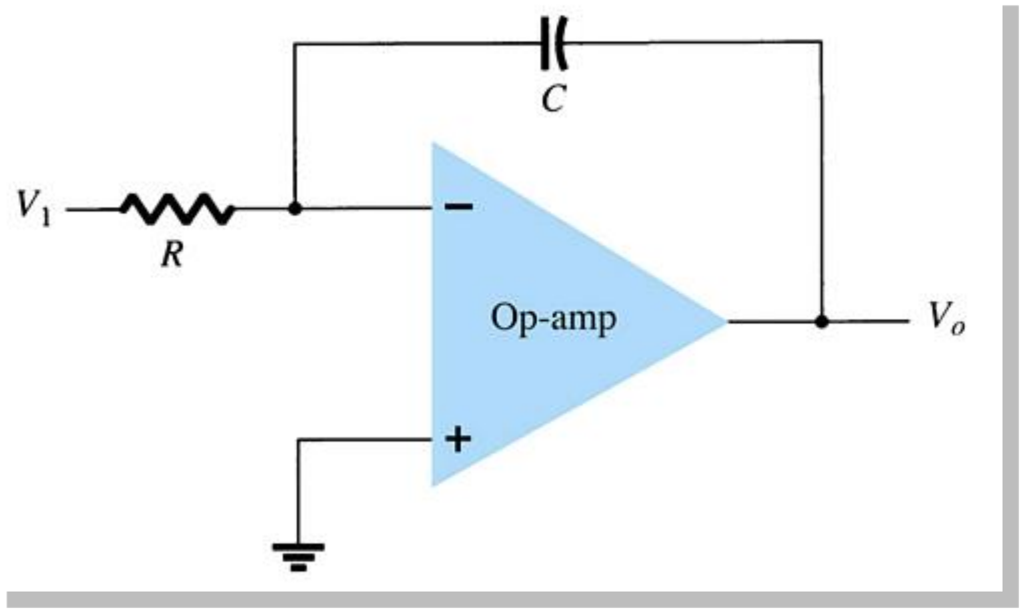
$$= \left(1+\frac{2}{a}\right)(V_1 - V_2)$$



Integrator

The output is the integral of the input. Integration is the operation of summing the area under a waveform or curve over a period of time. This circuit is useful in low-pass filter circuits and sensor conditioning circuits.

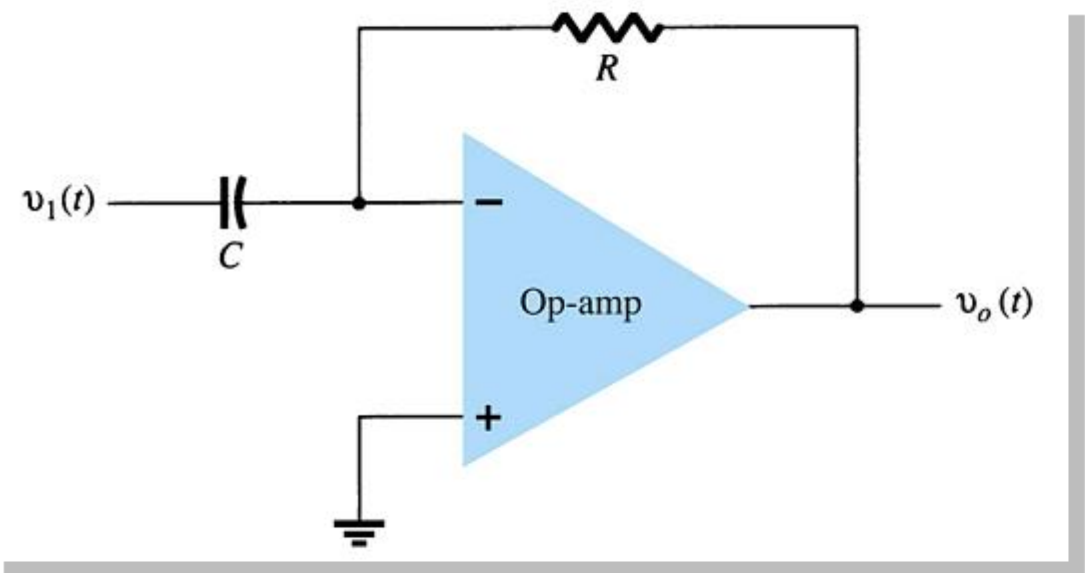
$$v_o(t) = -\frac{1}{RC}\int v_1(t)dt$$



Differentiator

The differentiator takes the derivative of the input. This circuit is useful in high-pass filter circuits.

$$v_o(t) = -RC\frac{dv_1(t)}{dt}$$

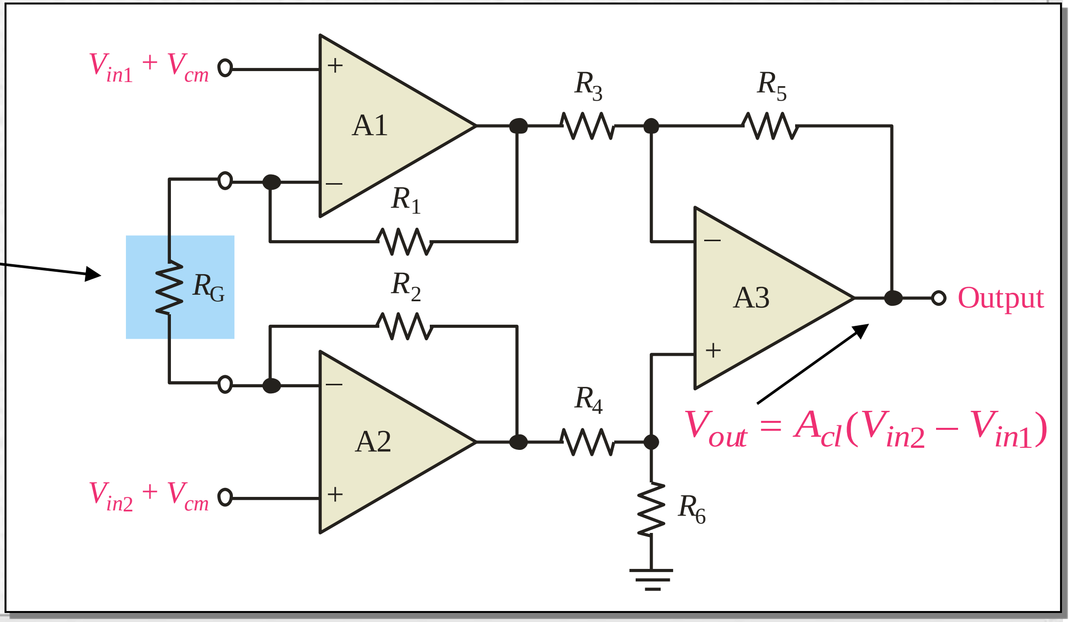


Practical Example of an Instrumentation Amplifiers

An **instrumentation amplifier** (IA) amplifies the voltage difference between its terminals. It is optimized for small differential signals that may be riding on a large common mode voltages.

The gain is set by a single resistor that is supplied by the user.

The output voltage is the closed loop gain set by R_G multiplied by the voltage difference in the inputs.



Signal Conditioning

Instrumentation Amplifiers

An IA that is based on the three op-amp design is the AD622. The formula for choosing R_G is:

$$R_G = \frac{50.5\ \text{k}\Omega}{A_v - 1}$$

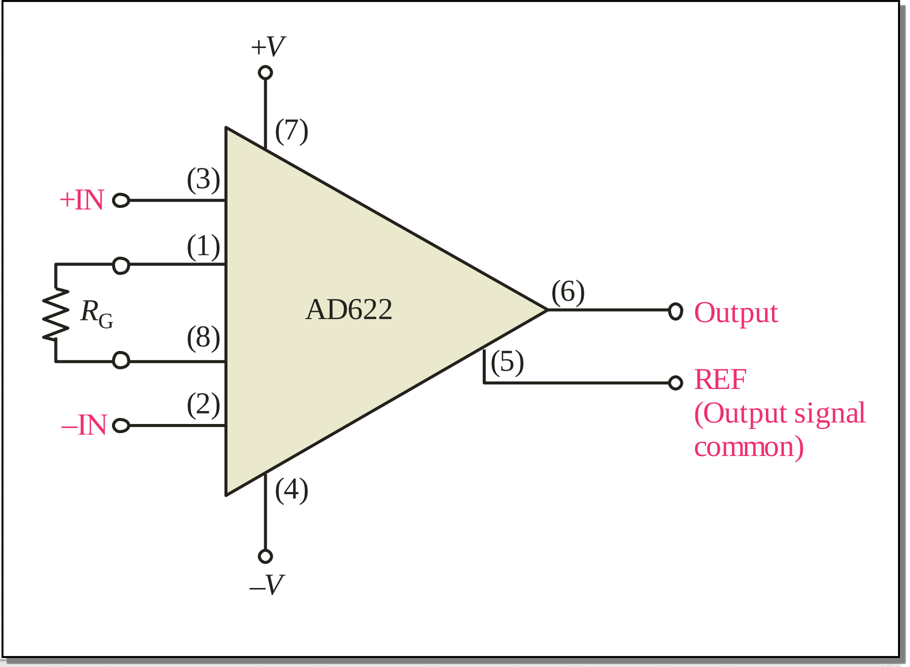
Example:

What value of R_G will set the gain to 35?

Solution:

$$R_G = \frac{50.5\ \text{k}\Omega}{A_v - 1} = \frac{50.5\ \text{k}\Omega}{35 - 1}$$

$= 1.5\ \text{k}\Omega$



Instrumentation Amplifiers

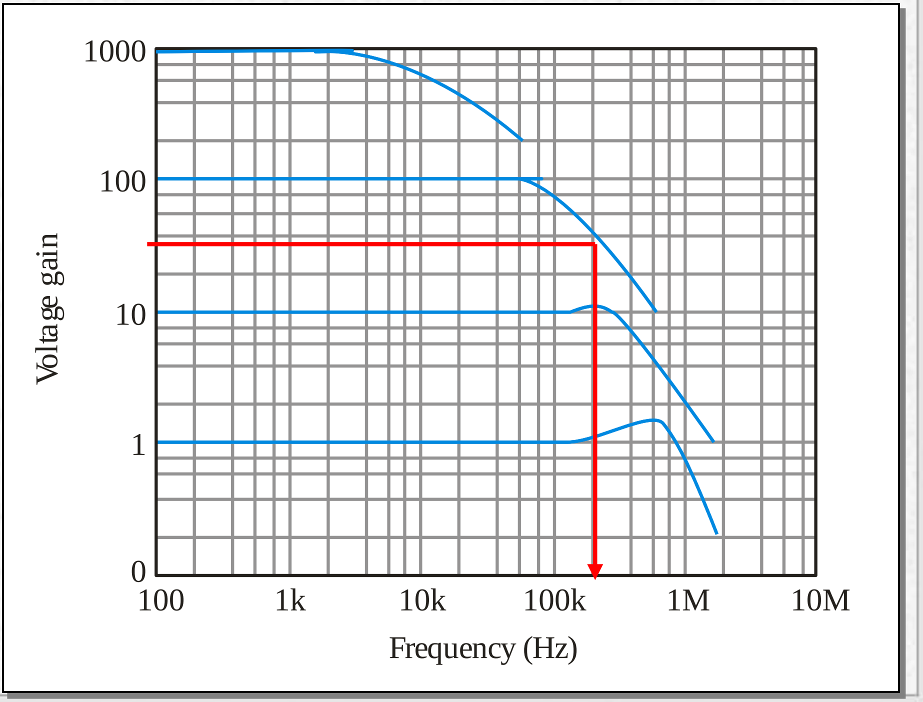
The bandwidth of any IA (or op-amp for that matter) is lower for higher gain. The graph shows the BW for various gains for the AD622.

Question:

What is the BW for a gain of 35?

Answer:

Reading the graph, the BW is approximately 200 kHz.



Summary

The Operational Transconductance Amplifier

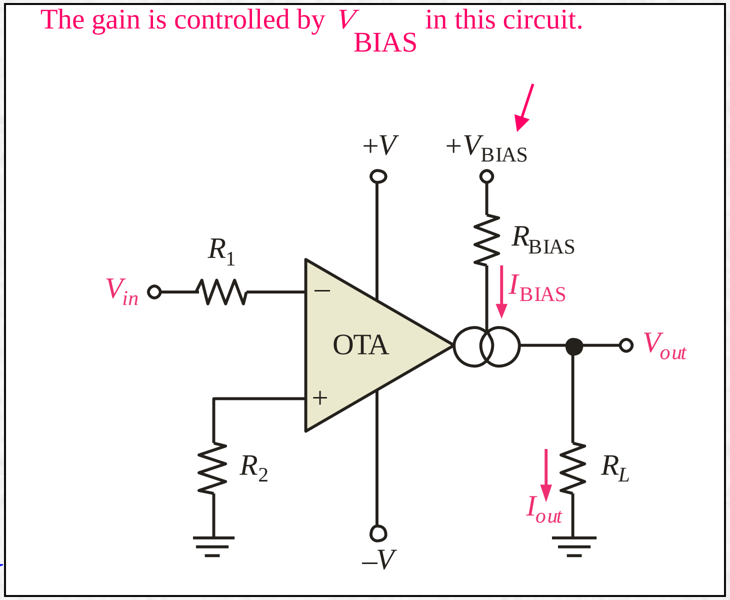
The **operational transconductance amplifier** (OTA) is a voltage-to-current amplifier. As in the case of FETs, the conductance is output current divided by input voltage. Thus,

$$g_m = \frac{I_{out}}{V_{in}}$$

Like FETs, the gain of an amplifier is written in terms of g_m:

$$A_v = g_m R_L$$

Unlike FETs, the OTA has a g_m that can be "programmed" by the amount of bias current.



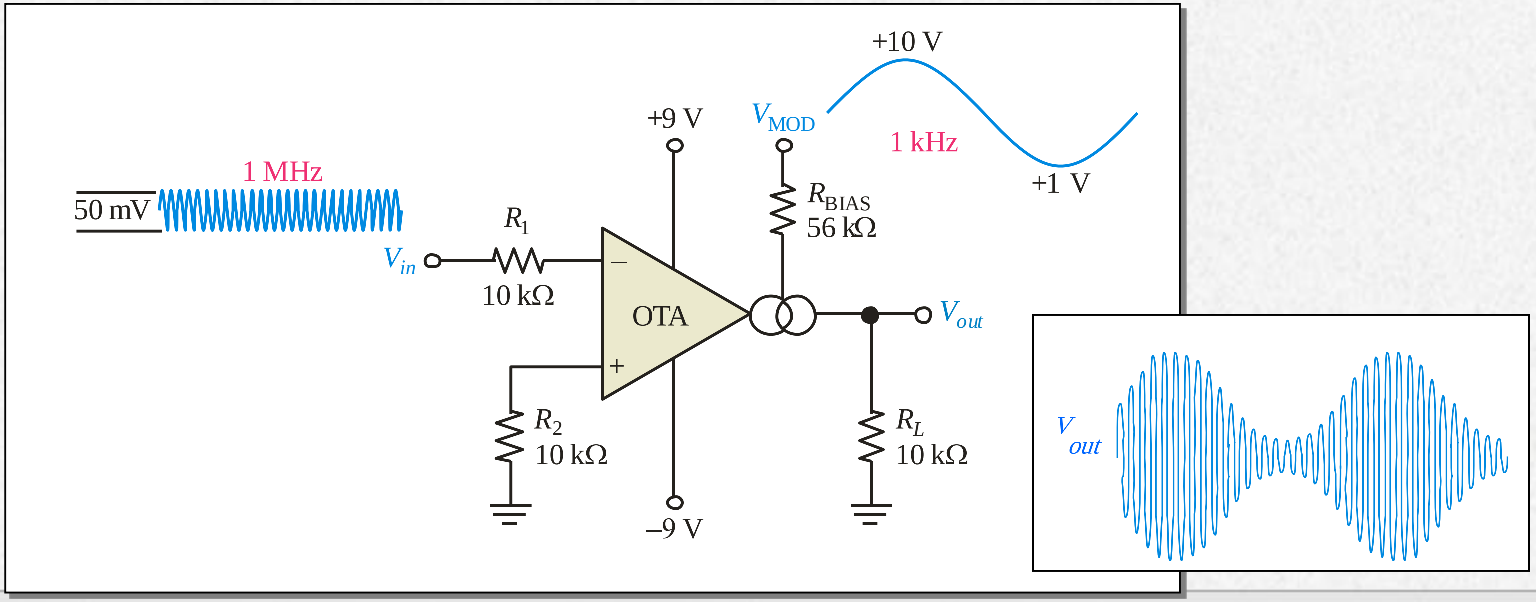
Thus gain can be changed electronically by varying a dc voltage.

Summary

The Operational Transconductance Amplifier

The OTA adds a measure of control to circuits commonly implemented with conventional op-amps. Applications for OTAs include voltage controlled low-pass or high-pass filters, voltage controlled waveform generators and amplifiers, modulators, comparators, and Schmitt triggers.

In this example, an amplitude modulator is shown.

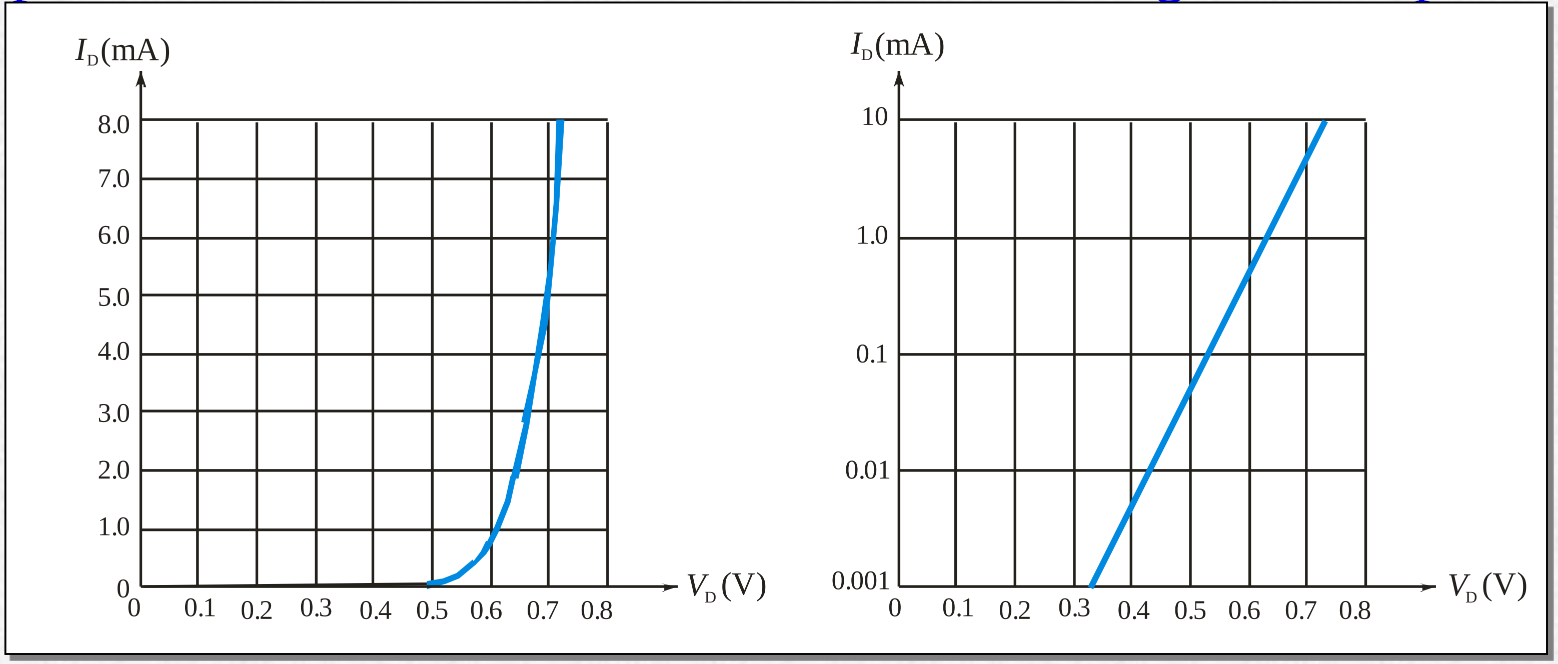


Summary

The Logarithmic Amplifier

A diode has the characteristic in which voltage across the diode is proportional to the log of the current in the diode.

Compare data for an actual diode on linear and logarithmic plots:

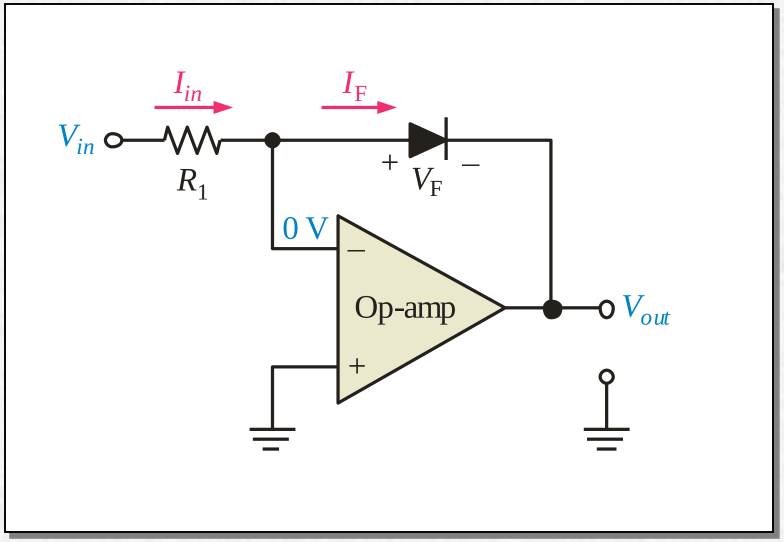


Summary

The Logarithmic Amplifier

When a diode is placed in the feedback path of an inverting op-amp, the output voltage is proportional to the log of the input voltage. The gain decreases with increasing input voltage; therefore the amplifier is said to compress signals.

Many sensors, particularly photo-sensors, have a very large dynamic range outputs.



Current from photodiodes can range over 5 decades. A log amp will amplify the small current more than the larger current to effectively compress the data for further processing.

Summary

The Logarithmic Amplifier

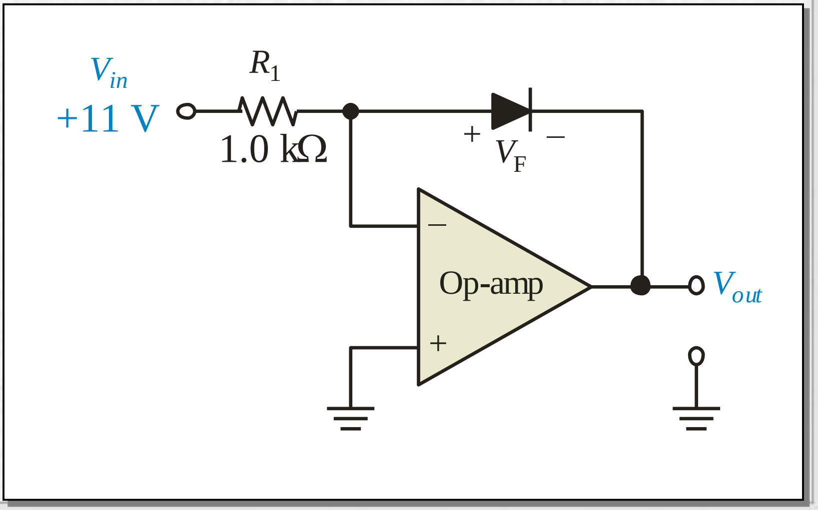
For the circuit shown, the equation for V_{out} is

$$V_{out} \cong -(0.025\text{ V})\ln\frac{V_{in}}{I_R R_1}$$

(I_R is a constant for a given diode.)

Example:

What is V_{out}? (Assume I_R = 50 nA.)



Solution:

$$V_{out} \cong -(0.025\text{ V})\ln\frac{11\text{ V}}{(50\text{ nA})(1.0\text{ k}\Omega)}$$

= –307 mV

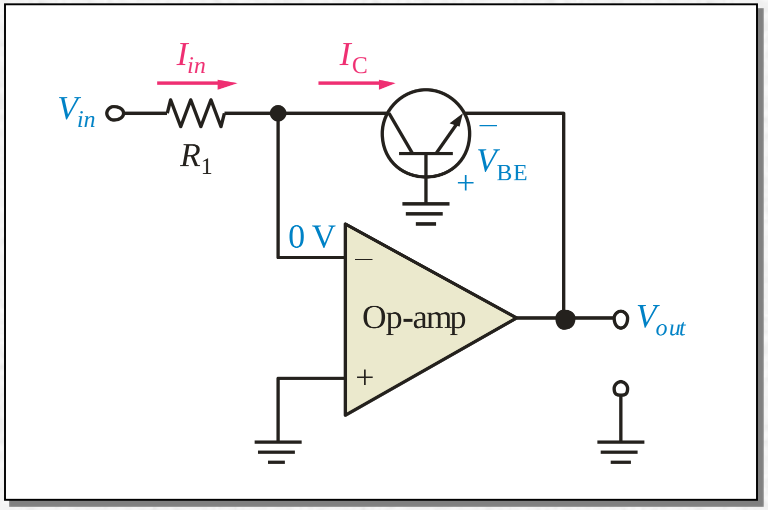
The Logarithmic Amplifier

When a BJT is used in the feedback path, the output is referred to the ground of the base connection rather than the virtual ground. This eliminates offset and bias current errors. For the BJT, I_{EBO} replaces I_R in the equation for V_{out}:

$$V_{out} = -(0.025\text{ V})\ln\frac{V_{in}}{I_{EBO}R_1}$$

Log amplifiers are available in IC form with even better performance than the basic log amps shown here.

For example, the MAX4206 operates over 5 decades and can measure current from 10 nA to 1 mA.



Summary

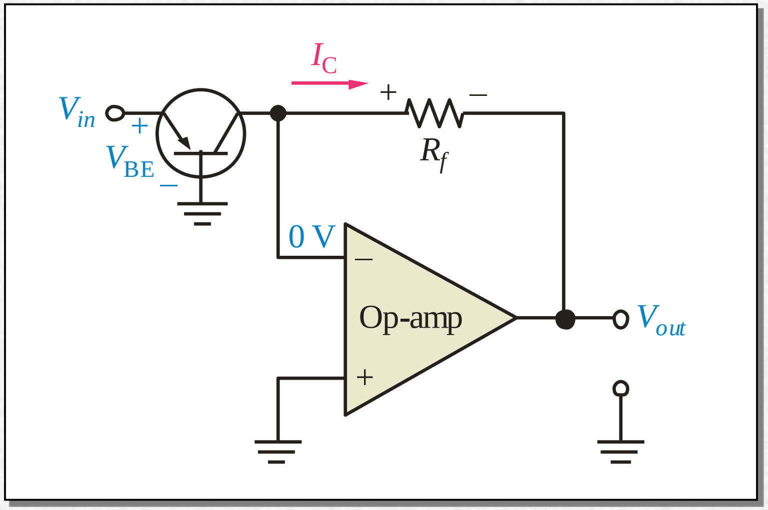
The Antilog Amplifier

An antilog amplifier produces an output proportional to the input raised to a power. In effect, it is the reverse of the log amp. The equation for V_{out} for the basic BJT antilog amp is:

$$V_{out} = -R_f I_{EBO} \text{antilog} \frac{V_{in}}{25 \text{ mV}}$$

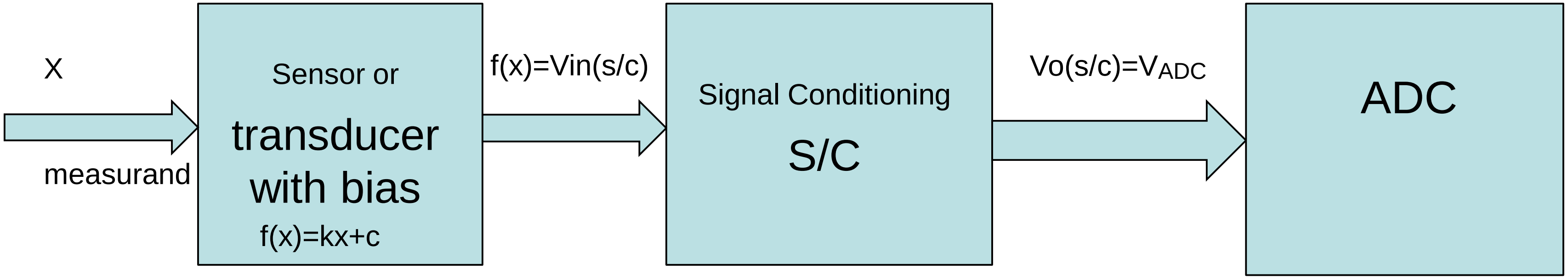
IC antilog amps are also available. For example, the Datel LA-8048 is a log amp and the Datel LA-8049 is its counterpart antilog amp.

These ICs are specified for a six decade range.



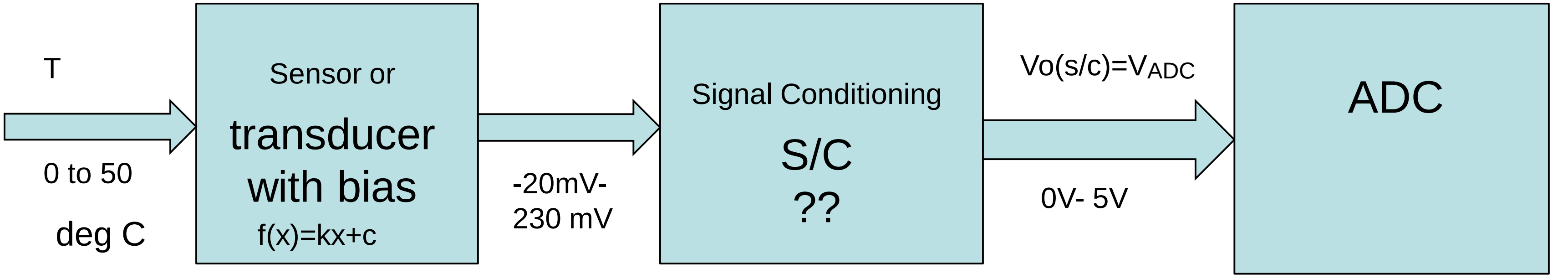
Bias Removal

- The signal conditioning block have two functions in this case:



- First is to remove the bias
- Second is to make the output range of s/c block match or equal the input range of the ADC block for best system resolution

Linearization (Bias Removal)



- Example : a sensor output changes from -20mV to +230mV as the temperature changes from 0 to 50 deg C
- Design and implement a s/c circuit such that its output matches the input range of the ADC 0-5V

x =T [C]	f(x)=Vin(sc)	Vo(sc)
0	-20mV	0
50	230mV	5

- Assuming that the sensor output is linearly dependant on the input
- Vo(sc) = a Vi(sc)+ b
- 0 = a (-20mV)+b ➔ b=0.02 a (1)
- 5V= a (230 mV)+ b (2)
- Substitute (1) in (2) and pay attention to units yields
- 5000mV =250mV x a ➔ a=20; b =0.4
- Vo(sc) =20 Vi(sc)+0.4

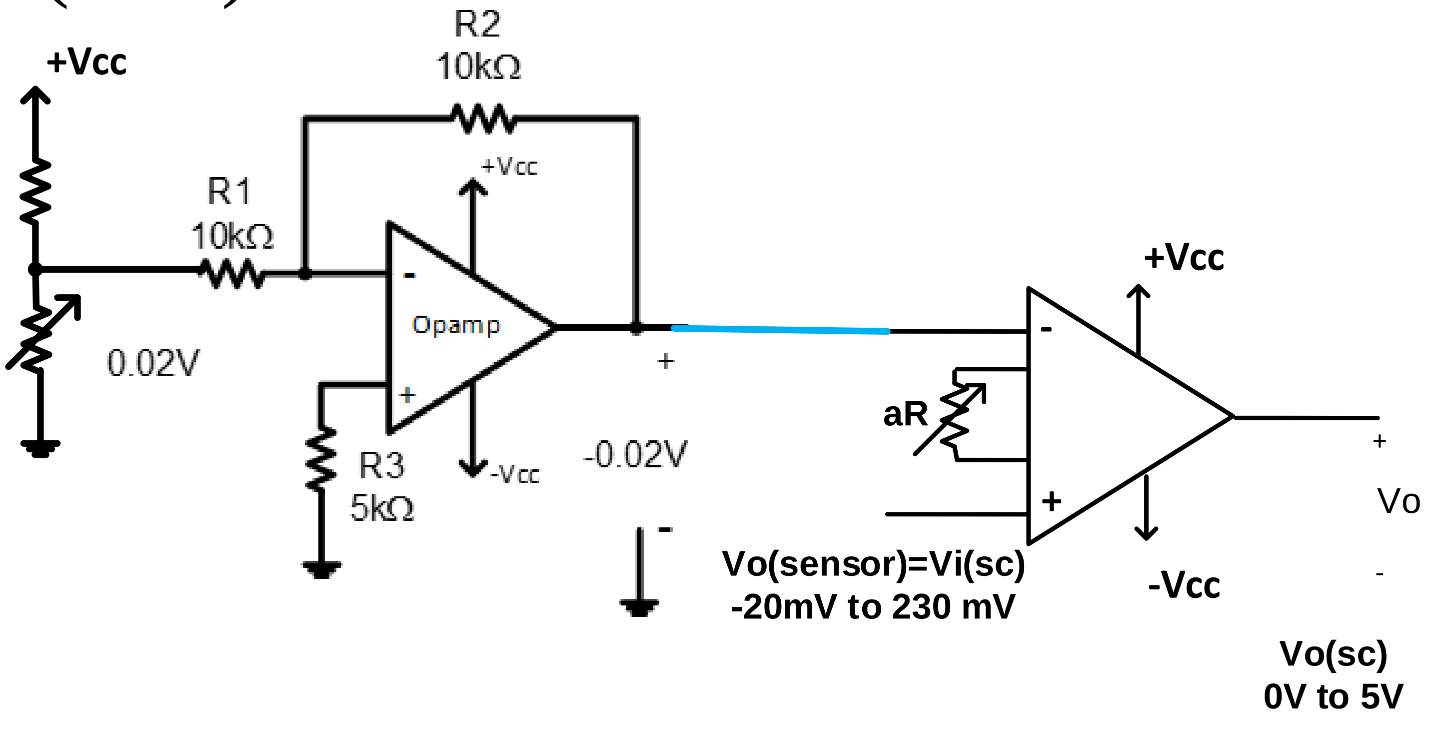
- Vo(sc) =20 Vi(sc)+0.4
- =20(Vi(sc)-(-0.02))

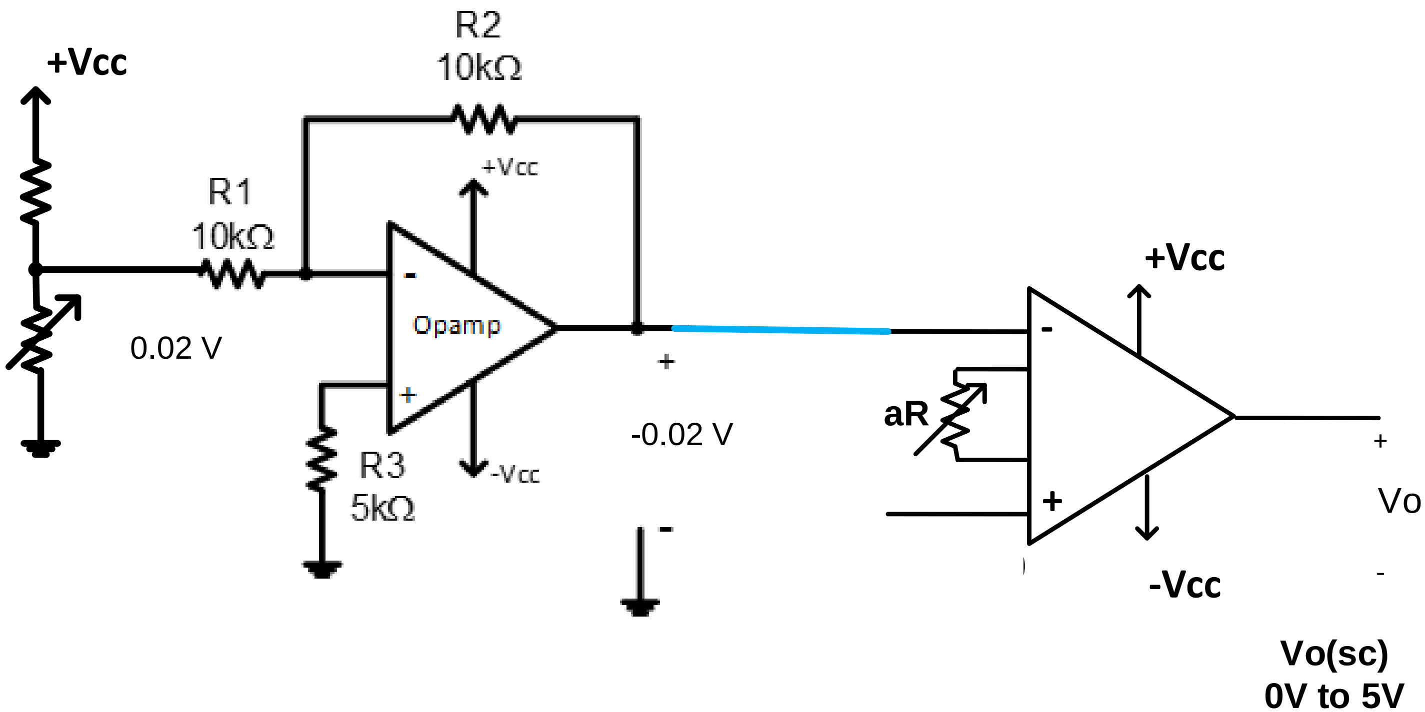
- The above function can be implemented in different ways such as instrumentation amplifier, difference amplifier and others

Implementation using IA

- 1+2/a=20 ==> a=2/19
- Assume Internal resistance of IA=20kΩ

then aR=(2/19)*20 kΩ = 2.105 kΩ

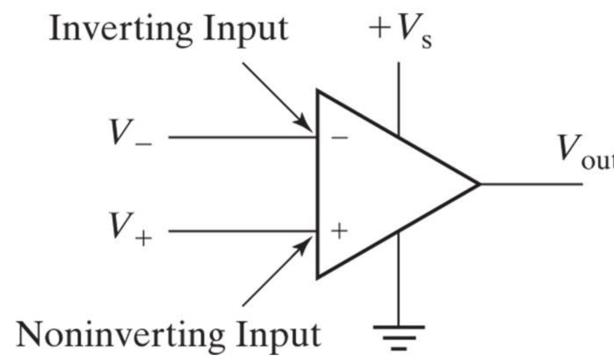




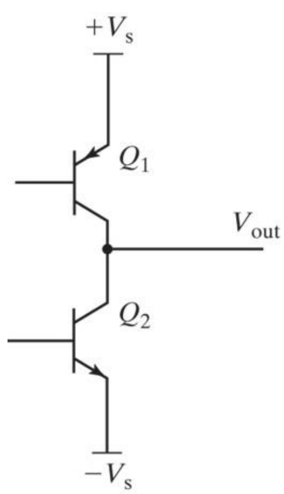
+Vcc
R2
10kΩ
+Vcc
R1
10kΩ
Opamp
0.02 V
+
R3
5kΩ
-Vcc
-0.02 V
+Vcc
aR
+
+
Vo
-Vcc
-
Vo(sc)
0V to 5V

The Comparator

- A specially designed op-amp, optimized to switch V_{out} ***fast***
  - If V+ > V-, then $V_{out} \approx$ Vs
  - If V- > V+, then $V_{out} \approx$ 0 V
- But usually output is '*open collector*'
  - Can pull *low*, but…
  - Needs external resistor (pull-up) to go high

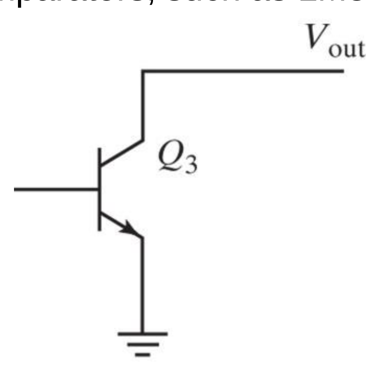


Typical op-amp output stage and *some* comparators (Push-Pull (Totem Pole))

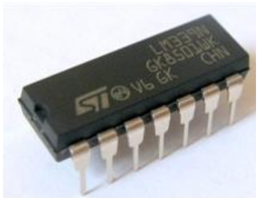


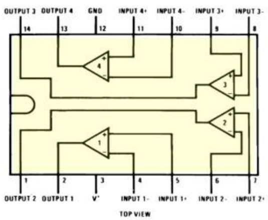
(a)

<u>Open collector</u> output stage (typical of most comparators, such as LM339)



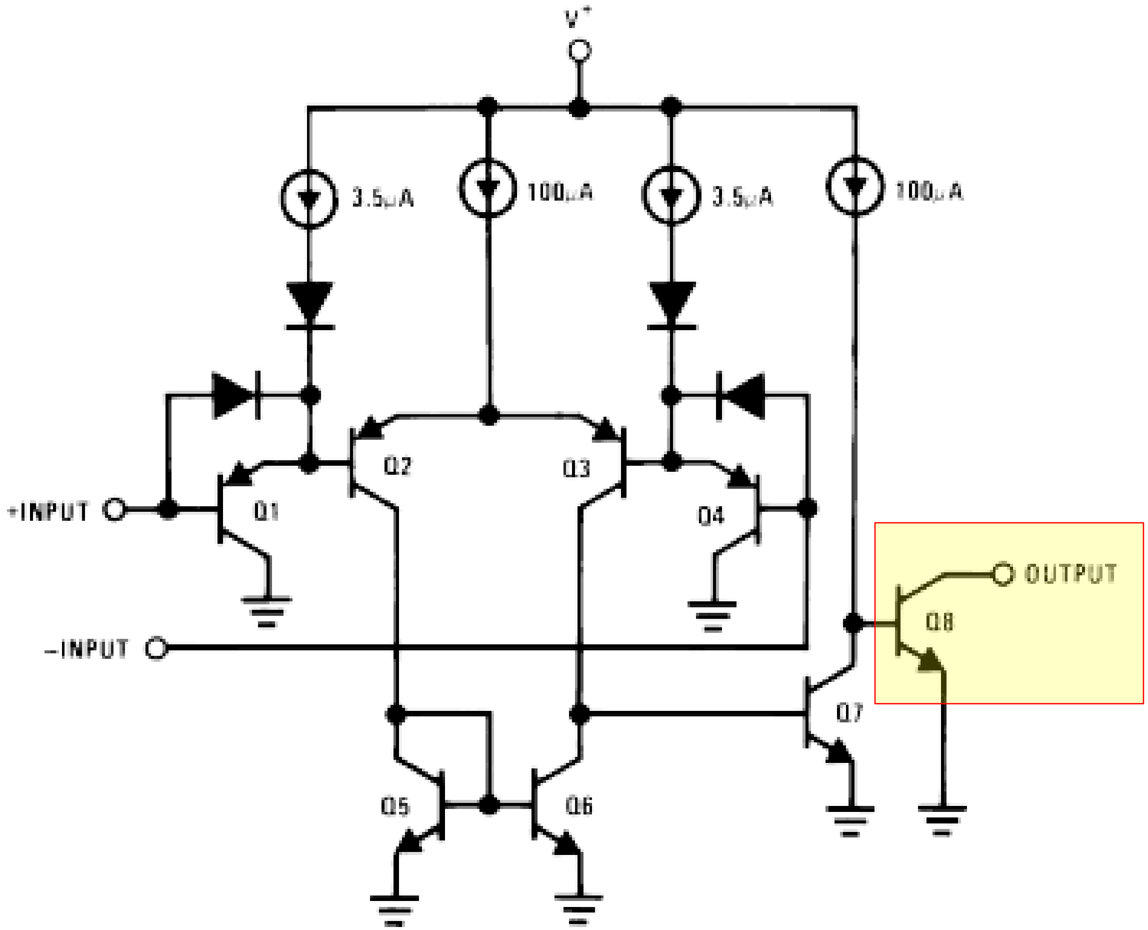
(b)


LM339 Quad IC



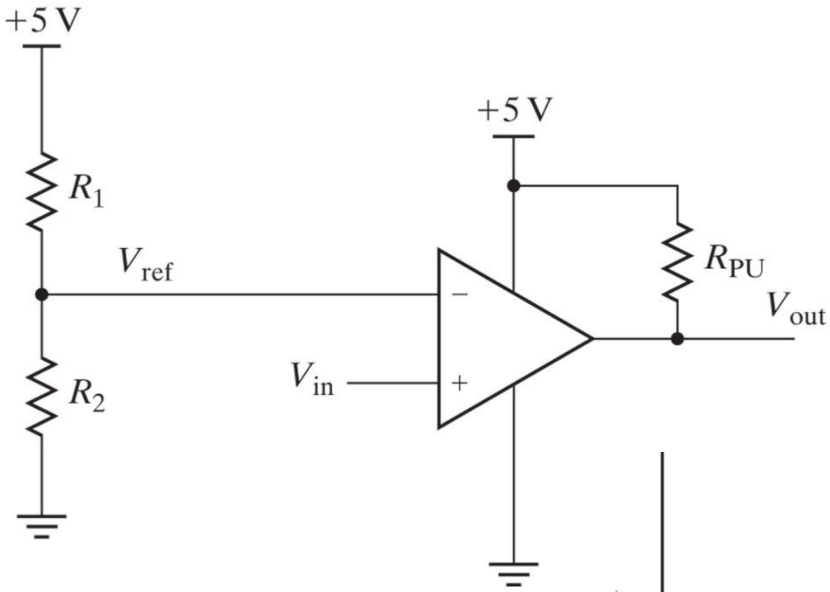
http://www.ermicro.com/blog/?p=1578

Inside the LM339 comparator

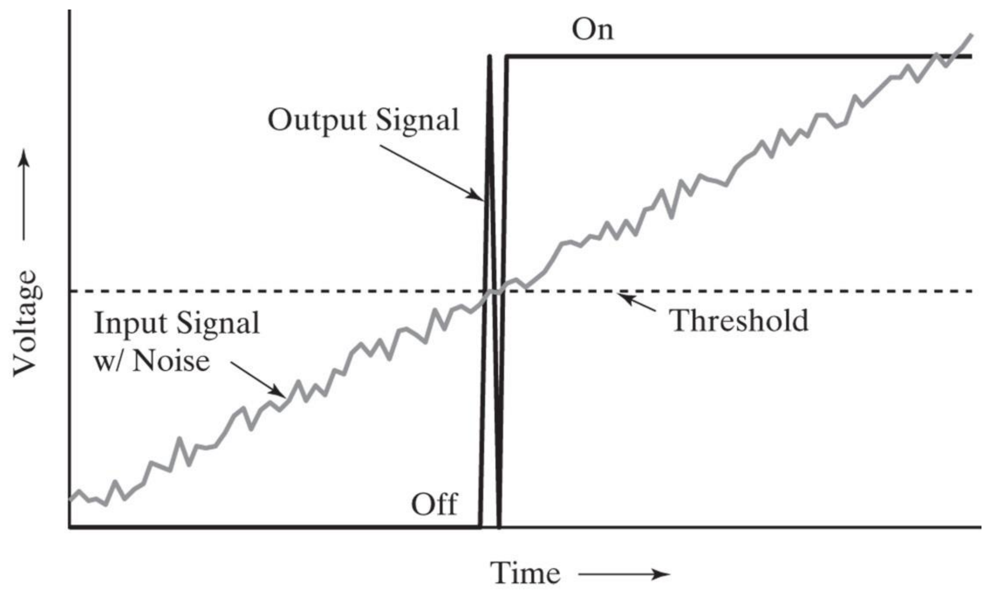


www.national.com/ds/LM/**LM339**.pdf

Simple Non-inverting Comparator

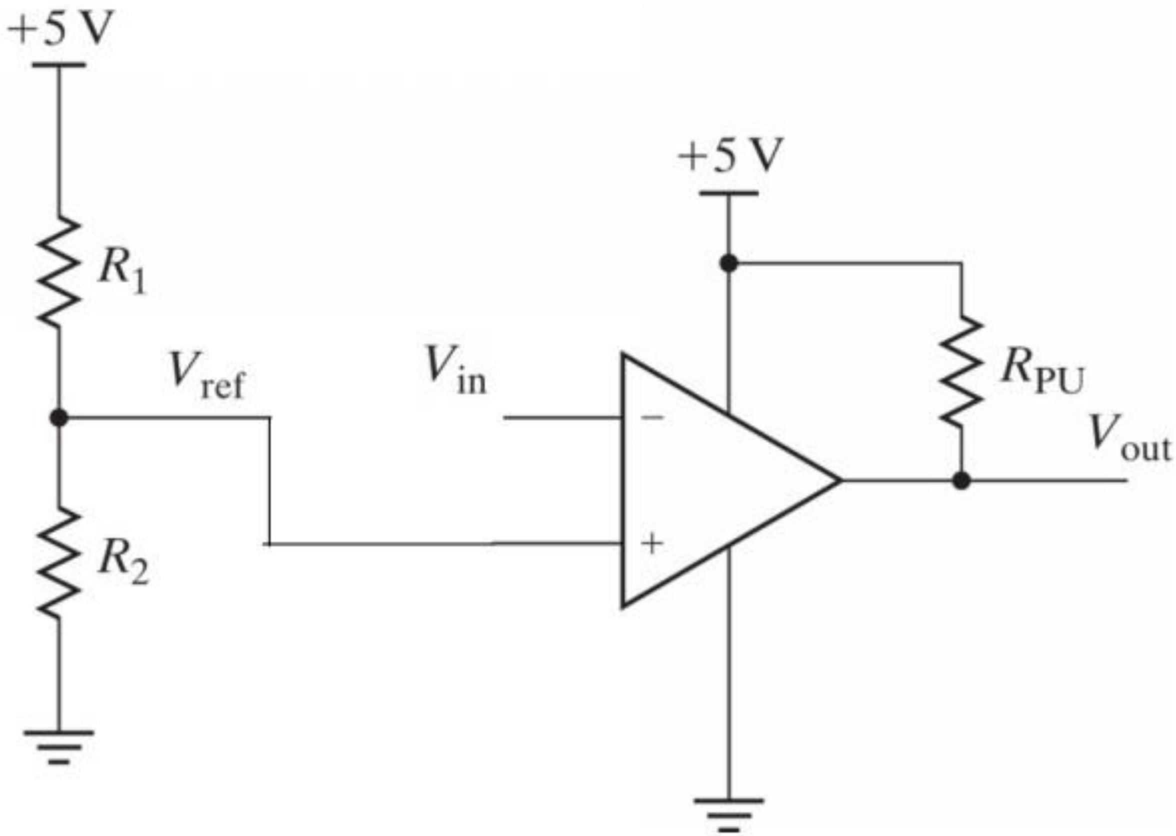


Intro to Mechatronic Design, Fig. 11.19, p. 246



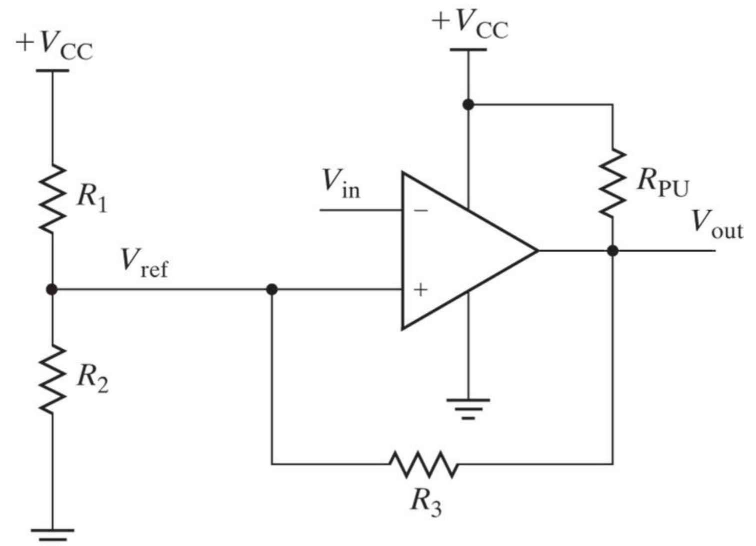
Intro to Mechatronic Design, Fig. 11.20, p. 247

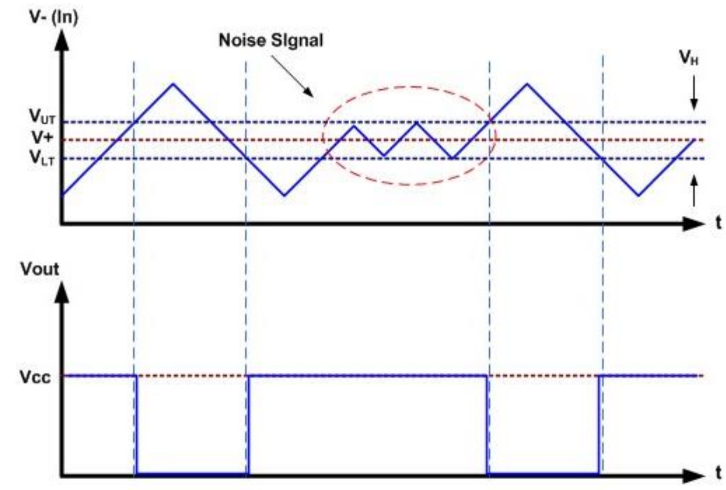
Inverting Comparator



Inverting Comparator with Hysteresis

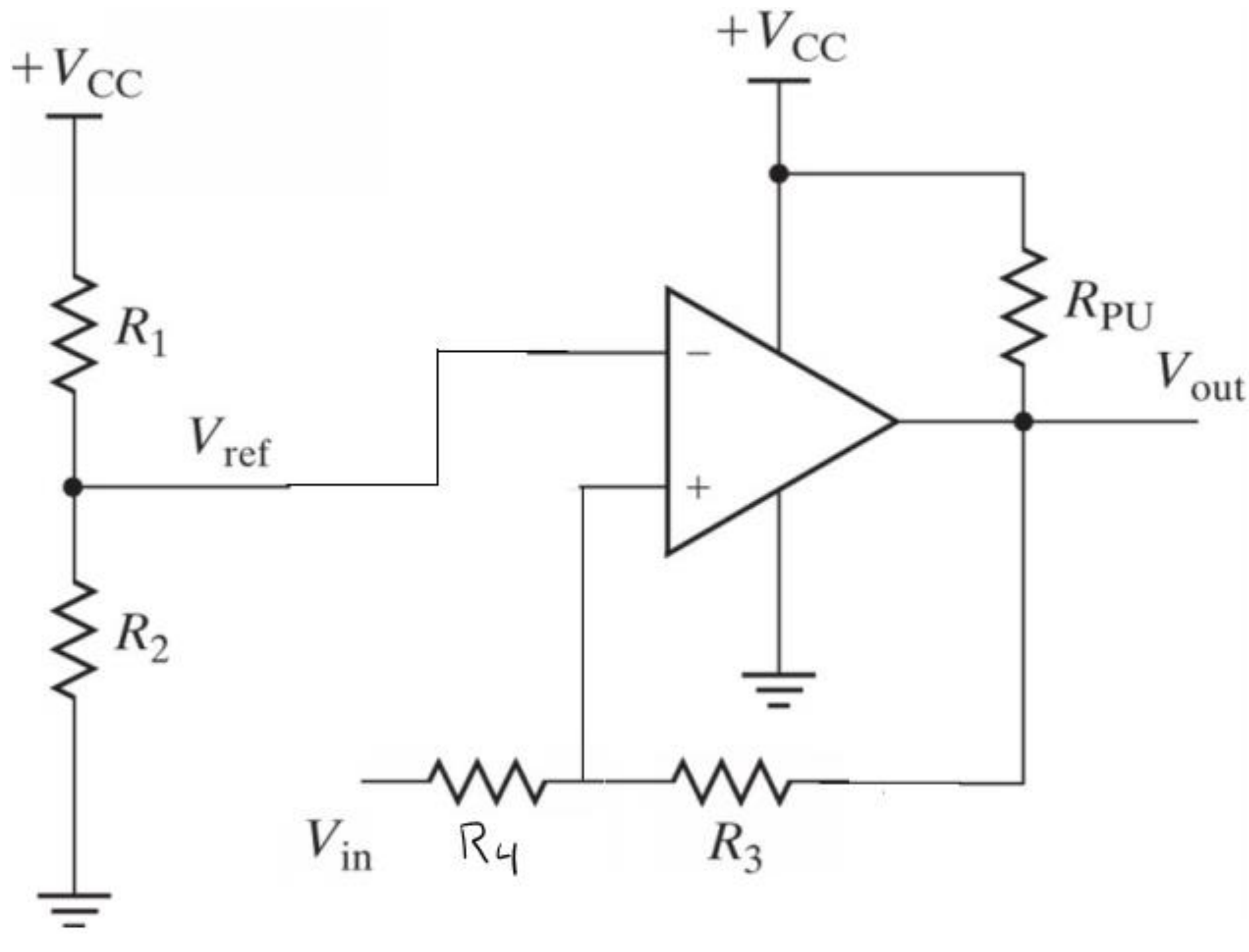
- Add hysteresis (i.e., a *change* in V_{ref} that depends on V_{out} by feeding back to the *non-inverting* terminal
  - When the input voltage *rises* to the threshold, the threshold *drops* to a *lower* value
  - When the input voltage *drops* to the threshold, the threshold is *raised* to a *higher* value

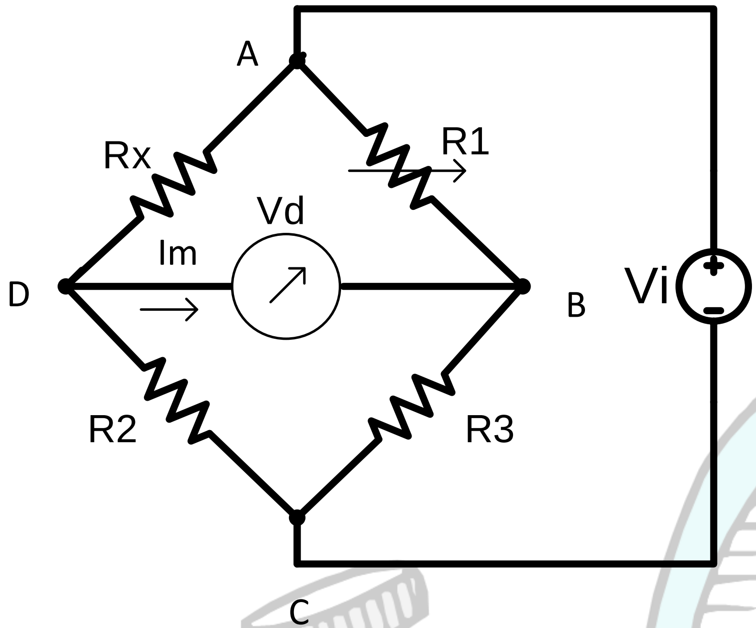




http://www.ermicro.com/blog/wp-content/uploads/2010/03/comp_10.jpg

Non-inverting comparator with hysteresis

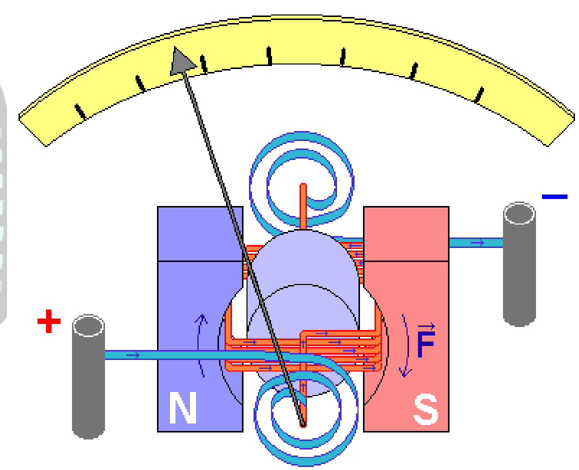




ENEE4304 Instrumentation and Measurements

T9

Variable conversion elements



Outline

- Variable Conversion Elements
- Bridge circuits:
  - DC Bridges
  - AC Bridges
- Other circuits

Need for Variable Conversion

- For sensor outputs that are initially in some non-voltage form, conversion to a measurement signal that is in a more convenient form can be achieved by various types of variable conversion element in the measurement system.
- Bridge circuits are a particularly important type of variable conversion element, and these will be covered in some detail.
- Following this, the various alternative techniques for transducing the outputs of a measurement sensor will be covered.

Need for Variable Conversion

- Outputs from measurement sensors that take the form of voltage signals can be measured using the voltage indicating and test instruments
- However, in many cases, the sensor output does not take the form of an electrical voltage.
- Examples of these other forms of sensor output include translational displacements and changes in various electrical parameters such as resistance, inductance, capacitance and current.
- In some cases, the output may alternatively take the form of variations in the phase or frequency of an a.c. signal.

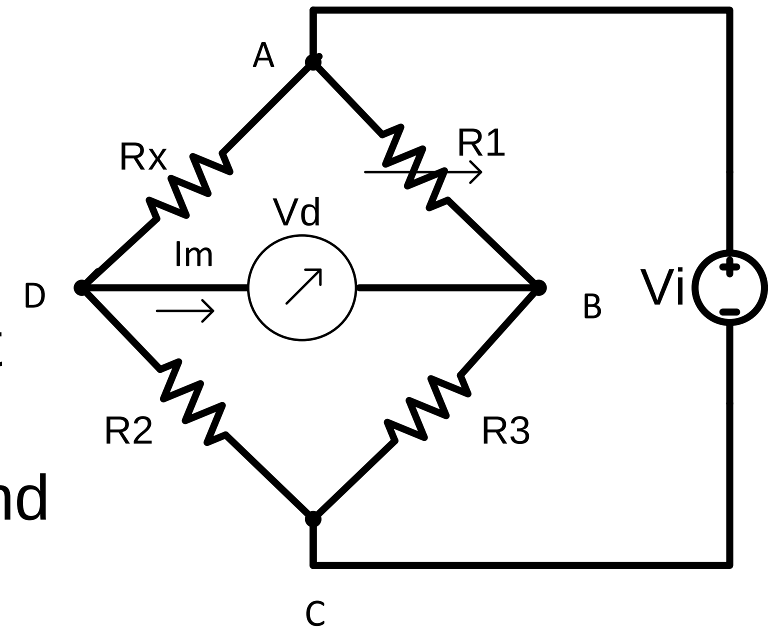
Bridge Circuits

- Bridge circuits are used very commonly as a variable conversion element in measurement systems and produce an output in the form of a voltage level that changes as the measured physical quantity changes.
- They provide an accurate method of measuring resistance, inductance and capacitance values, and enable the detection of very small changes in these quantities about a nominal value.
- They are of immense importance in measurement system technology because so many transducers measuring physical quantities have an output that is expressed as a change in resistance, inductance or capacitance

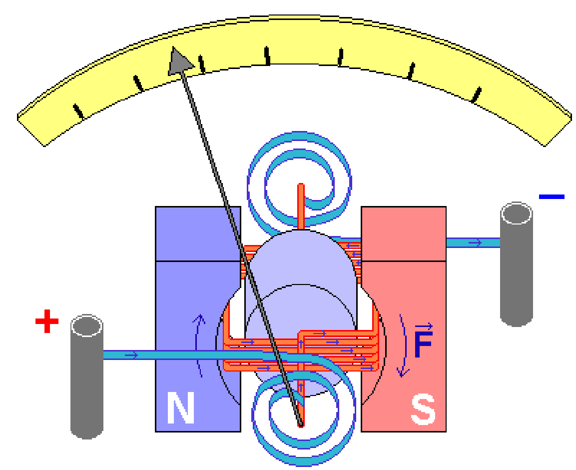
- The displacement-measuring strain gauge, which has a varying resistance output, is but one example of this class of transducers.
- Normally, excitation of the bridge is by a d.c. voltage for resistance measurement and by an a.c. voltage for inductance or capacitance measurement.
- Both null and deflection types of bridge exist, and, in a like manner to instruments in general, null types are mainly employed for calibration purposes and deflection types are used within closed-loop automatic control schemes.

Null-type, d.c. bridge (Wheatstone bridge)

- A null-type bridge with d.c. excitation, commonly known as a Wheatstone bridge, has the form shown below.



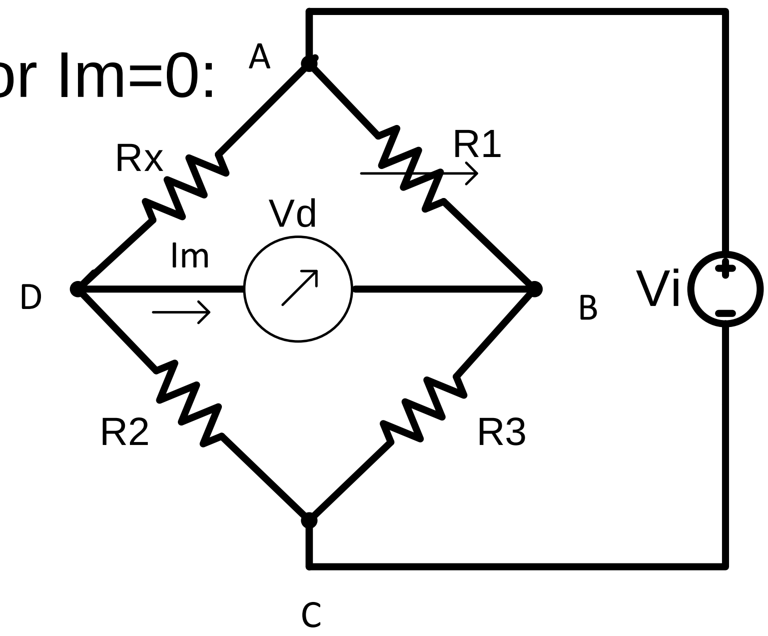
- The four arms of the bridge consist of the unknown resistance Rx, two equal value resistors R2 and R3 and a variable resistor R1 (usually a decade resistance box).
- A d.c. voltage Vi is applied across the points AC and the resistance R1 is varied until the voltage measured across points BD is zero.



- This null point is usually measured with a high sensitivity galvanometer.

Null-type, d.c. bridge (Wheatstone bridge)

- Normally, if a high impedance voltage-measuring instrument is used, the current Im drawn by the measuring instrument will be very small and can be approximated to zero.
- If this assumption is made, then, for Im=0:



$$V_d = \frac{R_2}{R_x + R_2} V_i - \frac{R_3}{R_1 + R_3} V_i$$

$$V_d = V_i \left(\frac{R_2}{R_x + R_2} - \frac{R_3}{R_1 + R_3} \right)$$

At balance:

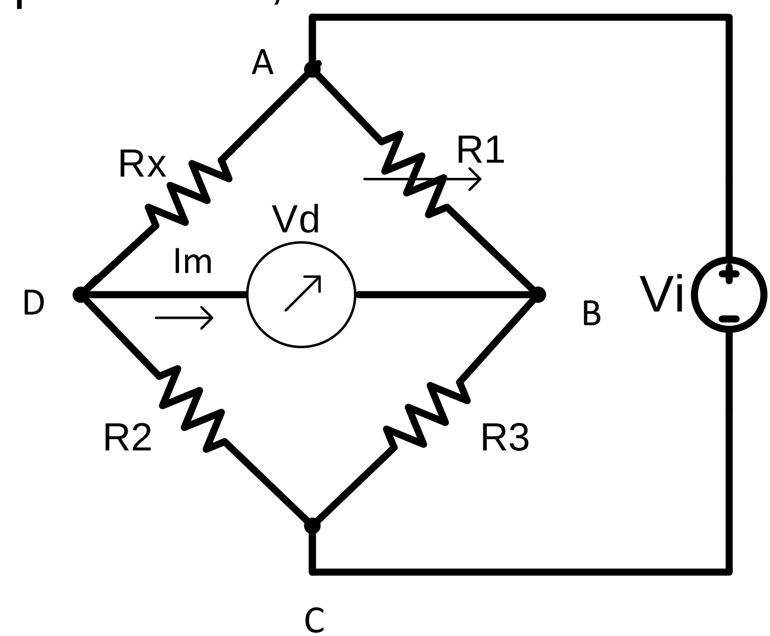
$$V_d = 0 \Rightarrow R_x = R_1 \frac{R_2}{R_3}$$

Known, constant

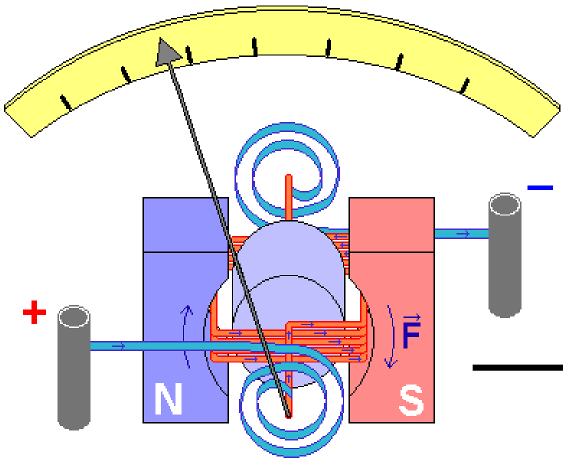
Null-type DC Wheatstone bridges are used for accurate resistance measurement

- The bridge is balanced when the voltage V_d is adjusted to **zero** by tuning R_1 while R_2 and R_3 are known and kept constant.
- The null-detector is usually some type of galvanometer
- The unknown resistance value can then be computed using the values of the other resistances
- Since there are no inductances (coils) or capacitances, a DC source is sufficient
- This type of bridge is used

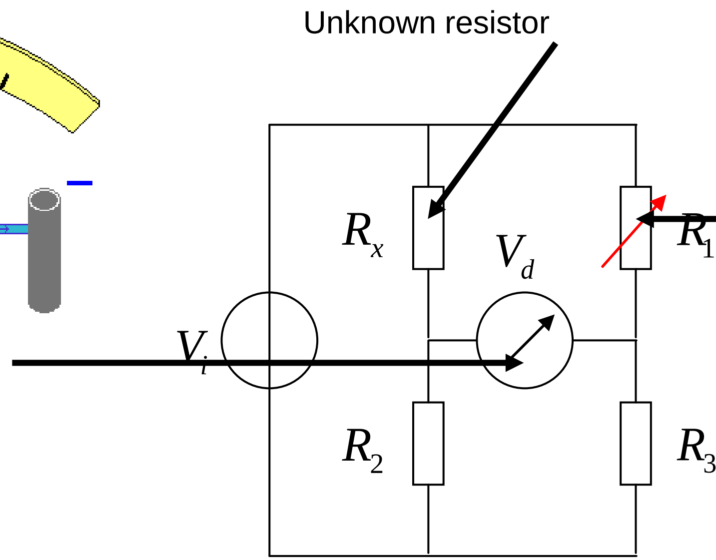
  for **strain gage** measurements



Measurement procedure using Galvanometer and decade resistor box



Galvanometer



Decade Box

$$V_d = \frac{R_2}{R_x + R_2} V_i - \frac{R_3}{R_1 + R_3} V_i$$

$$V_d = V_i \left(\frac{R_2}{R_x + R_2} - \frac{R_3}{R_1 + R_3} \right)$$

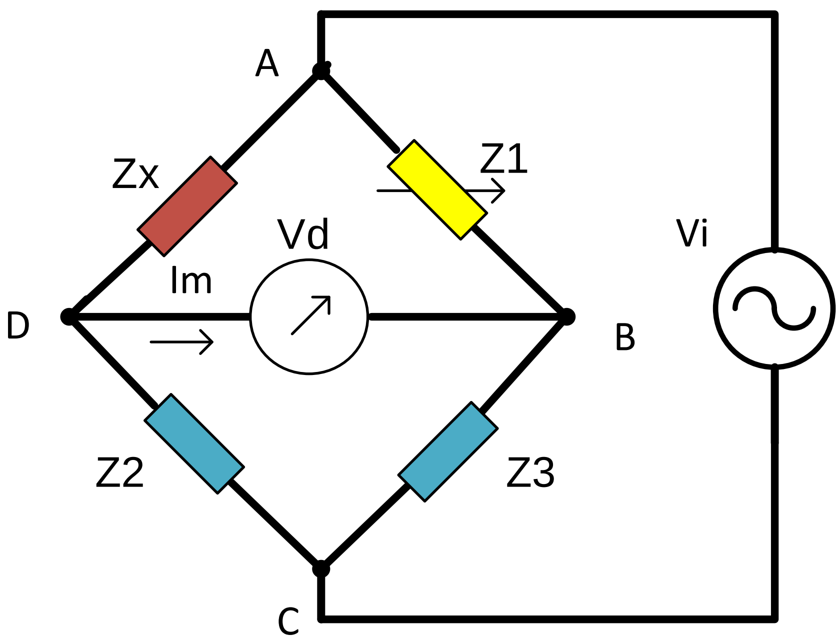
At balance:

$$V_d = 0 \Rightarrow R_x = R_1 \frac{R_2}{R_3}$$

Known, constant ($\frac{R_2}{R_3}$)

Null-type AC Wheatstone bridge for impedance measurement

- The bridge is balanced when the voltage V_d is adjusted to zero by tuning Z_1, Z_2 or Z_3



$$Z_x Z_3 = Z_1 Z_2$$

Equality of Magnitudes

$$|Z_x| = \left|\frac{Z_1}{Z_3}\right| |Z_2|$$

Equality of Phases

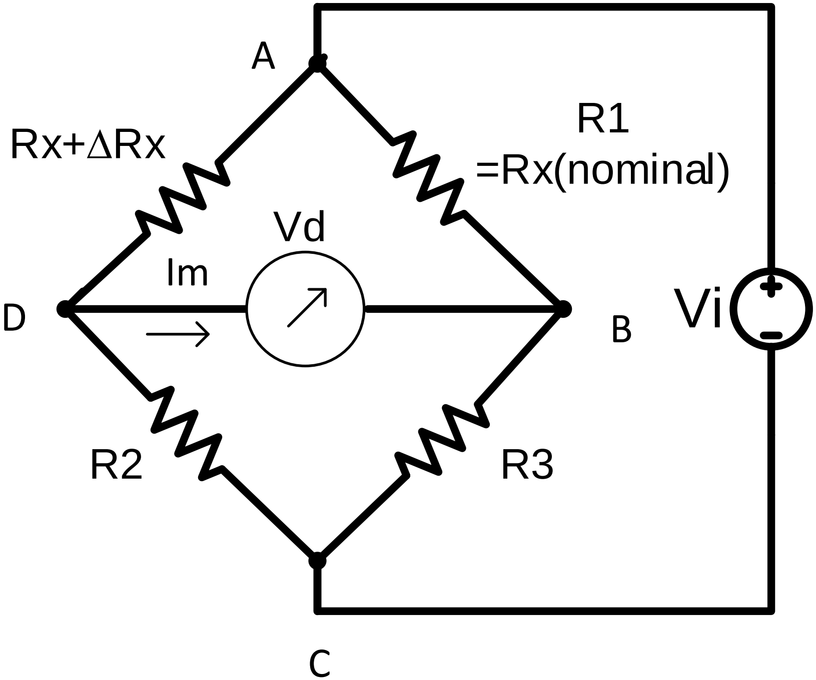
$$\varphi_x = \varphi_1 - \varphi_3 + \varphi_2$$

Deflection type DC Wheatstone bridge

- A deflection-type bridge with d.c. excitation is shown. This differs from the Wheatstone bridge mainly in that the variable resistance R1 is replaced by a fixed resistance of the same value as the nominal value of the unknown resistance Rx.
- As the resistance Rx changes, so the output voltage Vo=Vd varies, and this relationship between Vo and Rx must be calculated.
- This relationship is simplified if we again assume that a high impedance voltage measuring instrument is used.

$$V_d = \frac{R_2}{R_x + R_2} V_i - \frac{R_3}{R_1 + R_3} V_i$$

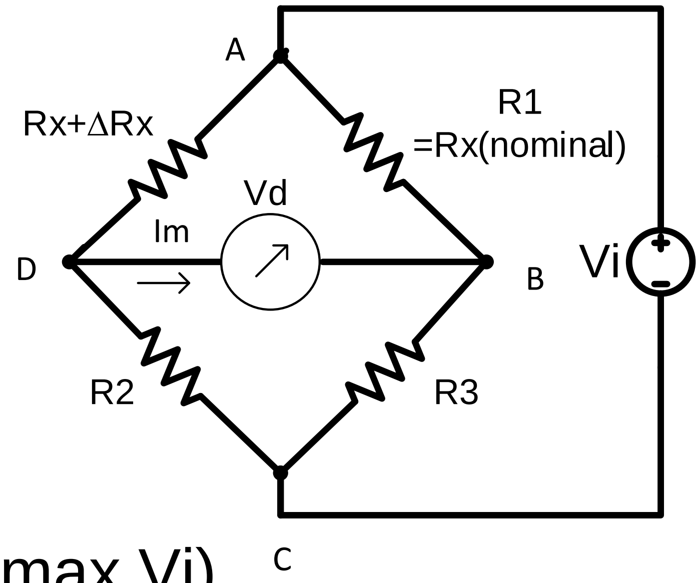
$$V_d = V_i \left(\frac{R_2}{R_x + R_2} - \frac{R_3}{R_1 + R_3} \right)$$



Example

- A certain type of pressure transducer, designed to measure pressures in the range 0–10 bar, consists of a diaphragm with a strain gauge cemented to it to detect diaphragm deflections.
- The strain gauge has a nominal resistance of 120 and forms one arm of a Wheatstone bridge circuit, with the other three arms each having a resistance of 120. The bridge output is measured by an instrument with infinite input impedance.
- If, in order to limit heating effects, the maximum permissible gauge current is 30 mA, calculate the maximum permissible bridge excitation voltage.
- If the sensitivity of the strain gauge is 338 mΩ / bar and the maximum bridge excitation voltage is used, calculate the bridge output voltage when measuring a pressure of 10 bar.

Example solution

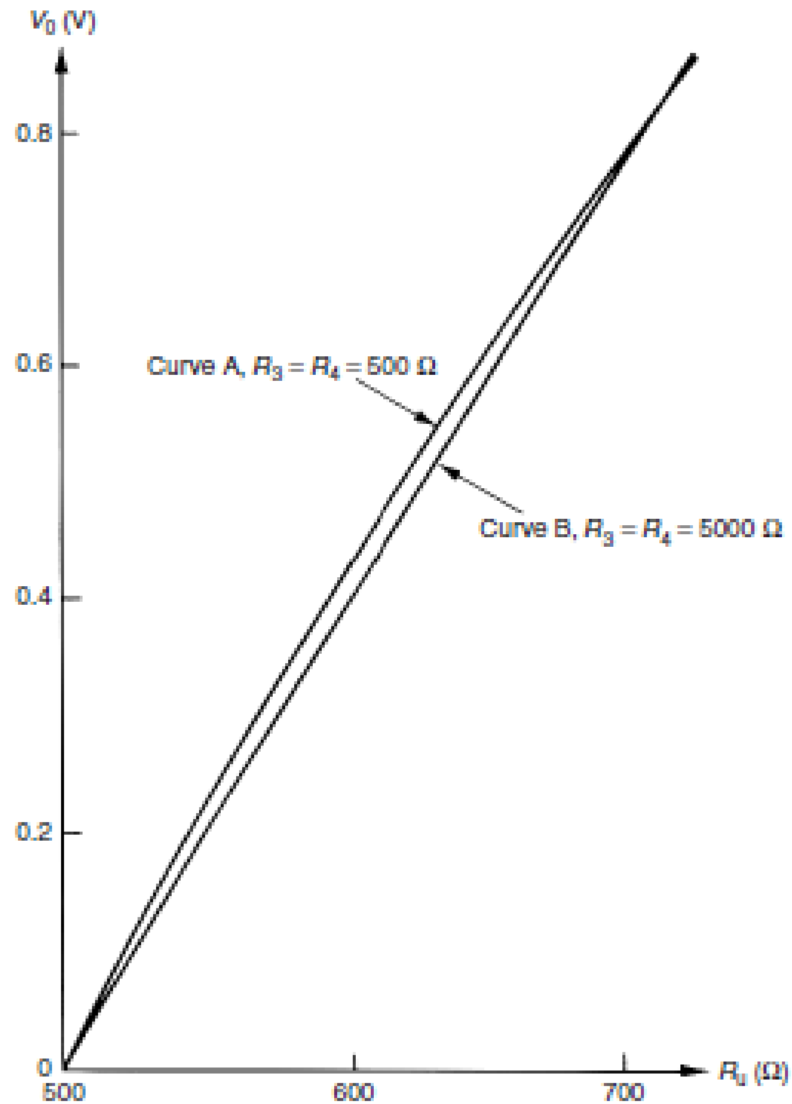


- R1 = R2 = R3 = 120 Ω
- I1= 30 mA
- Hence:
- Vi = 0.03*(120 +120)= 7.2 V <== (max Vi)
- For a pressure of 10 bar applied, ΔRx= 338 mΩ / bar *10 bar= 3.38 Ω, i.e. Rx=Rx(nom) + ΔRx=123.38 Ω
- $Vo = Vi\left(\frac{Rx}{Rx+R3} - \frac{R1}{R1+R2}\right)$
- $Vo = 7.2\left(\frac{123.38}{123.38+120} - \frac{120}{120+120}\right)$=50mV.
- This means that if ΔR is changed by 3.38 Ω, Vo is changed by 50 mV

- $\frac{\delta V_o}{\delta R_x} = \frac{V_i}{R_x + R_3}$ for $\delta R_x \ll R_x$
- In such cases, specific action must be taken to improve linearity in the relationship between the bridge output voltage and the measured quantity.
- **One common solution to this problem is to make the values of the resistances R2 and R3 at least ten times those of R1 and Rx(nominal).**
- The effect of this is best observed by looking at a numerical example.

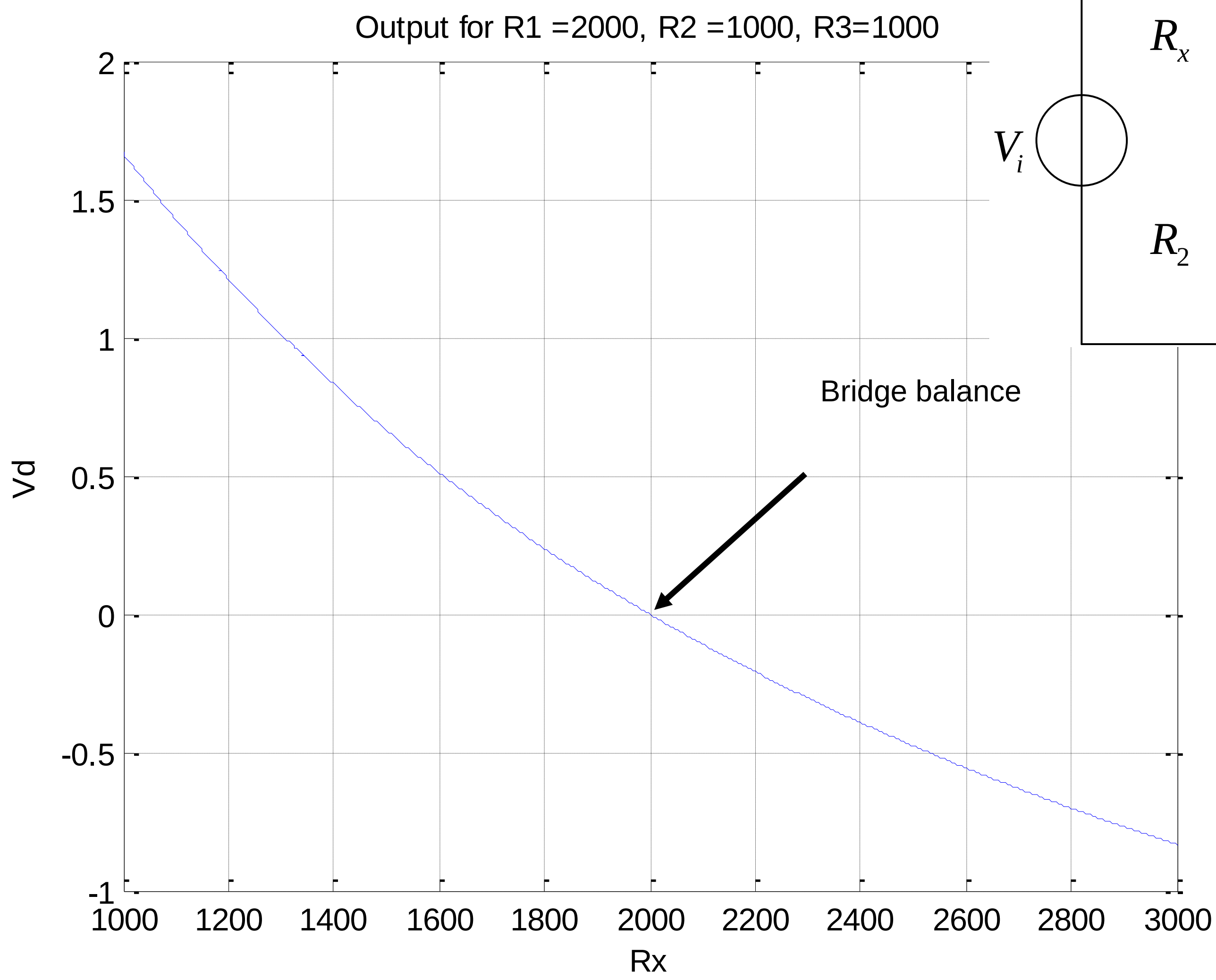
- Consider a platinum resistance thermometer with a range of 0°–50°C, whose resistance at 0°C is 500 and whose resistance varies with temperature at the rate of
- 4Ω /°C. Over this range of measurement, the output characteristic of the thermometer itself is nearly perfectly linear. (N.B. The subject of resistance thermometers is
- discussed later)
- Taking first the case where R1 = R2 = R3 = 500Ω and Vi = 10 V, and applying equation for Vd:
- $at\ 25\ degree\ \ C\ \ \ ,\Delta Rx = 25 * 4 = 100\Omega$
- $Vo = 10\left(\frac{600}{1100} - \frac{500}{1000}\right)$=455mV
- $at\ 50\ degree\ \ C\ \ \ ,\Delta Rx = 50 * 4 = 200\Omega$
- $Vo = 10\left(\frac{700}{1200} - \frac{500}{1000}\right)$=833mV

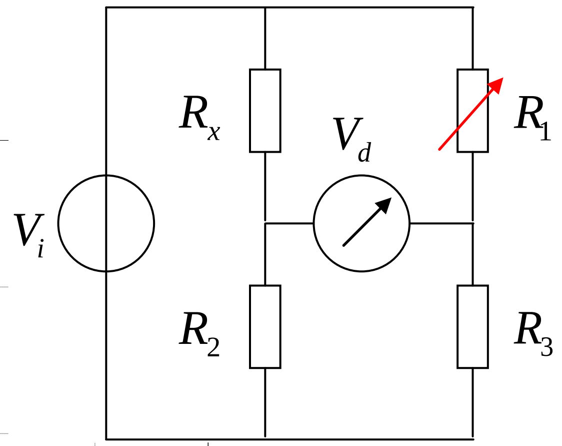
- We notice the non linear nature of the output, since for interval 0-25 deg C ==> ΔVo=455 mV while for interval 25-50 deg C ΔVo=833-455=378 mV
- Now choose R=5000 Ω and Vcc=26.1V (in orderv to have 833 mV at 50 deg C)
- $Vo = 26.1\left(\frac{600}{5600} - \frac{500}{5500}\right)$=423mV at 25 deg C
- $Vo = 26.1\left(\frac{700}{5700} - \frac{500}{15000}\right)$=833mV at 50 deg C
- Now for interval 0-25 deg C ==> ΔVo=424 mV while for interval 25-50 deg C ΔVo=833-424=409 mV which much better



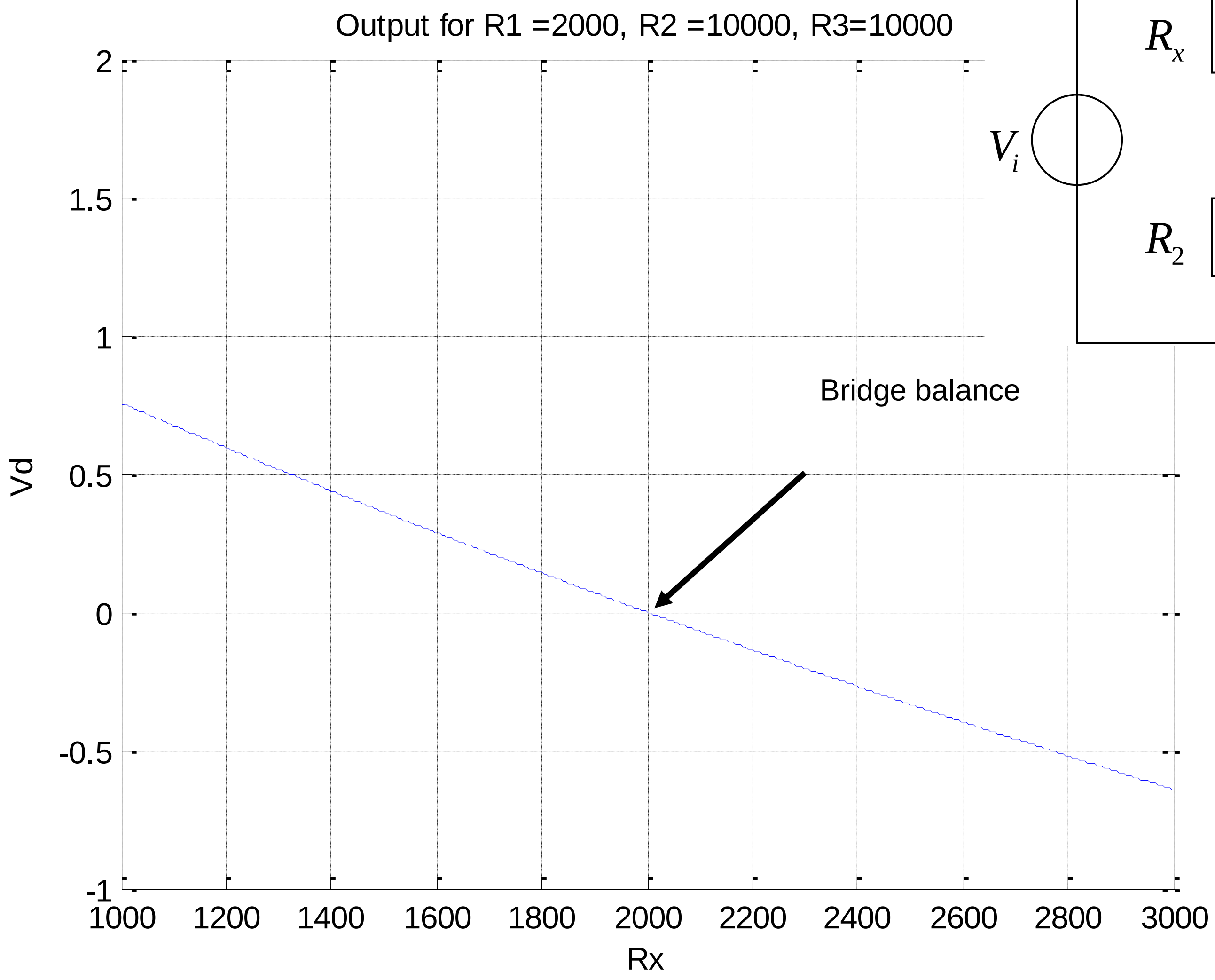
V_0 (V)
0.8
0.6
0.4
0.2
0
500
600
700
R_u (Ω)
Curve A, $R_3 = R_4 = 500\ \Omega$
Curve B, $R_3 = R_4 = 5000\ \Omega$

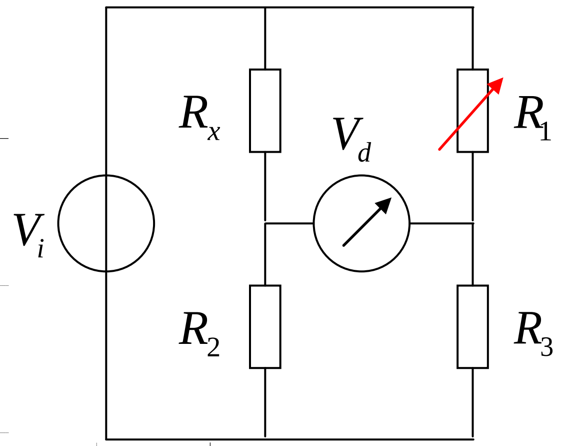
Output (deflection) for R_2, R_3 = 1,000 Ohm showing significant non-linearity





Output (deflection) for R_2, R_3 = 10,000 Ohm showing reduced non-linearity

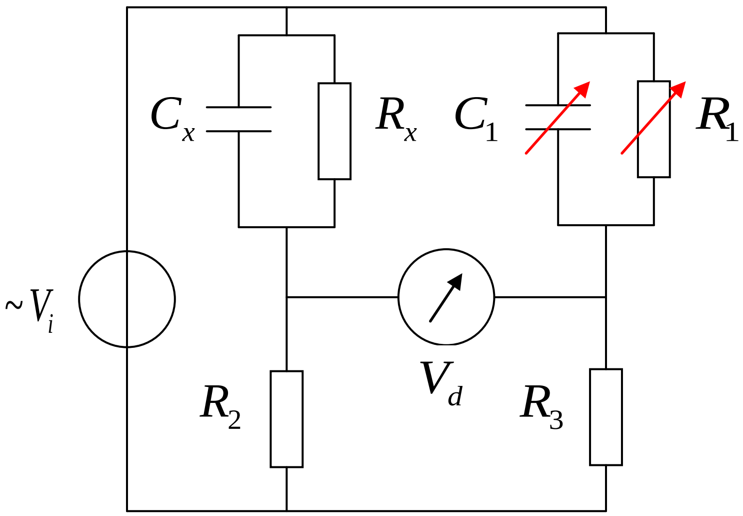




AC bridges

- Bridges with a.c. excitation are used to measure unknown impedances.
- As for d.c. bridges, both null and deflection types exist, with null types being generally used for calibration duties.

Null-type Parallel-Resistance-Capacitance bridge for capacitance and dissipation factor measurement



$$Z_x Z_3 = Z_1 Z_2$$

$$Z_x = \frac{R_x \dfrac{1}{j\omega C_x}}{R_x + \dfrac{1}{j\omega C_x}} = \frac{R_x}{1 + j\omega R_x C_x}$$

$$Z_3 = R_3 \Big\} \text{Known, fixed}$$

$$Z_1 = \frac{R_1 \dfrac{1}{j\omega C_1}}{R_1 + \dfrac{1}{j\omega C_1}} = \frac{R_1}{1 + j\omega R_1 C_1}$$

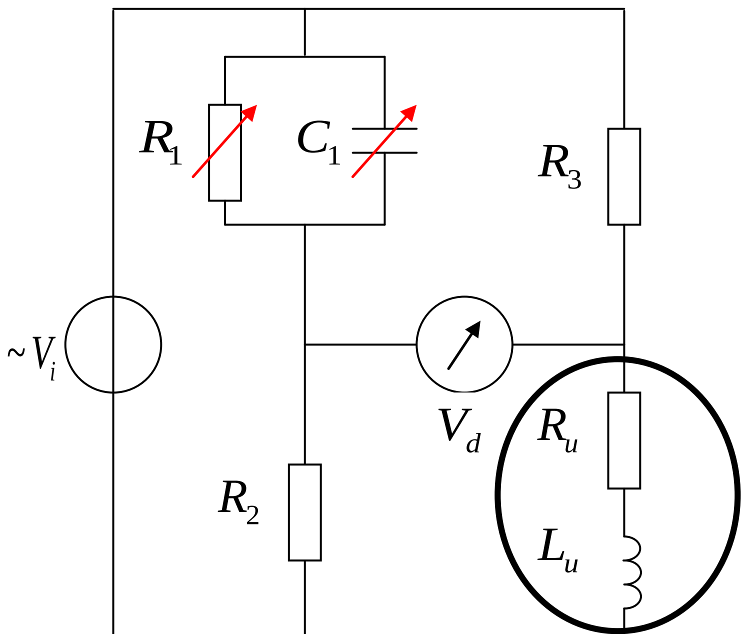
$$Z_2 = R_2 \Big\} \text{Known, fixed}$$

$$\frac{R_x}{1 + j\omega R_x C_x} = \frac{R_2}{R_3}\left(\frac{R_1}{1 + j\omega R_1 C_1}\right)$$

$$R_x R_3 \left(1 + j\omega R_1 C_1\right) = R_1 R_2 \left(1 + j\omega R_x C_x\right)$$

$$\left.\begin{aligned} \text{Re}: R_x &= R_1 \frac{R_2}{R_3} \\ \text{Im}: C_x &= C_1 \frac{R_3}{R_2} \end{aligned}\right\} \text{Independent of } \omega$$

Maxwell bridge to measure inductance, resistance and quality factor of low quality coils (Q<10)



$$Z_1 Z_u = Z_3 Z_2$$

$$Z_u = R_u + j\omega L_u$$

$$Z_1 = \frac{R_1 \dfrac{1}{j\omega C_1}}{R_1 + \dfrac{1}{j\omega C_1}} = \frac{R_1}{1 + j\omega R_1 C_1}$$

$$\left.\begin{aligned} Z_2 &= R_2 \\ Z_3 &= R_3 \end{aligned}\right\} \text{Known, fixed}$$

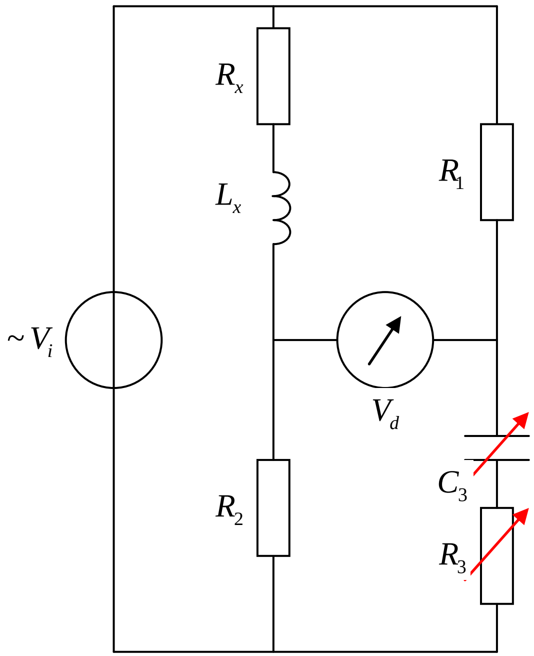
$$\left(R_u + j\omega L_u\right)\left(\frac{R_1}{1 + j\omega R_1 C_1}\right) = R_2 R_3$$

$$R_1\left(R_u + j\omega L_u\right) = R_2 R_3 \left(1 + j\omega R_1 C_1\right)$$

$$\left.\begin{aligned} \mathrm{Re}: R_u &= \frac{R_2 R_3}{R_1} \\ \mathrm{Im}: L_u &= R_2 R_3 C_1 \end{aligned}\right\} \text{Independent of } \omega$$

$$Q \equiv \frac{\omega L_u}{R_u} = \omega R_1 C_1$$

Hay bridge to measure inductance, resistance and quality factor of high quality coils (Q>10)



$$Z_x Z_3 = Z_1 Z_2$$

$$Z_x = R_x + j\omega L_x$$

$$Z_3 = R_3 + \frac{1}{j\omega C_3} = \frac{1 + j\omega R_3 C_3}{j\omega C_3}$$

$$\left. \begin{aligned} Z_1 &= R_1 \\ Z_2 &= R_2 \end{aligned} \right\} \text{Known, fixed}$$

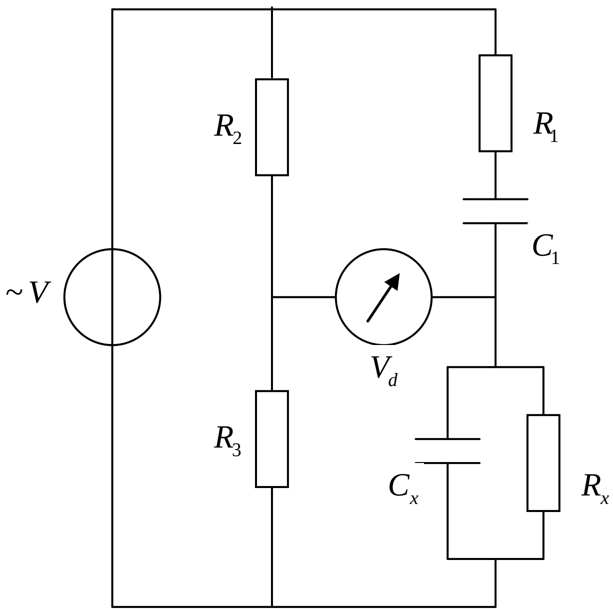
$$(R_x + j\omega L_x)\left(\frac{1 + j\omega R_3 C_3}{j\omega C_3}\right) = R_1 R_2$$

$$(R_x + j\omega L_x)(1 + j\omega R_3 C_3) = j\omega R_1 R_2 C_3$$

$$L_x = \frac{R_1 R_2 C_3}{1 + \omega^2 R_3^2 C_3^2} \qquad R_x = \frac{\omega^2 R_1 R_2 R_3 C_3^2}{1 + \omega^2 R_3^2 C_3^2}$$

$$Q = \frac{\omega L_x}{R_x} = \frac{1}{\omega R_3 C_3}$$

Wien bridge for frequency measurement



$$Z_2 Z_x = Z_3 Z_1$$

$$Z_2 = R_2 \} \text{Known, fixed}$$

$$Z_x = \frac{R_x \dfrac{1}{j\omega C_x}}{R_x + \dfrac{1}{j\omega C_x}} = \frac{R_x}{1 + j\omega R_x C_x}$$

$$Z_3 = R_3 \} \text{Known, fixed}$$

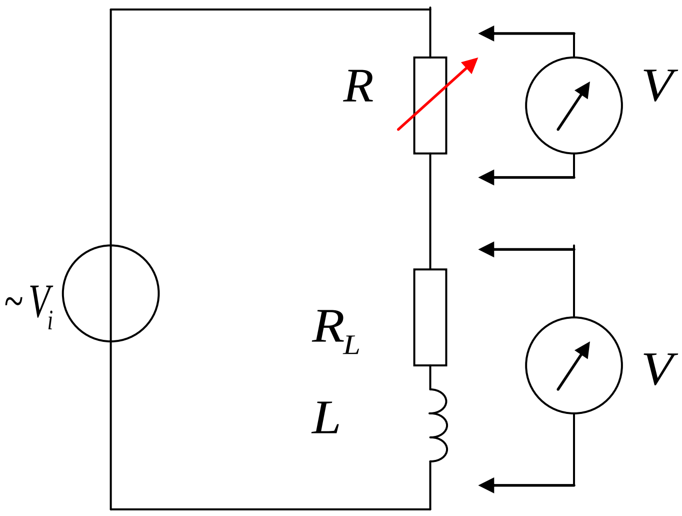
$$Z_1 = R_1 + \frac{1}{j\omega C_1} = \frac{1 + j\omega R_1 C_1}{j\omega C_1}$$

$$\omega^2 = \frac{1}{R_1 C_1 R_x C_x}$$

$$R_x = R_3 \left(\frac{1 + \omega^2 R_1{}^2 C_1{}^2}{\omega^2 R_1 R_2 C_1{}^2} \right)$$

$$C_x = \frac{R_2 C_1}{R_3 \left(1 + \omega^2 R_1{}^2 C_1{}^2 \right)}$$

The coil characteristics inductance and series resistance can be measured by equalizing the voltage across a variable resistor and the coil itself



$$Z_L = R_L + j\omega L$$

$$Z_R = R$$

$$V = i\left(R_L + j\omega L\right) = iR$$

$$\left|V\right| = i\left(\sqrt{R_L^{\ 2} + \left(\omega L\right)^2}\right) = iR$$

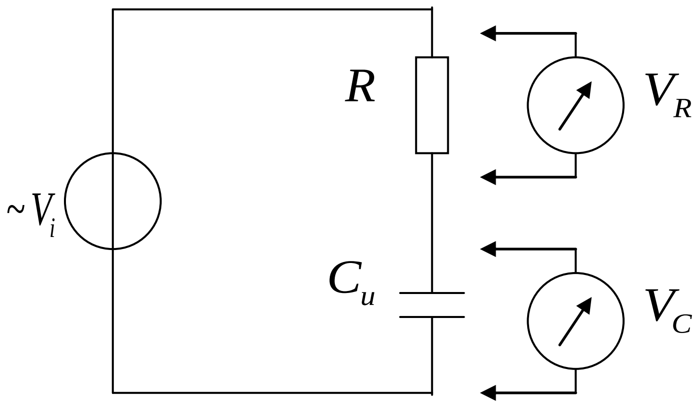
$$R_L^{\ 2} + \left(\omega L\right)^2 = R^2$$

$$\boxed{L = \frac{1}{\omega}\sqrt{R^2 - R_L^{\ 2}}}$$

Series resistance of the coil *RL* measured with a DVM

Approximate method of measuring capacitance

- Measure the AC Voltages **for a known input frequency** across resistor R and capacitor C



$$Z_C = \frac{1}{j\omega C}$$

$$Z_R = R$$

$$|V_C| = i\frac{1}{\omega C}$$

$$|V_R| = iR$$

$$\frac{|V_C|}{|V_R|} = \frac{1}{\omega RC}$$

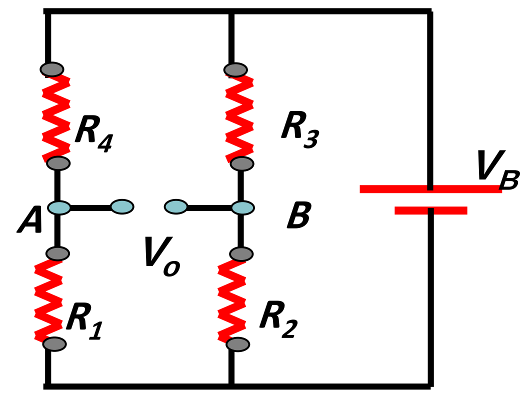
$$C = \frac{1}{\omega R}\frac{|V_R|}{|V_C|}$$

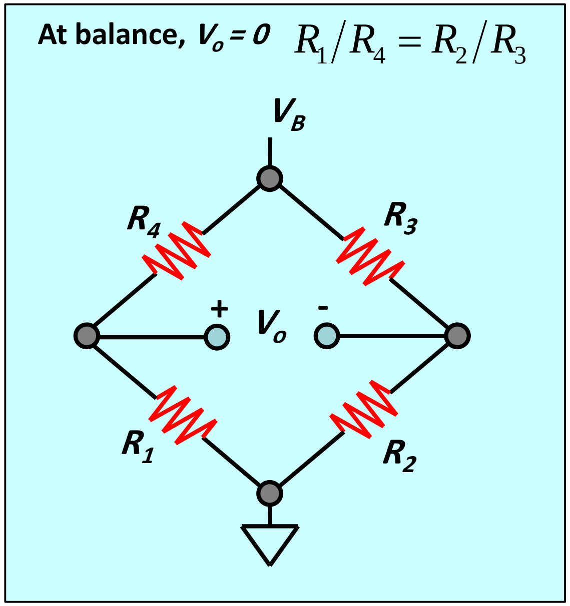
Resistance measured with a DVM

Deflection Bridges with More than one variable element

Resistance Bridges: Deflection Type Measurement

- For the majority of sensor applications employing bridges, the deviation of one or more resistors in a bridge from an initial value is measured as an indication of the magnitude (or a change) in the measured variable. In this case, the output voltage change is an indication of the resistance change.
- Because very small resistance changes are common, the output voltage change may be as small as tens of millivolts, even with V_B = 10V (a typical excitation voltage for a load cell application).

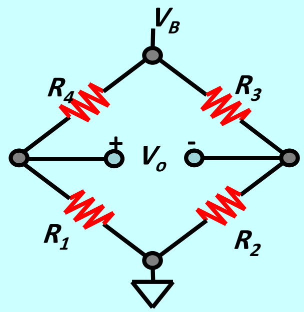




Deflection Type Resistance Bridges: Variable Resistance Configurations

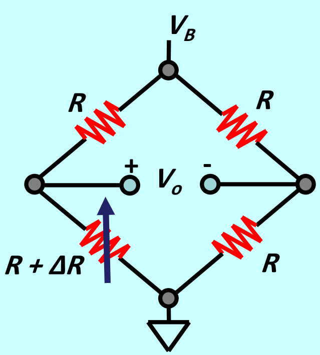
- In many bridge applications, there may be two, or even four elements which vary.
- Note that since the bridge output is directly proportional to V_B, the measurement accuracy can be no better than that of the accuracy of the excitation voltage.

General Bridge



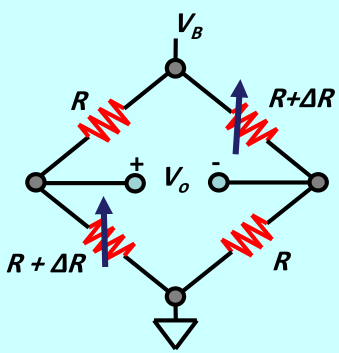
$$V_o = V_B\left(\frac{R_1}{R_1+R_4} - \frac{R_2}{R_2+R_3}\right)$$

Single Varying Element



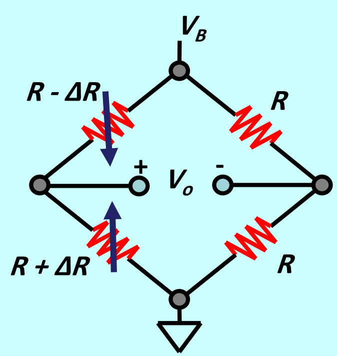
$$V_o = \frac{V_B}{4}\left(\frac{\Delta R}{R+\Delta R/2}\right)$$

Two Co-varying Elements



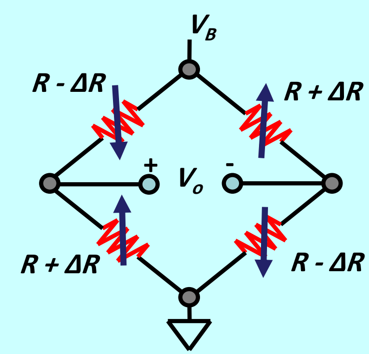
$$V_o = \frac{V_B}{2}\left(\frac{\Delta R}{R+\Delta R/2}\right)$$

Two Anti-varying Elements



$$V_o = \frac{V_B}{2}\left(\frac{\Delta R}{R}\right)$$

Four Varying Elements

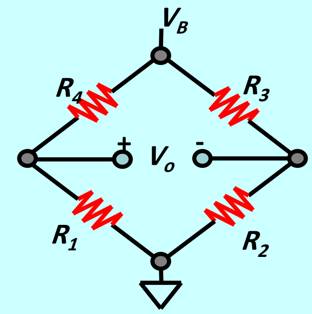


$$V_o = V_B\left(\frac{\Delta R}{R}\right)$$

Deflection Type Resistance Bridges: Variable Resistance Configurations

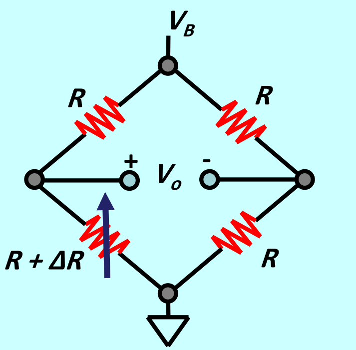
- In each case, the value of the fixed bridge resistor, R, is chosen to be equal to the nominal value of the variable resistor(s).
- The deviation of the variable resistor(s) about the nominal value is proportional to the quantity being measured, such as strain (in the case of a strain gage) or temperature (in the case of an RTD).

General Bridge



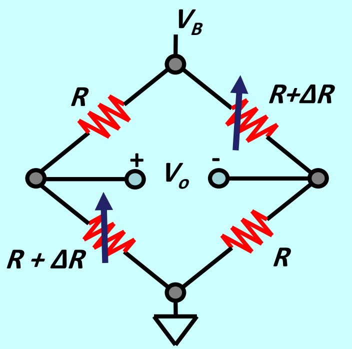
$$V_o = V_B\left(\frac{R_1}{R_1+R_4} - \frac{R_2}{R_2+R_3}\right)$$

Single Varying Element



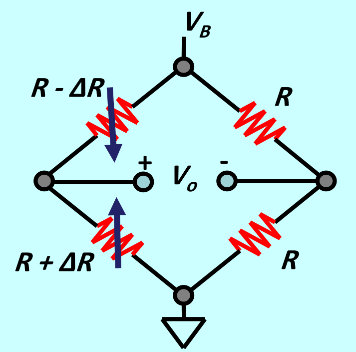
$$V_o = \frac{V_B}{4}\left(\frac{\Delta R}{R+\Delta R/2}\right)$$

Two Co-varying Elements



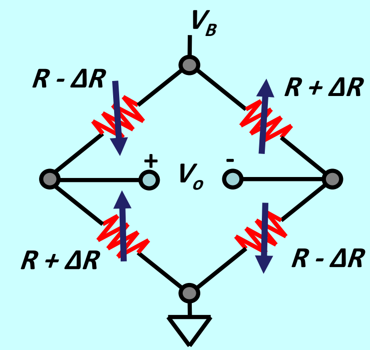
$$V_o = \frac{V_B}{2}\left(\frac{\Delta R}{R+\Delta R/2}\right)$$

Two Anti-varying Elements



$$V_o = \frac{V_B}{2}\left(\frac{\Delta R}{R}\right)$$

Four Varying Elements

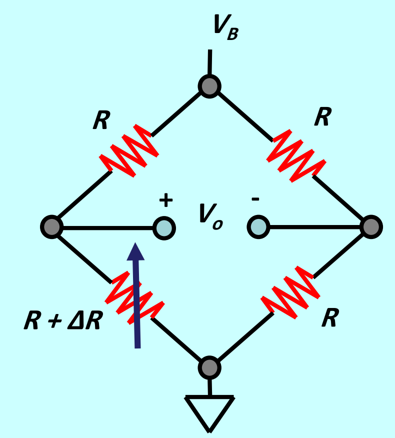


$$V_o = V_B\left(\frac{\Delta R}{R}\right)$$

Deflection Type Resistance Bridges: Single Varying Element Configurations

- The single-element varying bridge may be used for temperature sensing using RTDs or thermistors.
- This configuration is also used with a single resistive strain gage. All the resistances are nominally equal, but one of them (the sensor) is variable by an amount ΔR.
- The relationship between the bridge output and ΔR is not linear. Since there is a fixed relationship between the bridge resistance change and its output, software can be used to remove the linearity error in digital systems.
- Alternative bridge configurations can also be used to linearize the bridge output directly.

Single Varying Element



$$V_o = \frac{V_B}{4}\left(\frac{\Delta R}{R + \Delta R/2}\right)$$

Deflection Type Resistance Bridges: Two Co-varying Elements Configurations

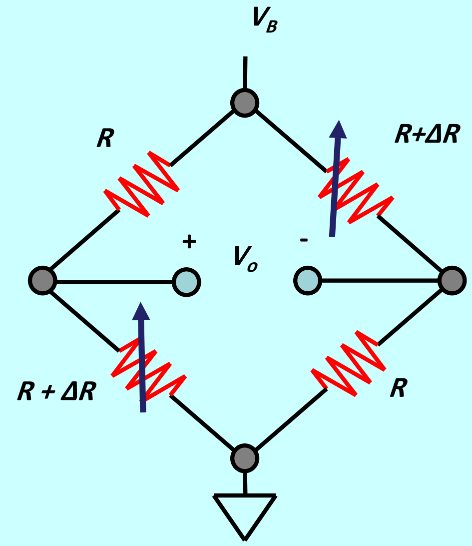
- In this configuration, both elements change in the same direction. The nonlinearity is the same as that of the single-element varying bridge, however the gain is twice that of the single-element varying bridge.

- The two-element varying bridge is commonly found in pressure sensors and flow meter systems.

$$V_o = V_B\left(\frac{R+\Delta R}{2R+\Delta R} - \frac{R}{2R+\Delta R}\right)$$

$$= V_B\left(\frac{\Delta R}{2R+\Delta R}\right)$$

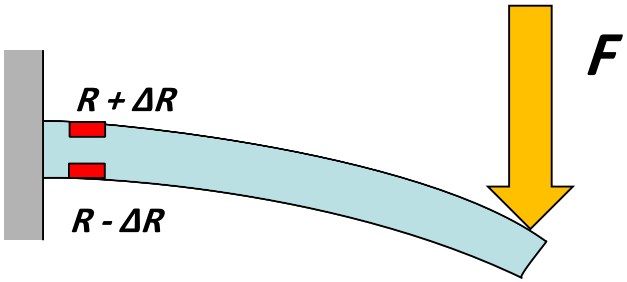
Two Co-varying Elements



$$V_o = \frac{V_B}{2}\left(\frac{\Delta R}{R+\Delta R/2}\right)$$

Deflection Type Resistance Bridges: Two Anti-varying Elements Configurations

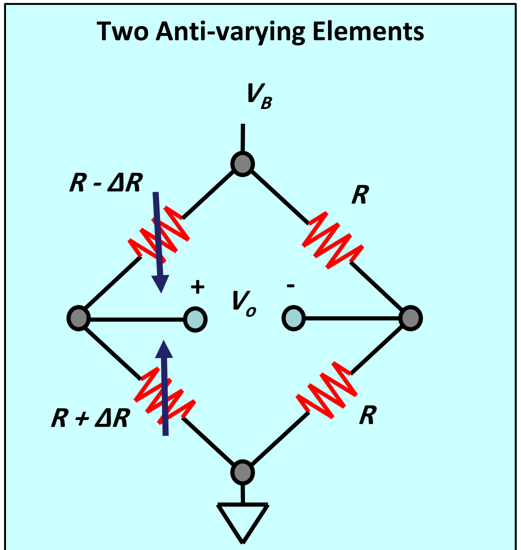
- This configuration requires two identical elements that vary in opposite directions. This could correspond to two identical strain gages: one mounted on top of a flexing surface, and one on the bottom.



- Such a configuration could be used for measuring force, pressure, stress, strain, etc. It produces a linear output, and it has twice the gain of the single-element configuration.

$$V_o = V_B\left(\frac{R+\Delta R}{2R} - \frac{R}{2R}\right)$$

$$= V_B\left(\frac{R+\Delta R - R}{2R}\right)$$



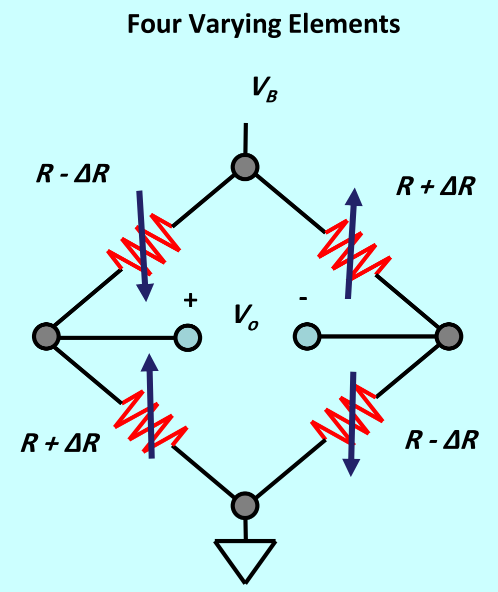
$$V_o = \frac{V_B}{2}\left(\frac{\Delta R}{R}\right)$$

Deflection Type Resistance Bridges: Four Varying Elements Configurations

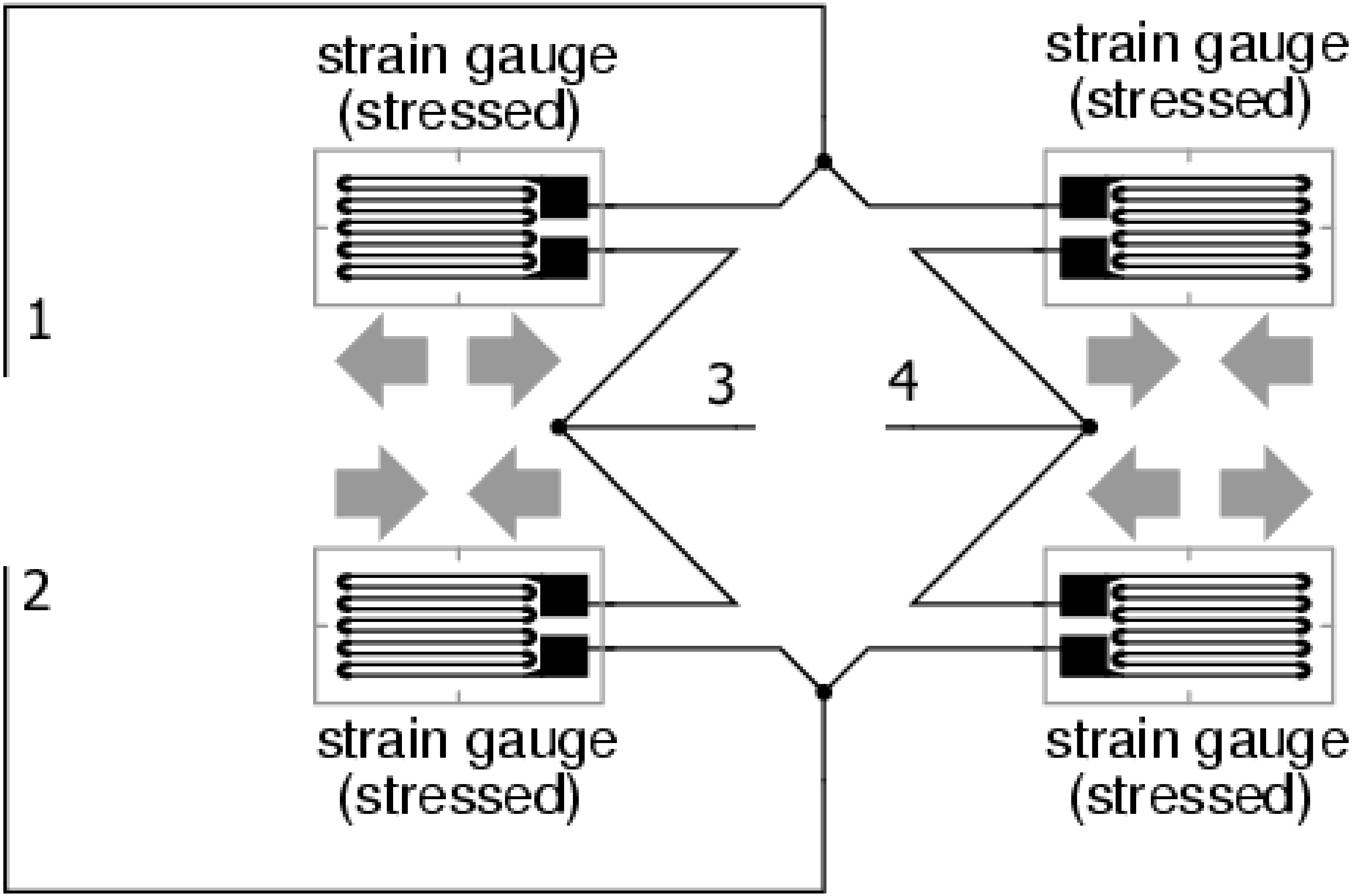
- The four varying elements bridge produces the most signal for a given resistance change and is inherently linear.
- It is an industry-standard configuration for load cells used in electronic scales which are constructed from four identical strain gages.

$$V_o = V_B\left(\frac{R+\Delta R}{2R} - \frac{R-\Delta R}{2R}\right)$$

$$= V_B\left(\frac{R+\Delta R - R + \Delta R}{2R}\right)$$



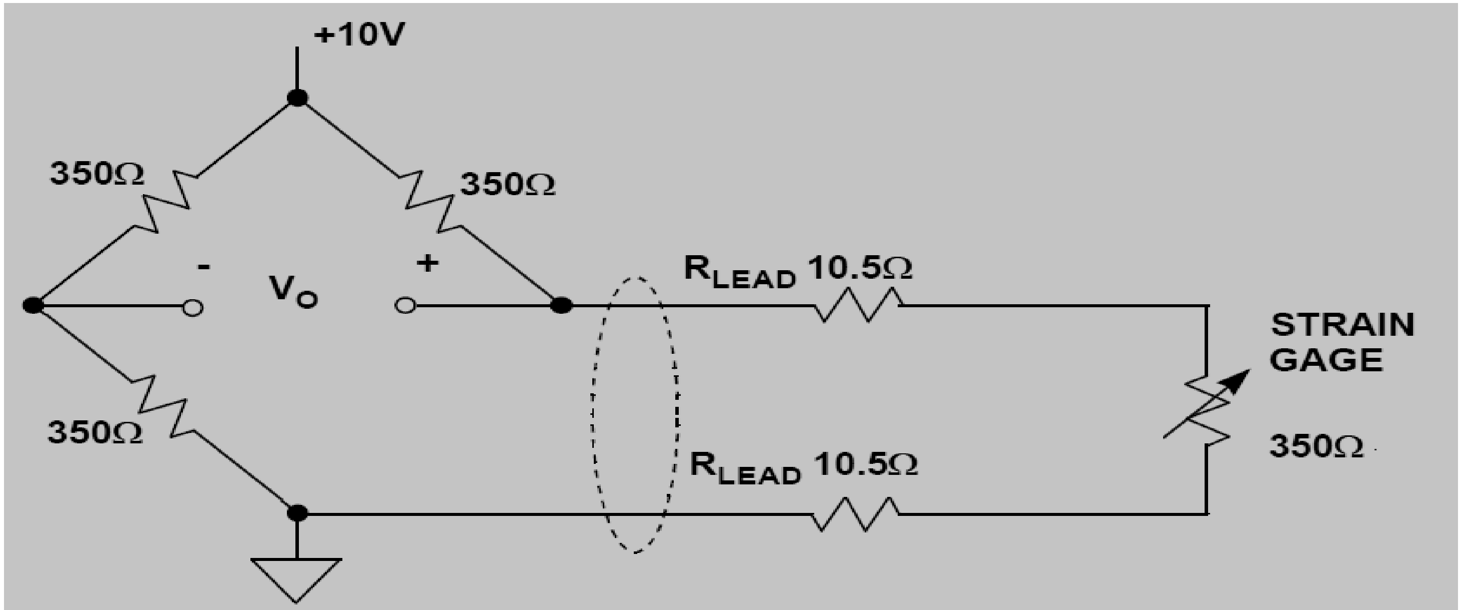
$$V_o = V_B\left(\frac{\Delta R}{R}\right)$$



strain gauge
(stressed)
strain gauge
(stressed)
1
3
4
2
strain gauge
(stressed)
strain gauge
(stressed)

Example: Errors Produced by Wiring Resistance in Remote Resistive Bridge Sensor

- A **350Ω** nominal resistance strain gage is used as a sensing element in a single varying element Wheatstone bridge.
- The gauge is connected to the rest of the bridge circuit by **100 feet of 30 gauge twisted pair copper wire with a resistance of 0.105 Ω /ft**, **at 25°C** and a temperature coefficient of **0.385%/°C**.
- The full scale variation of the strain gage resistance (with flex) above its nominal 350 Ω value is **+1%.** **Calculate the offset error in the bridge output due to the lead resistance.**



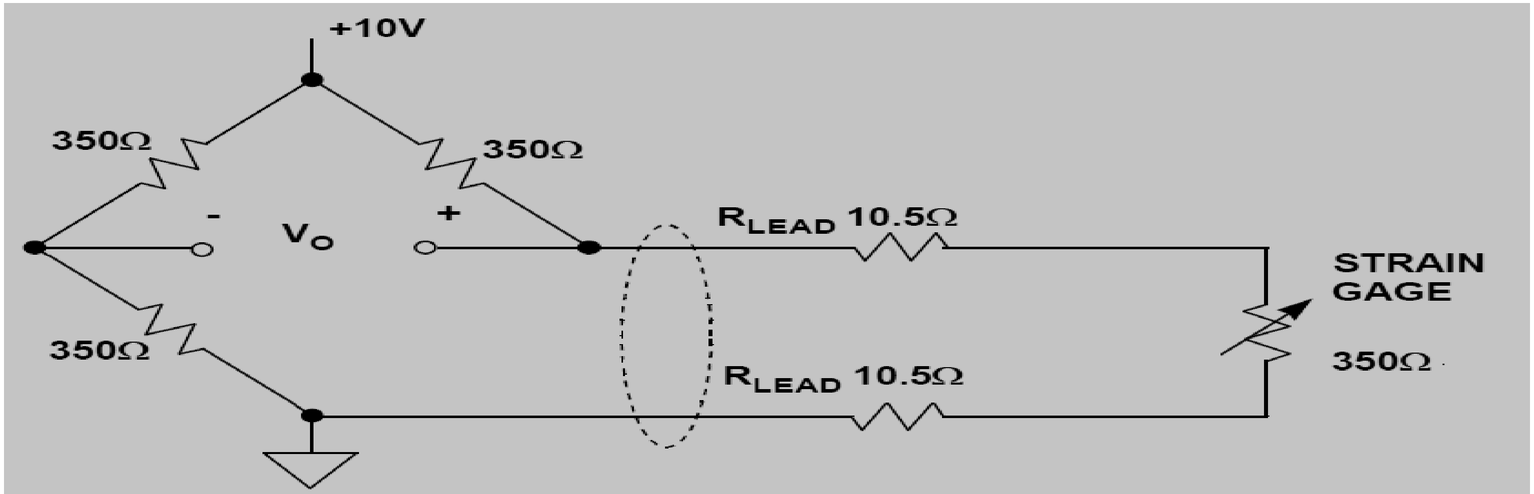
Errors Produced by Wiring Resistance in Remote Resistive Bridge Sensor

Offset error due to lead resistance

- The resistance of each 100 ft copper cable **is Rlead=100 ft x 0.105 Ω /ft = 10.5Ω**, and the total lead resistance in series with the 350Ω strain gage is therefore 21 Ω at 25°C.
- The bridge output voltage is simply the difference between the output of two voltage dividers, each driven from a +10V source.

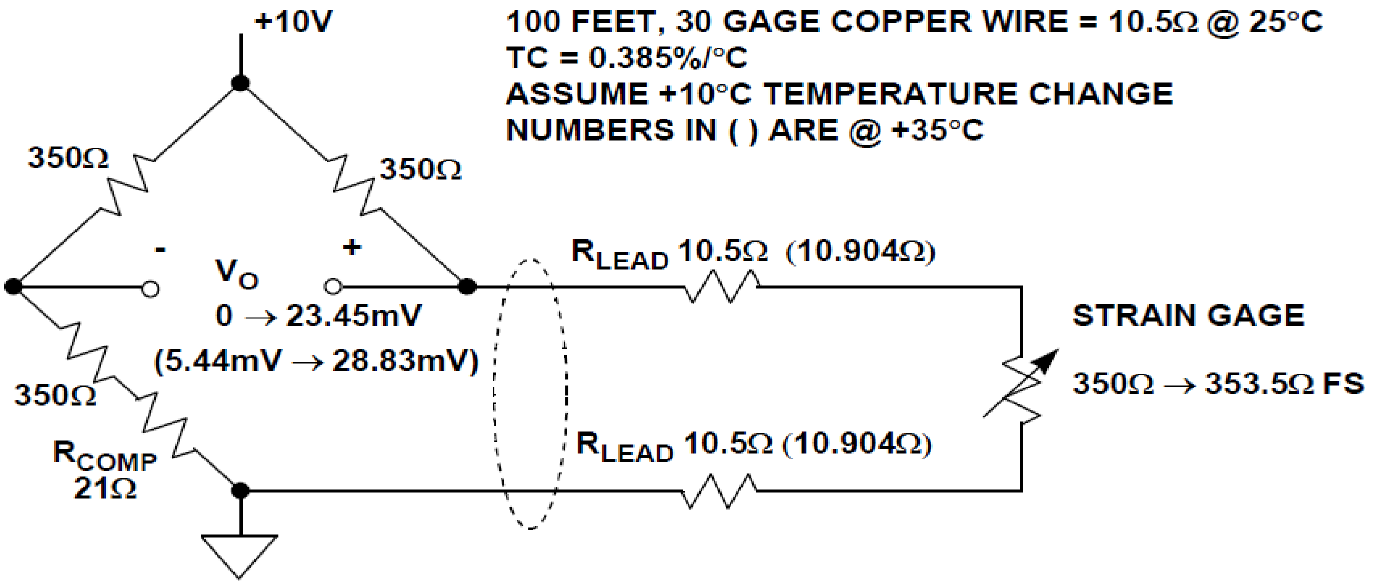
$$V_o = V_B\left(\frac{R_1}{R_1+R_4} - \frac{R_2}{R_2+R_3}\right) = 10\left(\frac{350+21}{700+21} - \frac{350}{700}\right) = 0.14563\,\text{V}$$

- When the load on the gauge is zero, the bridge would have an output offset voltage of **145.63mV** for a nominal strain gage resistance of 350Ω.



Errors Produced by Wiring Resistance in Remote Resistive Bridge Sensor

- **If a 21Ω compensating resistance R_{COMP}** is used as shown to compensate for the lead resistance, **Calculate the full scale bridge output at 25°C and the percentage zero error (offset error) and the sensitivity error (gain error) due to a +10°C temperature rise in the cable.**



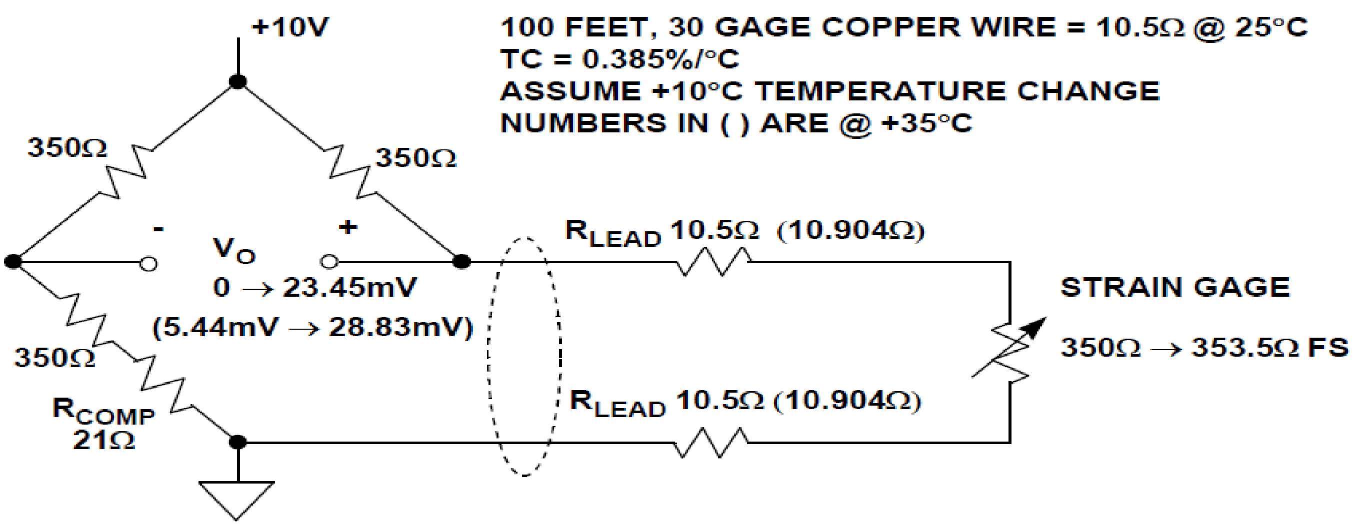
Errors Produced by Wiring Resistance in Remote Resistive Bridge Sensor

Full scale bridge output at 25°C

- **The full scale bridge output voltage takes place when the gauge resistance is of 350 Ω + (350 Ω × 1%) = 353.5 Ω**

$$V_o = V_B\left(\frac{R_1}{R_1+R_4}-\frac{R_2}{R_2+R_3}\right)=10\left(\frac{353.5+21}{703.5+21}-\frac{350+21}{700+21}\right)=0.02345$$

- The full scale output of the bridge at 25°C is **23.45 mV**.



Example: Errors Produced by Wiring Resistance in Remote Resistive Bridge Sensor

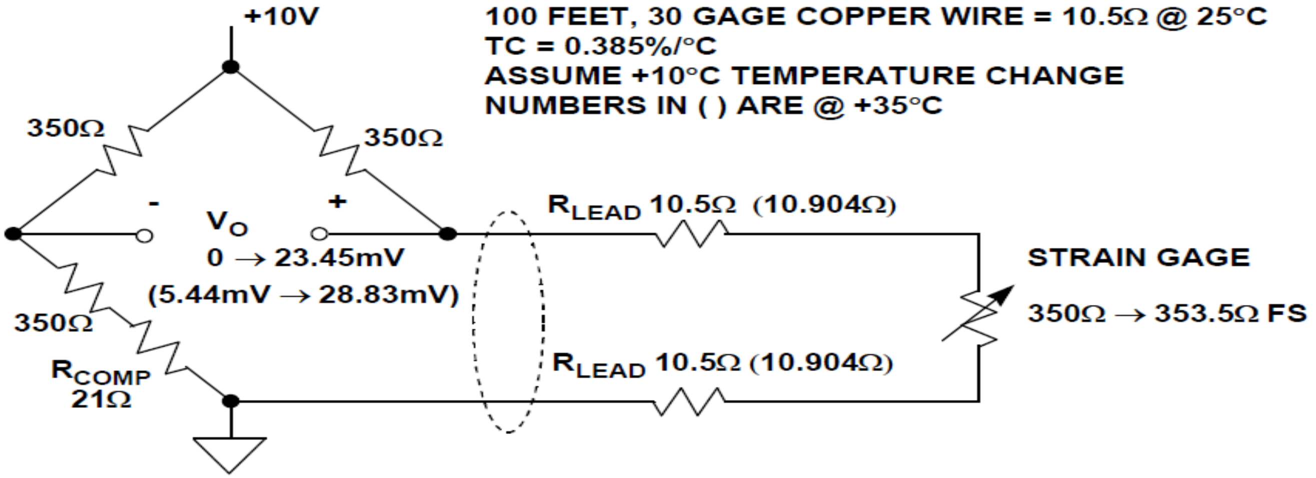
Zero error (zero offset) due to 10°C

With +10°C temperature rise, ΔR_{LEAD} = 10 × (0.385/100) × 10.5 = 0.404 Ω, R_{LEAD} = 10.5 Ω + 0.404 Ω = 10.904 Ω.

Total lead resistance in series with the gauge = 2 × 10.904 = 21.808

$$V_o = V_B\left(\frac{R_1}{R_1+R_4} - \frac{R_2}{R_2+R_3}\right) = 10\left(\frac{350+21.808}{700+21.808} - \frac{350+21}{700+21}\right) = 0.005434$$

With the compensating resistance, an offset error of 5.434 mV is present at 10°C temperature rise which is (5.343/23.45) **= 23.2%** of full scale output.



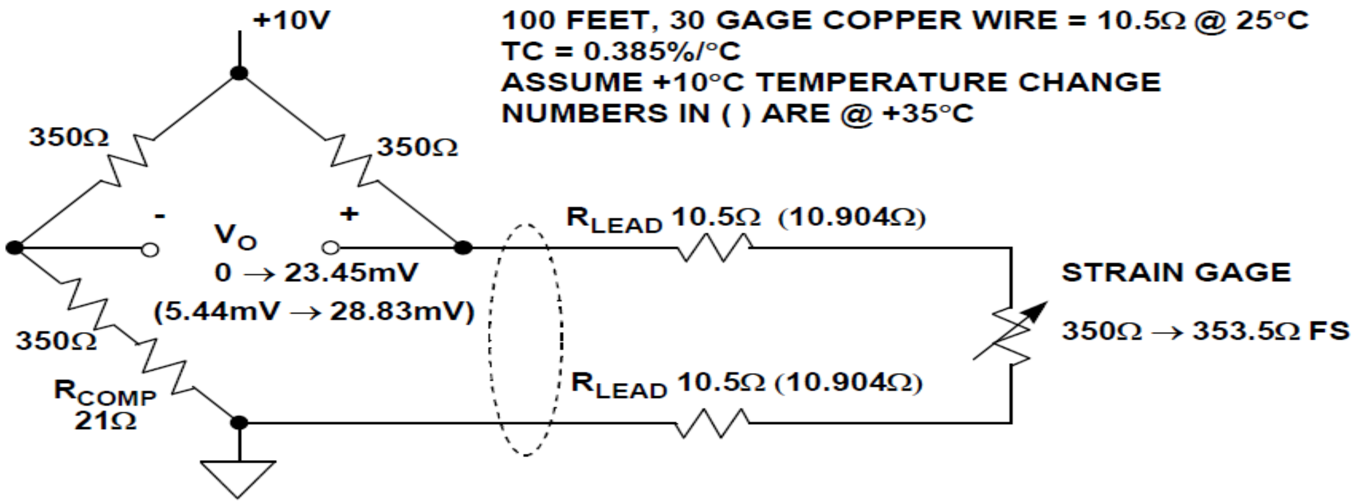
Errors Produced by Wiring Resistance in Remote Resistive Bridge Sensor

Gain error due to 10°C temperature rise

- The full scale bridge output at 35°C is calculated based on a gauge resistance of 350Ω + (350Ω × 1%) = 353.5Ω. The lead wire resistance, however, is (2 ×10.904Ω = 21.808Ω

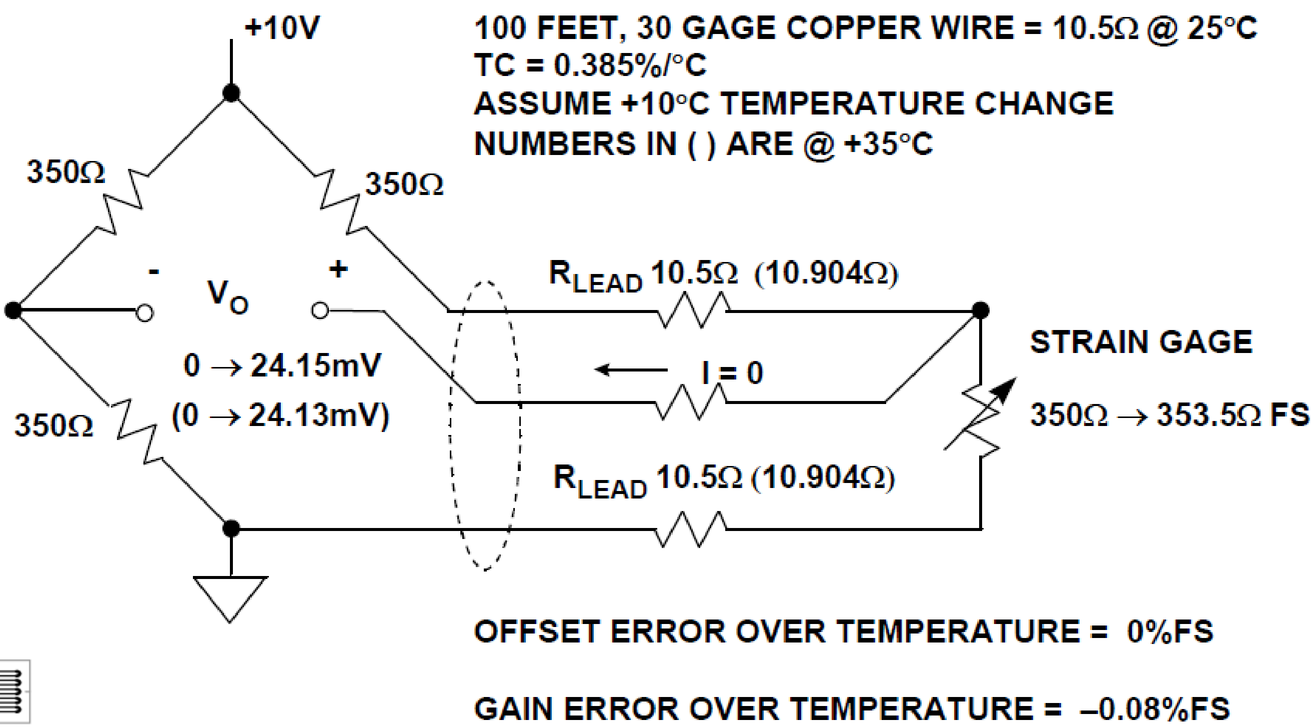
$$V_o = V_B\left(\frac{R_1}{R_1+R_4} - \frac{R_2}{R_2+R_3}\right) = 10\left(\frac{353.5+21.808}{703.5+21.808} - \frac{350+21}{700+21}\right) = 0.02883$$

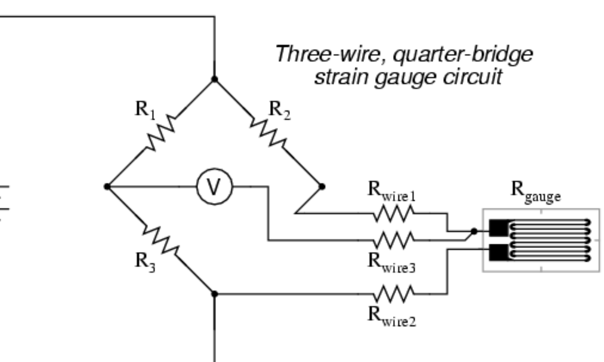
- The full scale output due to 10°C temp rise is 28.83 mV giving a deflection from zero load of (28.83 - 5.434 = 23.396 mV) with an error of (23.396 – 23.45 = -0.054 mV) or (-0.054/23.45) = -0.23% of full scale output



Error Reduction in remote single varying element bridge : Three Wire Sensing

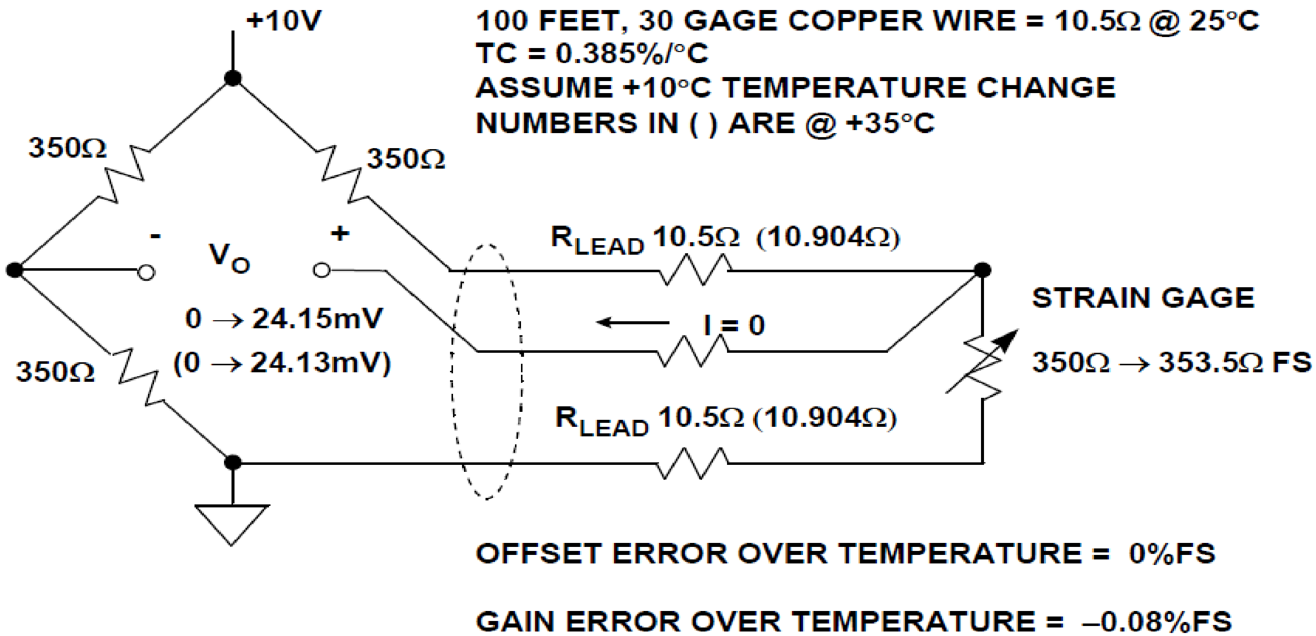
- The effects of wiring resistance on the bridge output can be minimized by the 3-wire connection.
- The sense lead measures the voltage output of a divider: the top half is the bridge resistor plus the lead resistance, and the bottom half is strain gage resistance plus the lead resistance.





Error Reduction in remote single varying element bridge : Three Wire Sensing

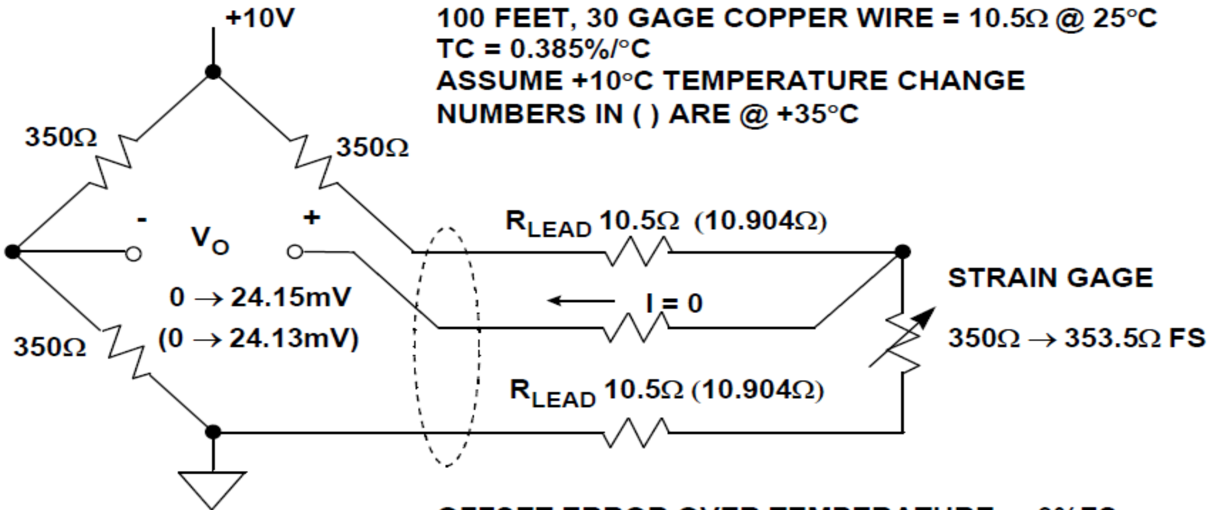
- The nominal sense voltage is independent of the lead resistance. When the strain gage resistance increases to full-scale (353.5Ω), the bridge output increases to +24.15mV.



Error Reduction in remote single varying element bridge : Three Wire Sensing

Gain error due to 10°C temperature rise

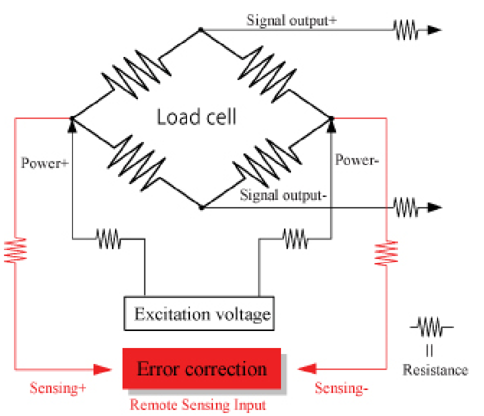
- Increasing the temperature to +35ºC increases the lead resistance by +0.404Ω in each half of the divider.
- The full-scale bridge output voltage decreases to +24.13mV because of the small loss in sensitivity, but there is no offset error. The gain error due to the temperature increase of +10ºC is therefore only –0.02mV, or –0.08% of full-scale.



Kelvin Sensing

(for all element varying Bridge)

- However, all-element varying bridges generally are housed in a complete assembly, as in the case of a load cell.
- When these bridges are remotely located from the conditioning electronics, special techniques must be used to maintain accuracy.
- **Of particular concern is maintaining the accuracy and stability of the bridge excitation voltage.**
- The bridge output is directly proportional to the excitation voltage, and any drift in the excitation voltage produces a corresponding drift in the output voltage.
- For this reason, most all-element varying bridges (such as load cells) are six-lead assemblies: two leads for the bridge output, two leads for the bridge excitation, and two *sense* leads.
- This method (called Kelvin or 4-wire sensing)

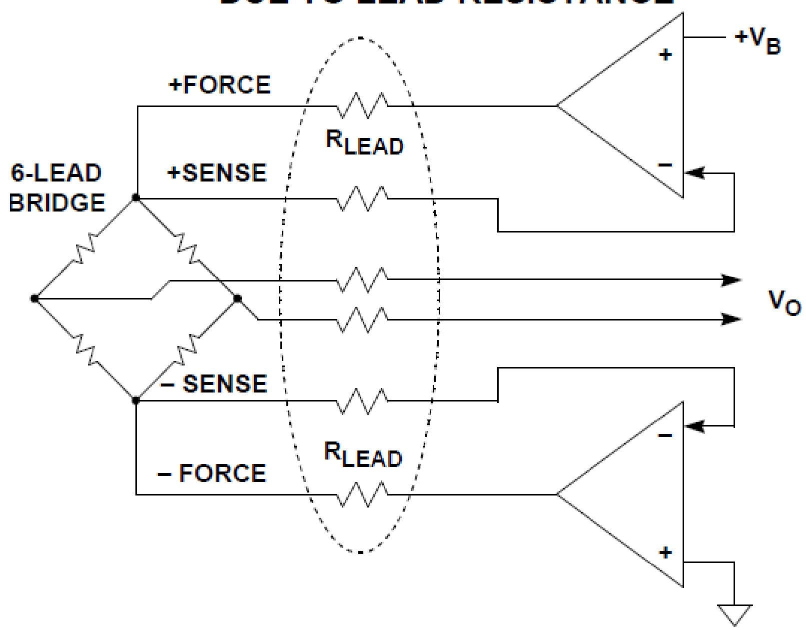


Kelvin Sensing

(for all element varying Bridge)

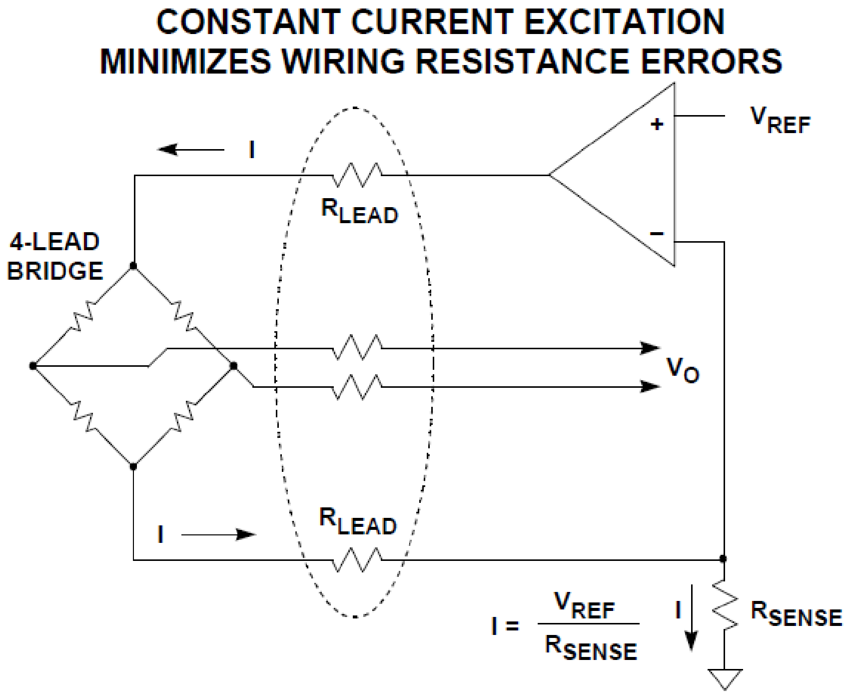
- This method (called Kelvin or 4-wire sensing) is shown in Figure
- The sense lines go to high impedance op amp inputs, thus there is minimal error due to the bias current induced voltage drop across their lead resistance.
- The op amps maintain the required excitation voltage to make the voltage measured between the sense leads always equal to VB.
- Although Kelvin sensing eliminates errors due to voltage drops in the wiring resistance, the drive voltages must still be highly stable since they directly affect the bridge output voltage.
- **In addition, the op amps must have low offset, low drift, and low noise.**

KELVIN (4-WIRE) SENSING MINIMIZES ERRORS DUE TO LEAD RESISTANCE



The constant current excitation

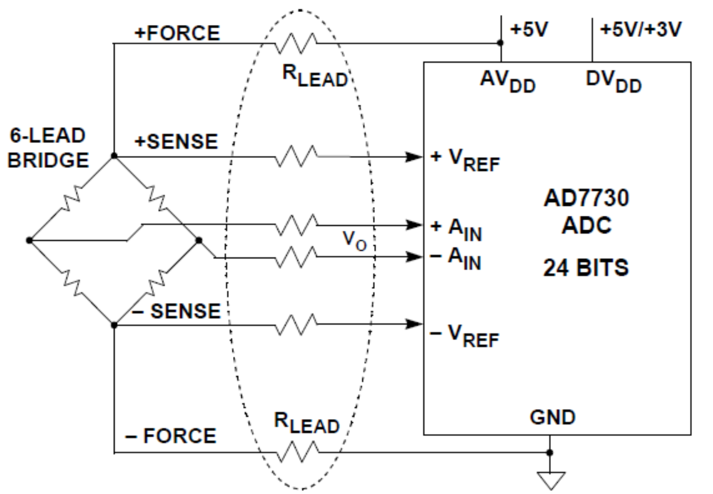
- The constant current excitation method shown in Figure is **another method for minimizing the effects of wiring resistance on the measurement accuracy**.
- However, the accuracy of the reference, the sense resistor, and the op amp all influence the overall accuracy.



Ratio-metric technique

- A very powerful *ratio-metric* technique which includes Kelvin sensing to **minimize errors due to wiring resistance and also eliminates the need for an accurate excitation voltage** is shown
- The AD7730 ADC can be driven from a single supply voltage which is also used to excite the remote bridge.
- Both the analog input and the reference input to the ADC are high impedance and fully differential.
- By using the + and – SENSE outputs from the bridge as the differential reference to the ADC, there is no loss in measurement accuracy if the actual bridge excitation voltage varies.

DRIVING REMOTE BRIDGE USING KELVIN (4-WIRE) SENSING AND RATIOMETRIC CONNECTION TO ADC



Extra S/C example

Temperature is to be measured in the range of 250°C to 450°C with an accuracy of ±2°C. The sensor is a resistance that varies linearly from 280 Ω to 1060 Ω for this temperature range. Power dissipated in the sensor must be kept below 5 mW. Develop analog signal conditioning that provides a voltage varying linearly from −5 to +5 V for this temperature range. The load is a high-impedance recorder.

Extra S/C example

Temperature is to be measured in the range of 250°C to 450°C with an accuracy of ±2°C. The sensor is a resistance that varies linearly from 280 Ω to 1060 Ω for this temperature range. Power dissipated in the sensor must be kept below 5 mW. Develop analog signal conditioning that provides a voltage varying linearly from −5 to +5 V for this temperature range. The load is a high-impedance recorder.

Solution

Following the guidelines, let us first identify all the elements of the problem.

Measured Variable Parameter: Temperature

Range: 250° to 450°C

Accuracy: ±2°C

Noise: unspecified

Sensor Signal

Parameter: resistance

Transfer function: linear

Time response: unspecified

Range: 280 Ω to 1060 Ω, linear

Power: maximum 5 mW dissipated in sensor

Signal Conditioning

Parameter: voltage, linear

Range: −5 to +5 V

Input impedance: keep power in sensor below 5 mW

Output impedance: no problem, high-impedance recorder

The accuracy is ±0.8% at the low end and ±0.44% at the high end. Therefore, we will keep three significant figures to provide 0.1% on values selected.

The 5-mW maximum sensor dissipation means the current must be limited. To find the maximum current, we note that

$$P = I^2 R$$

$$0.005 = I^2 R$$

$$I = \sqrt{0.005/R}$$

The minimum current will thus occur at the maximum resistance,

$$I_{max} = \sqrt{0.005/1060} = 2.17\,\text{mA}$$

Thus, the design must always keep the sensor current below 2 mA.

Since the system must be linear, we should set up a linear equation between the sensor resistance and the output voltage. Then it is a matter of determining what circuits will implement the equation.

$$V_{out} = mR_s + V_0$$

We solve for m and V_0 by using the given information,

$$-5 = 280m + V_0$$

$$+5 = 1060m + V_0$$

Subtracting the first equation from the second gives

$$10 = 780m \quad \text{or} \quad m = 0.0128$$

Then, using this in the first equation,

$$-5 = 280(0.0128) + V_0$$
$$V_0 = -8.58$$

So the transfer function equation is

$$V_{out} = 0.0128R_s - 8.58$$

This can be provided by an inverting amplifier with the sensor resistor in the feedback, followed by an inverting summer to get the signs correct. Figure 47 shows one possible so-

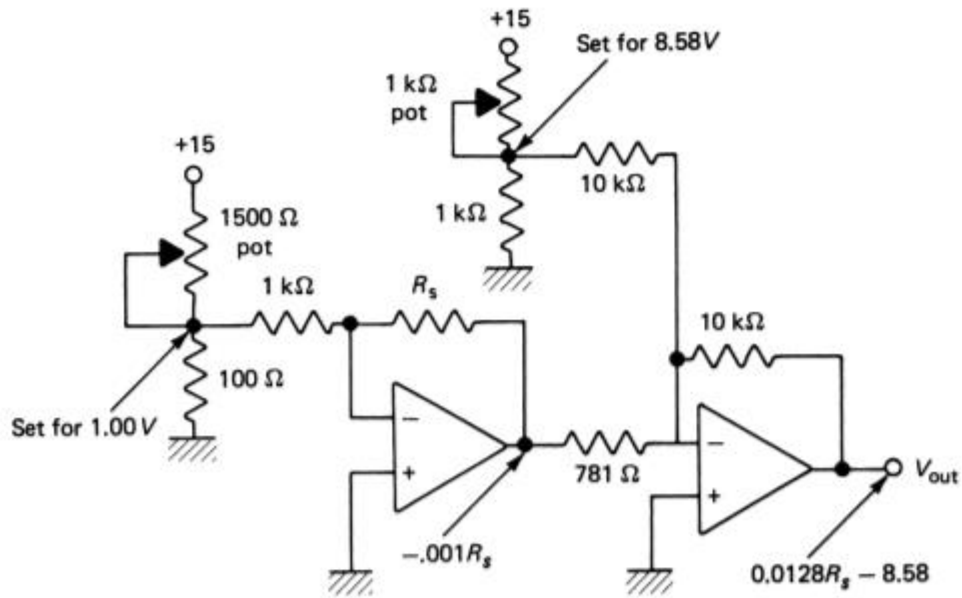
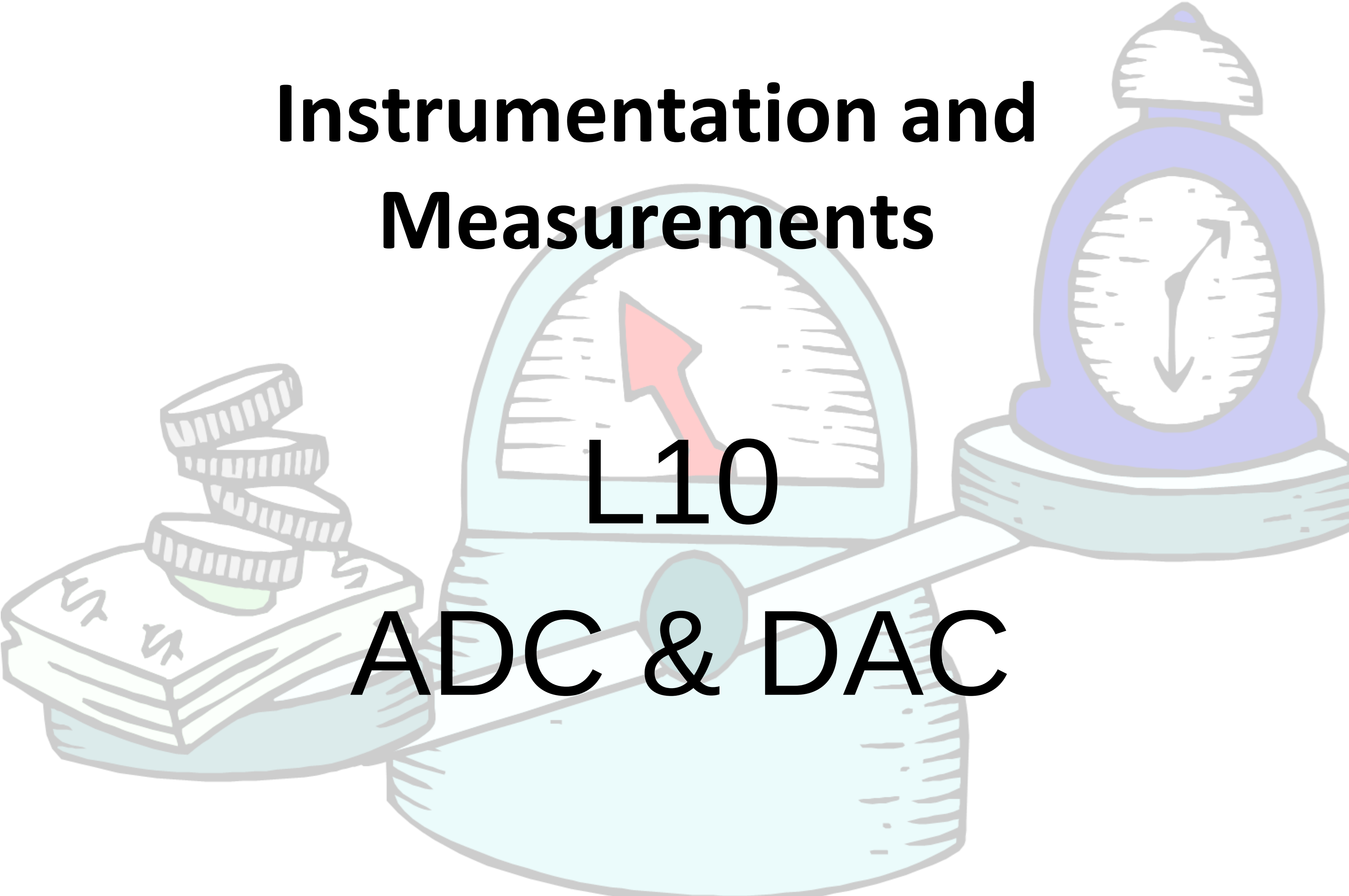


FIGURE 47
One possible solution for Example 25.

lution. The fixed input voltage and input resistor of the first op amp have been selected to satisfy the 5-mW maximum power dissipation. This has been done by noting that the current through the sensor is just equal to the current through the input circuit. Thus, by using 1.00 kΩ and 1.00 V, the current will always be 1 mA and thus less than 2 mA, as required.

As in Example 24, trimmers are used in dividers so the fixed voltages can be adjusted to 1.00 and 8.58 V and thus account for supply voltage differences. The alternative would be to use a zener diode as the source.

Instrumentation and Measurements



L10

ADC & DAC

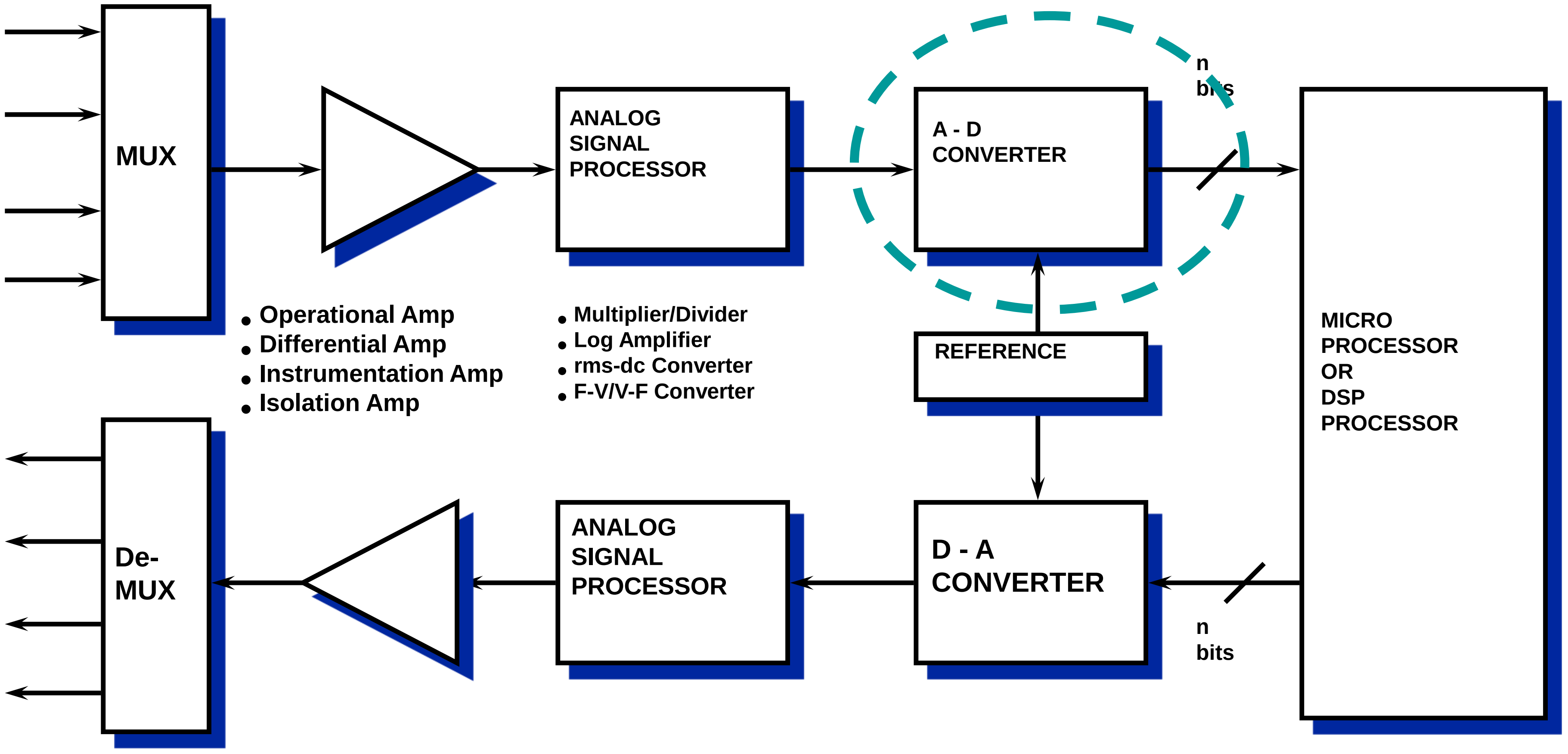
Outline

- Digital Signal Processing:
- Sampling;
- Sample and Hold;
- Analog to Digital Conversion;
- Digital to Analog Conversion.

Introduction

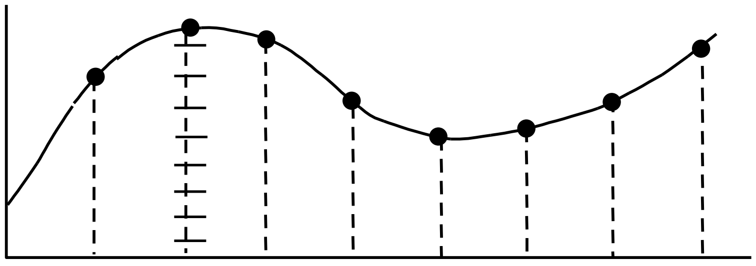
- Most Instrumentation systems include a digital processing device (PC, Microprocessor, DSP, Microcontroller….)
- These devices require information in digital format (binary, grey code, signed 2's complement , BCD…..etc)
- This requires some form of digitizer, or *analog-to-digital converter (ADC)*
- An ADC converts real-world signals (usually voltages) into digital numbers so that a computer or digital processor can (1) acquire signals automatically, (2) store and retrieve information about the signals, (3) process and analyze the information, and (4) display measurement results.

The Measurement & Control Loop



- The two main functions of an ADC are ***sampling*** and ***quantization***
- These two processes convert analog signals into digital numbers having discrete amplitudes, at discrete times.
- To represent changing signals at every instant in time or at every possible voltage would take an infinite amount of storage.

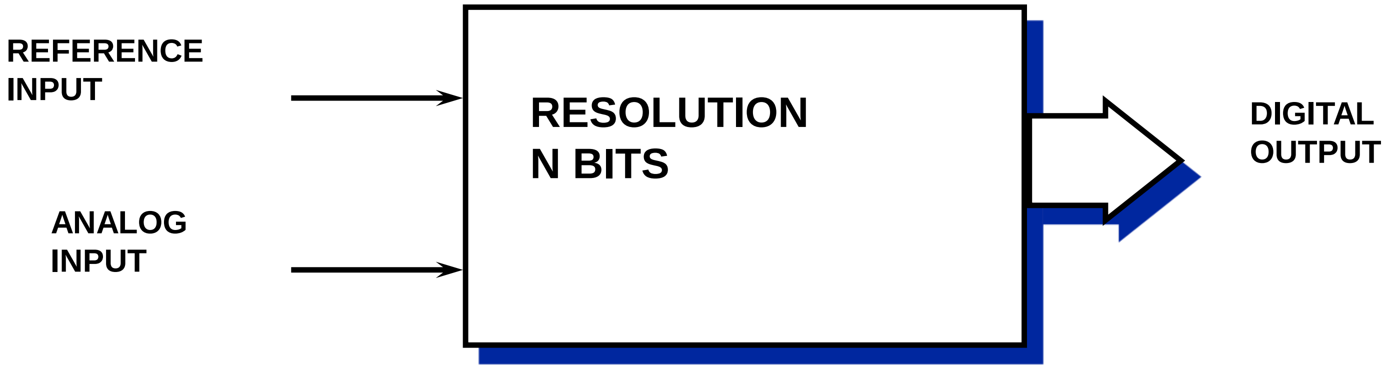
ADC SAMPLED AND QUANTIZED WAVEFORM



Sampling & Quantization

- For every system there is an appropriate ***sampling rate*** and ***degree of quantization (resolution)*** so that the system retains as much information as it needs about the input signals
- Ultimately, the purpose of sampling and quantization is to reduce as much as possible the amount of information about a signal that a system must store in order to reconstruct or analyze it meaningfully.

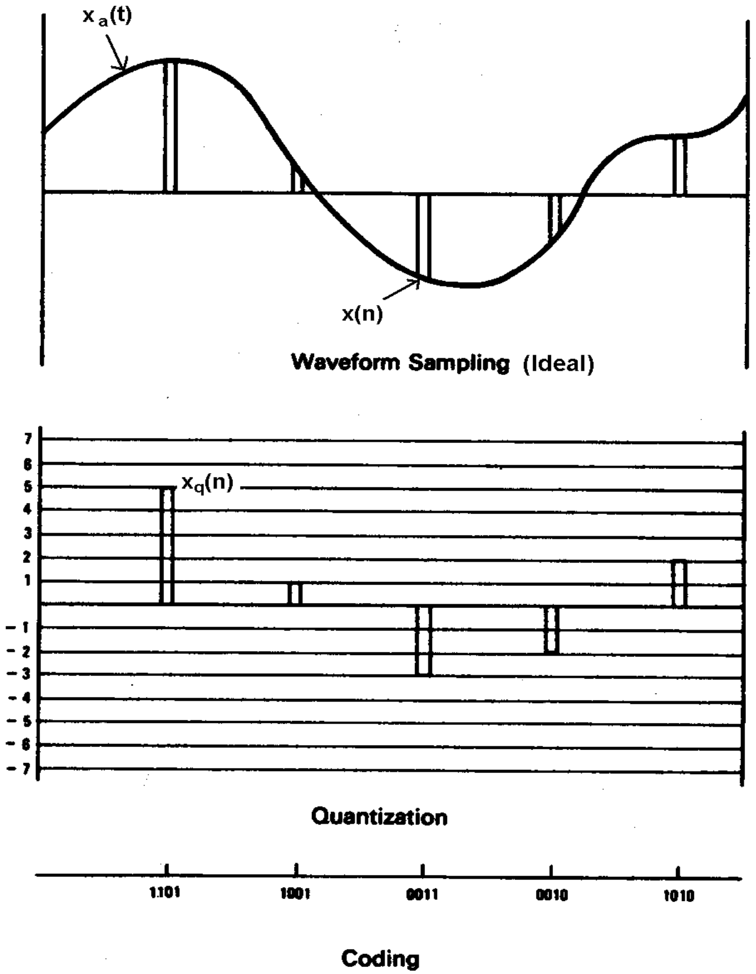
What is an Analog-Digital Converter?



- A devise that produces a Digital Output Corresponding to the Value of the Signal Applied to Its Input Relative to a Reference Voltage
- Finite Number of Discrete Values : 2^N Resulting in Quantization Uncertainty (N defines the resolution)
- Sampling and Quantization Impose Fundamental yet Predictable Limitations

Sampling

- **Sampling is the process of picking one value of a signal to represent the signal for some interval of time.**
- Sampling can be done at regular (constant) or variable rate.



- Sampling is done by a circuit called a *sample-and-hold (S/H)* , which, at a sampling instant, transfers the input signal to the output and holds it steady, even though the input signal may still be changing.
- Most modern ADC chip has a built-in S/H or T/H, and virtually all data acquisition systems include them.
- Of course, sampling necessarily throws away some information, so the art of sampling is in choosing the right sample rate so that enough of the input signal is preserved.

Minimum sampling rate (Nyquest Rate)

- **Nyquest criterion states that the sampling rate must be at least twice the highest frequency of the signal of interest:**

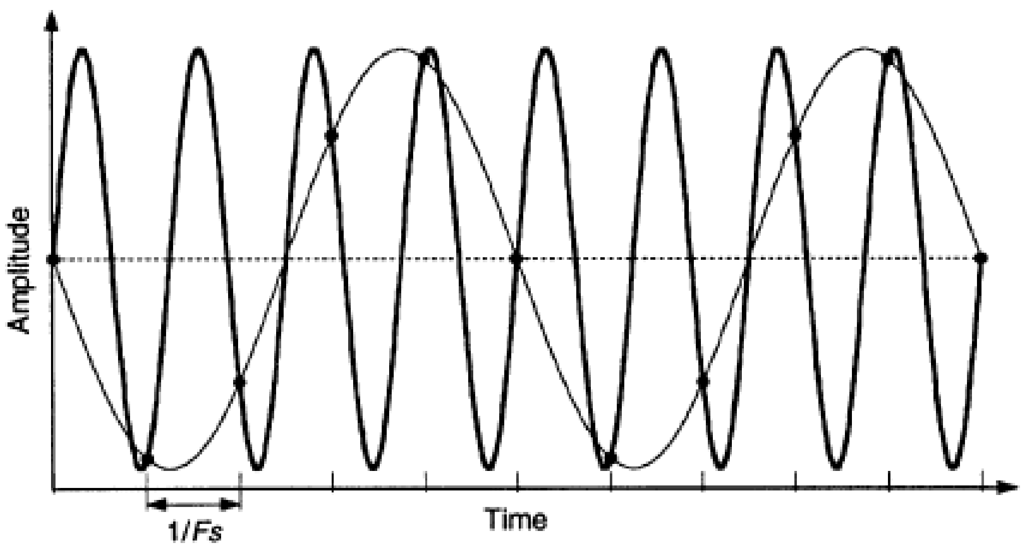
$$f_{sampling} > 2f_{signal}$$

- **Nyquest criterion guarantees the preservation of the frequency content of the signal, but not the time dependency**
- **In order to be able to reconstruct the signal in time domain, as a rule of thump , we use : fsampling > 10*fsignal**
- Aliasing occurs when the sampling is done at a rate less than Nyquest rate

Minimum sampling rate (Nyquest Rate)

- Sample rates are specified in samples/s, or S/s, and it is also common to specify rates in kS/s, MS/s, and even GS/s.
- It is not always necessary to worry about **aliasing**.
- When an instrument is measuring slow-moving dc signals or is gathering data for statistical analysis, for instance, getting frequencies right is not important.

aliasing



- In those cases

we choose the sample rate so that we can take enough data in a reasonable amount of time.

Antialias Filter

- On the other hand, if the instrument is a spectrum analyzer, where frequency does matter, or an oscilloscope, where fine time detail is needed, aliasing certainly is an issue.
- When aliased signals from beyond the frequency band of interest can interfere with measurement, an instrument needs to have an *antialias filter* before the S/H.
- An antialias filter is a low-pass filter with a gain of 1 throughout most of the frequency band of interest.
- As frequency increases, it begins to attenuate the signal; by the Nyquist frequency it must have enough attenuation to prevent higher-frequency signals from reaching the S/H with enough amplitude to disturb measurements.

Quantization

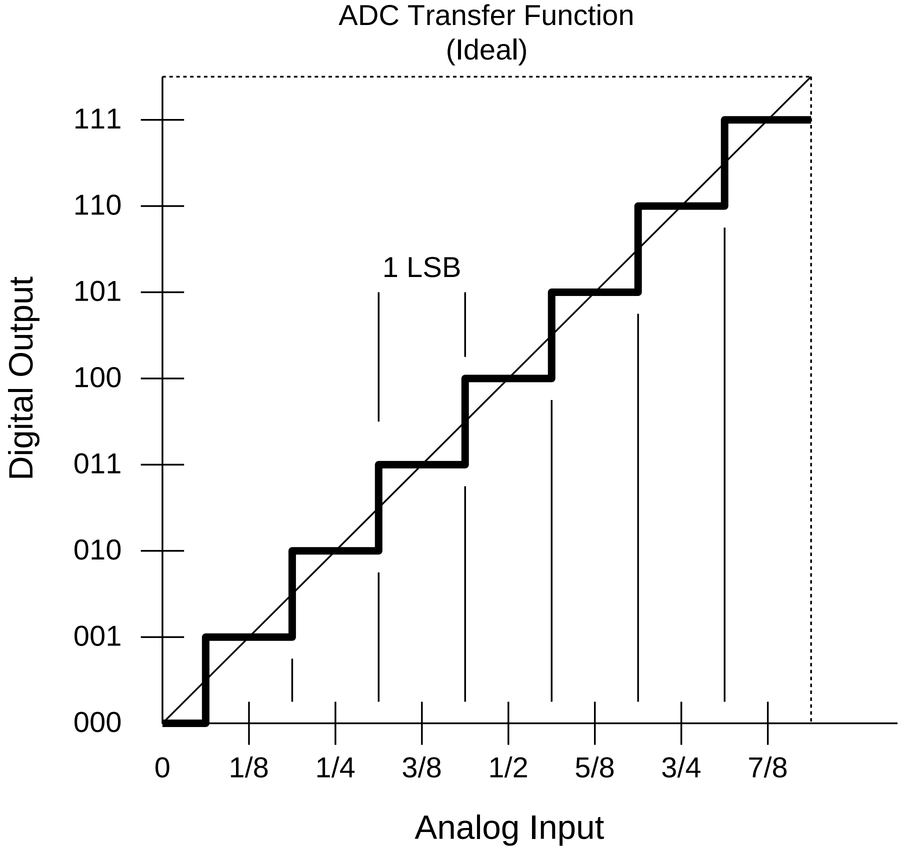
- **Quantization is the second step in ADC in which the samples are converted into equivalent digital value**
- What sampling accomplishes in the time domain, quantization does in the amplitude domain
- Conversion takes finite time , and next sample cannot be taken before the last sample conversion is completed.
- The smaller the intervals between the samples, the higher the sampling rate (sampling frequency)

Quantization

- An ADC quantizes a sampled signal by picking one integer value from a predetermined, finite list of integer values to represent each analog sample.
- Each integer value in the list represents a fraction of the total analog input range.
- Normally, an ADC chooses the value closest to the actual sample from a list of uniformly spaced values.
- **This rule gives the *transfer function* of analog input to- digital output a uniform "staircase" characteristic.**

- Figure represents a three-bit quantizer, which maps a continuum of analog input values to only eight (2^3) possible output values.
- Each step in the staircase has (ideally) the same width along the *x* -axis, which we call *code width* and define as 1*LSB (least significant bit)*

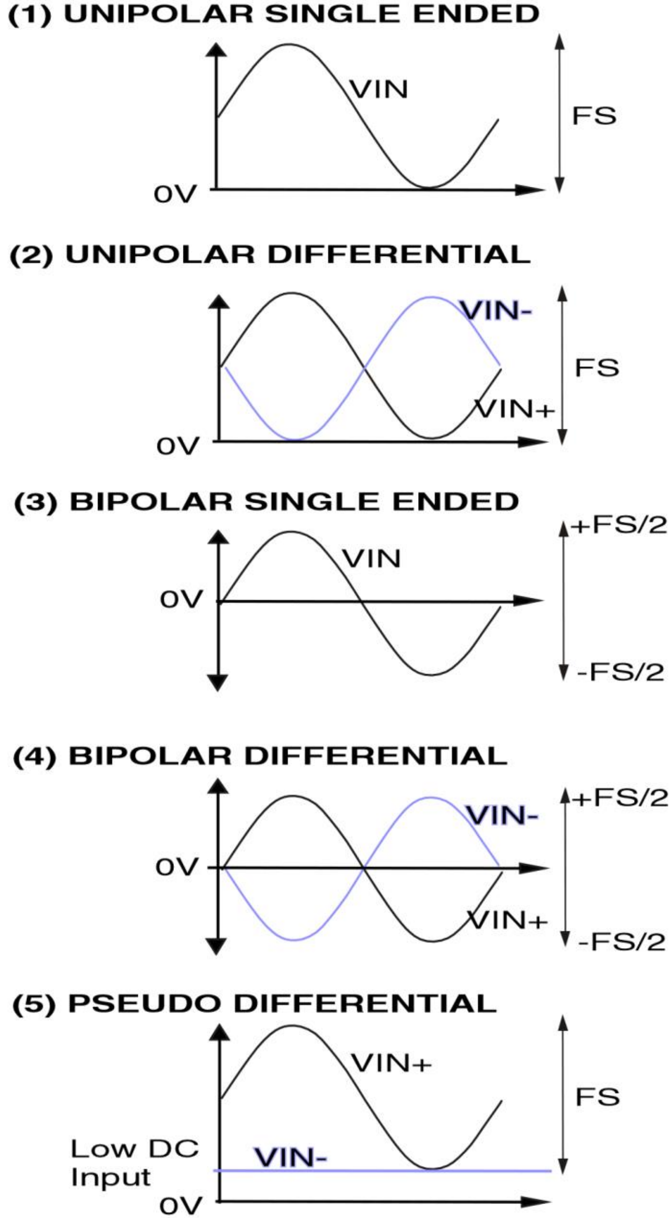
- In this case 1 LSB is equal to 1/8 V. Each digital code corresponds to one of eight 1-LSB intervals making up the analog input range, which is 8 LSB (and also 1 V in this case).



ADC Specifications

- 1. Range: The input range of ADC is the span of voltage over which the ADC can make conversion
- The end points at the bottom and the top of the range are called –*full-scale* and + *full-scale* , respectively.
- When –full-scale = 0 V the range is called *unipolar*
- when –full-scale is a negative voltage of the same magnitude as +full-scale the range is said to be *bipolar*
- **When the input voltage exceeds the input range, the conversion data are certain to be wrong**, and most ADCs report the code at the end point of the range closest to the input voltage.
- This condition is called an *over-range*

Analog Input Signal Definitions



FS - FULL SCALE

- $Range = V_{FSR} = +Full\ Scale\ - (-Full\ Scale)$
- For Example : Unipolar 0 to 15 V

  Range=15-0=15V
- Bipolar : -5V to +5V

  Range =5-(-5)=10 V

- **2)The resolution** of an ADC is the smallest change in voltage the ADC can detect, which is inherently **1 LSB**.
- It is customary to refer to the resolution of an ADC by the number of binary bits or decimal digits it produces; for example, “12 bits” means that the ADC can resolve one part in 2 ^12 (= 4096).
- In the case of a digital voltmeter that reads decimal digits, we refer to the number of digits that it resolves.
- A “6-digit” voltmeter on a 1 V scale measures from

–0.999999 V to +0.999999 V in 0.000001 V steps; it resolves one part in 2 000 000.

- It is also common to refer to a voltmeter that measures from –1.999999 to +1.999999 as a “6 ½digit” voltmeter.

- Resolution of ADC is the smallest detectable change in voltage ; however some refer to number of bits as resolution
- $\Delta = LSB = Q = \frac{V_{FSR}}{2^n}$
- Example : 8 bit ADC with a range 0-2.5 V input

$\Delta = LSB = Q = \frac{2.5}{2^8} = \frac{2500mV}{256}$=9.765 mV

Or as % $\Delta = \frac{9.765}{2500} * 100\% = 0.3906\%$

Or 0.003906 ➔ 3906 ppm (parts per million)

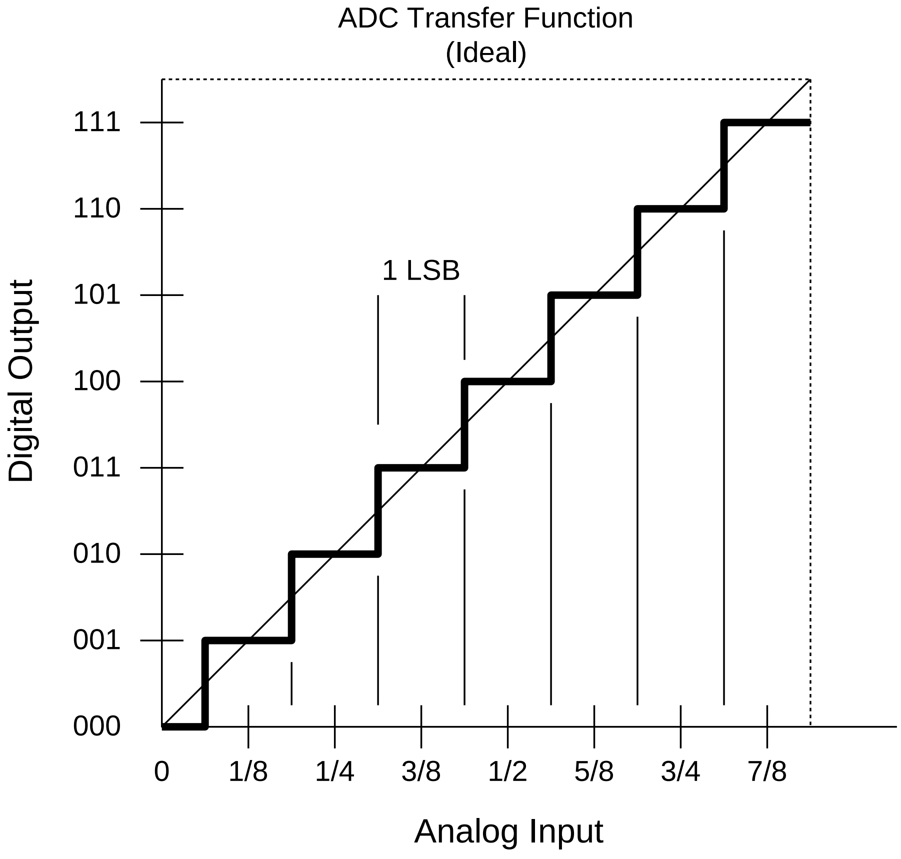
ADC Resolution vs. Quantization Parameters

Resolution, Bits (n)	2^n	LSB, mV (2.5V FS)	% Full Scale	ppm Full Scale	dB Full Scale
8	256	9.77	0.391	3906	-48.0
10	1024	2.44	0.098	977	-60.0
12	4096	0.610	0.024	244	-72.0
14	16,384	0.153	0.006	61	-84.0
16	65,536	0.038	0.0015	15	-96.0
18	262,164	0.0095	0.00038	3.8	-108.0

- Higher n gives better resolution

DC Specifications (Ideal-midtread linear type)

- 3 bit, 0-1 V range
- There are 2^3 codes.
- For this 3-bit ADC, 1 LSB = ($1V/2^3$ = 1/8th)
- Each "step" is centered on an eighth of full scale
- $ADC_{CODE} = Round\left(\frac{2^n}{V_{FSR}}.Vin\right)$



Example

- A 5 bit ADC with a 0-5V input range have a 3.127V input signal at its input, what is the output **binary code** at the output?
- Solution:
- $ADC_{CODE} = Round\left(\frac{2^5}{5}.3.127\right)$=$(20)_{10}$
- $(20)_{10}$ =$(10100)_2$

Example

- Given a sensor with 0.02 V / degree C sensitivity, choose a suitable size ADC with V_{FSR}=2V such that to be able to measure 0-100 deg C with :
- a) 1 deg C resolution
- b) 0.1 $\deg C$ resolution
- <u>**Solution:**</u>
- 0 deg C => 0.0 V
- 100 deg C => 100x 0.02=2V
- We have an ADC with V_{FSR}= 2 V range
- For 1 deg C resolution , ADC resolution Δ = 0.02 V
- $\Delta = 0.02V = \frac{V_{FSR}}{2^n} = \frac{2}{2^n} \Longrightarrow 2^n$=100==> n =$\log_2(100)$=6.644
- N must be an integer, so we choose n=7

Example

sensor output matched to ADC input

- For 0.1 deg C resolution , ADC resolution Δ = 0.002 V
- $\Delta = 0.002V = \frac{V_{FSR}}{2^n} = \frac{2}{2^n} ==\Rightarrow 2^n$=1000==> n =$\log_2$(1000)=9.97
- N must be an integer, so we choose n=10

Example: ADC range 5 V

(not matched by sensor output "2V")

- **Solution:**
- 0 deg C => 0 V ; 1 deg C ➔ 0.02V
- 100 deg C => 100x 0.02=2V
- Suppose we have an ADC with V_{FSR}= 5 V range
- For 1 deg C resolution , ADC resolution Δ = 0.02 V
- $\Delta = 0.02V = \frac{V_{FSR}}{2^n} = \frac{5}{2^n} \Longrightarrow 2^n$=250==> n =$\log_2$(250)=7.96
- N must be an integer, so we choose n=8
- For 0.1 deg C resolution , ADC resolution Δ = 0.002 V
- $\Delta = 0.002V = \frac{V_{FSR}}{2^n} = \frac{5}{2^n} \Longrightarrow 2^n$=2500==> n =$\log_2$(2500)=11.3
- N must be an integer, so we choose n=12
-

Example: ADC range 5 V

(matched by sensor output through S/C block)

- **Solution:** **S/C**
- 1 deg C => 0.02V ===> **multiplied by 2.5 ==> 0.05 V**
- 100 deg C => 100x 0.02=2V **===> X 2.5 = 5V**
- Suppose we have an ADC with V_{FSR}= 5 V range
- For 1 deg C resolution , ADC resolution Δ = 0.02 V
- $\Delta = 0.05V = \frac{V_{FSR}}{2^n} = \frac{5}{2^n} \Longrightarrow 2^n$=100==> n =$\log_2$(250)=6.64
- N must be an integer, so we choose n=7
- For 0.1 deg C resolution , ADC resolution Δ = 0.005 V
- $\Delta = 0.005V = \frac{V_{FSR}}{2^n} = \frac{5}{2^n} \Longrightarrow 2^n$=1000==> n =$\log_2$(1000)=9.96
- N must be an integer, so we choose n=10

Conclusion about range matching

- When the ranges are not matched, higher number of bits “n” is required to achieve higher measurement resolution
- When we match the output range of the sensor to the input range of ADC, we can get better resolution of a given ADC with given number of bits

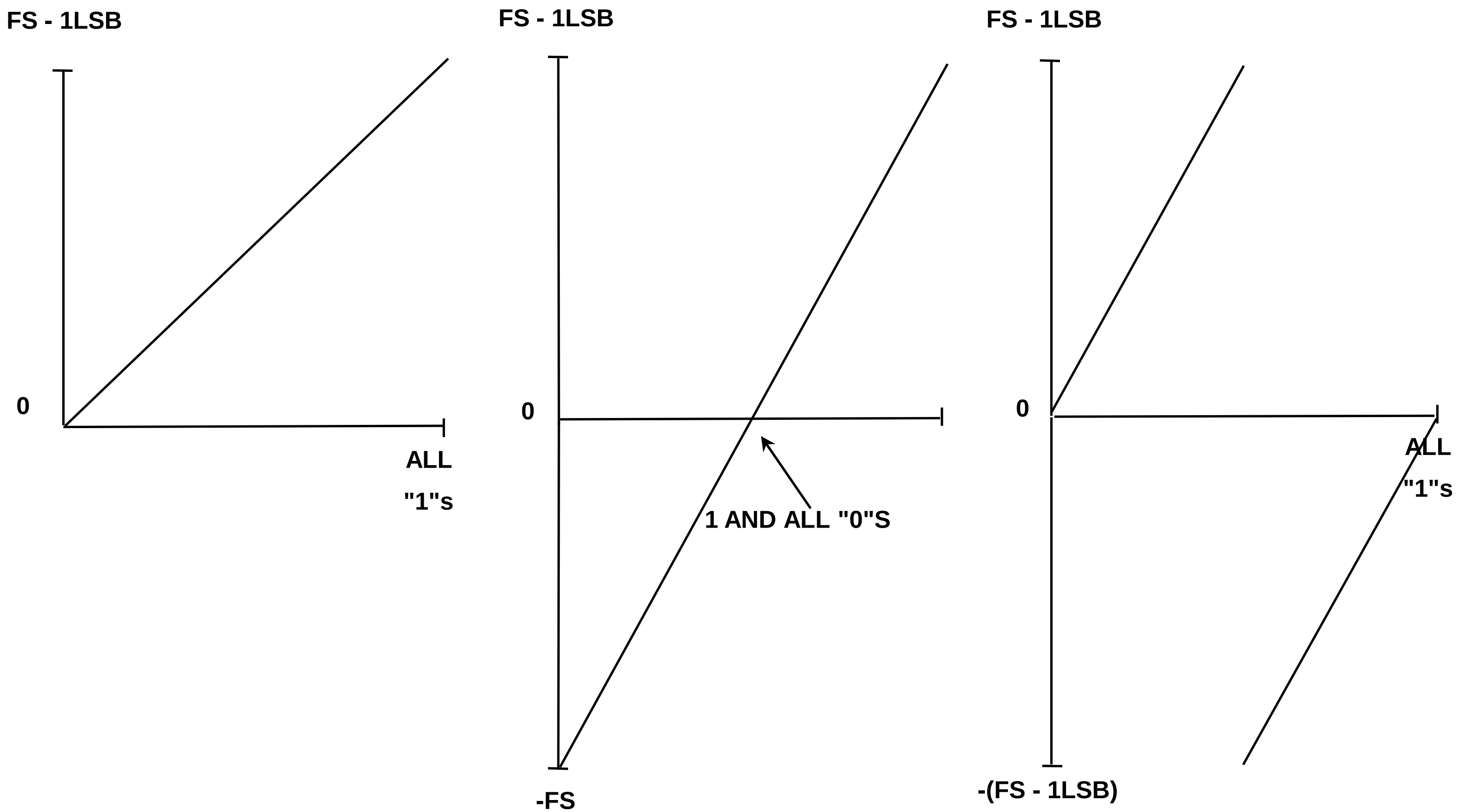
Coding Conventions

- There are several different formats for ADC output data:
  - Unipolar
  - Bipolar
- An ADC using *binary* coding produces all 0s (e.g., 000 for the three-bit converter) at –full-scale and all 1s (e.g., 111) at +full-scale.
- If the range is bipolar, so that –full-scale is a negative voltage, binary coding is sometimes called *offset binary* since the code 0 does not refer to 0 V.
- To make digital 0 correspond to 0 V, bipolar ADCs use *two's complement* coding, which is identical to offset binary coding except that the *most significant bit (MSB)* is inverted, so that 100 … 00 corresponds to –full-scale, 000 … 00 corresponds to 0 V (*midscale*), and 011 … 11 corresponds to +full-scale.

Coding Conventions-BCD

- Decimal-digit ADCs, such as those used in digital voltmeters, use a coding scheme call *binary-coded decimal (BCD)*
- BCD data consists of a string of four-bit groups of binary digits.
- Each four-bit group represents a decimal digit, where 0000 is 0, 0001 is 1, and so on, up to 1001 for 9.
- The other six combinations (1010 through 1111) are invalid, or can be used for special information, such as the sign of the conversion.

Unipolar and Bipolar Converter Codes



UNIPOLAR

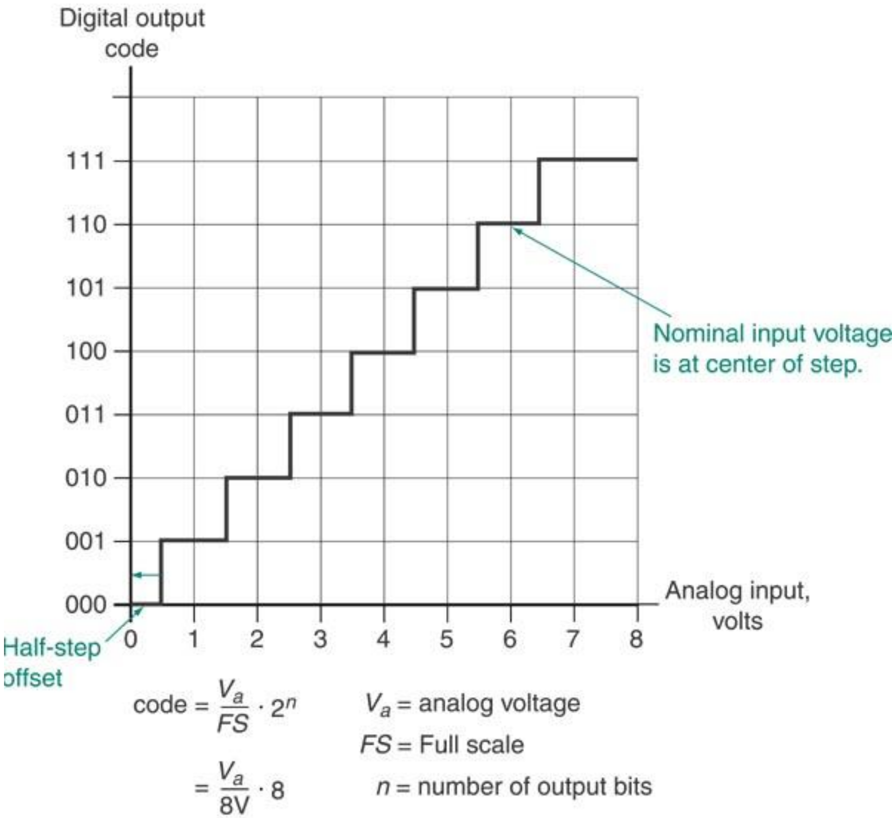
OFFSET BINARY

2's COMPLEMENT

Unipolar ADC Code Equation

$$\text{code} = \frac{V_a}{V_{FS}} \times 2^n$$

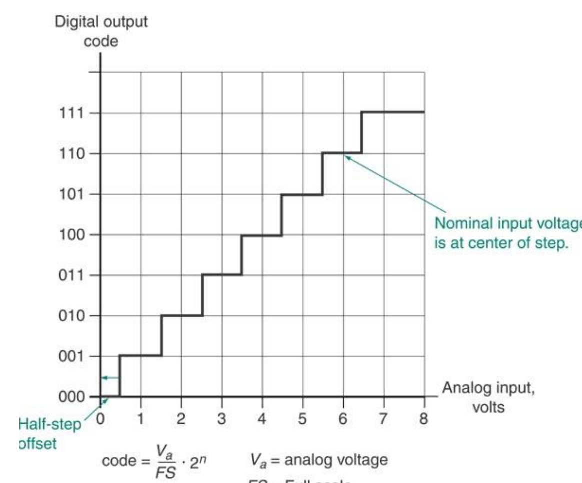
- V_a = analog input voltage to be sampled.
- V_{FS} = Full scale range of input voltage.
- n = number of bits in the output code.



Unipolar ADC Output Codes

Nominal Voltage of Input Step (volts)	Range (volts)	Output Code
0.0	0.0 - 0.5	000
1.0	0.5 - 1.5	001
2.0	1.5 - 2.5	010
3.0	2.5 - 3.5	011
4.0	3.5 - 4.5	100
5.0	4.5 - 5.5	101
6.0	5.5 - 6.5	110
7.0	6.5 - 8.0	111

$$\text{code} = \frac{V_a}{V_{FS}} \times 2^n$$

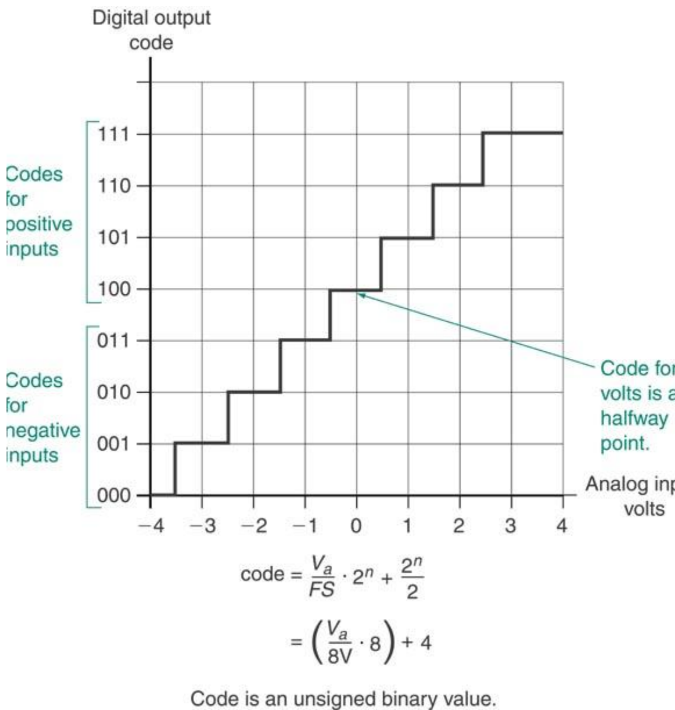


Bipolar ADC (Offset Binary Coding)

- Used to represent positive and negative input voltages.
- Output code an unsigned binary number.
- Numbers below 0 V are negative.
- Numbers above 0 V are positive.

$$\text{code} = \left(\frac{V_a}{V_{FS}} \times 2^n \right) + \text{offset}$$

$$= \left(\frac{V_a}{V_{FS}} \times 2^n \right) + \frac{2^n}{2}$$

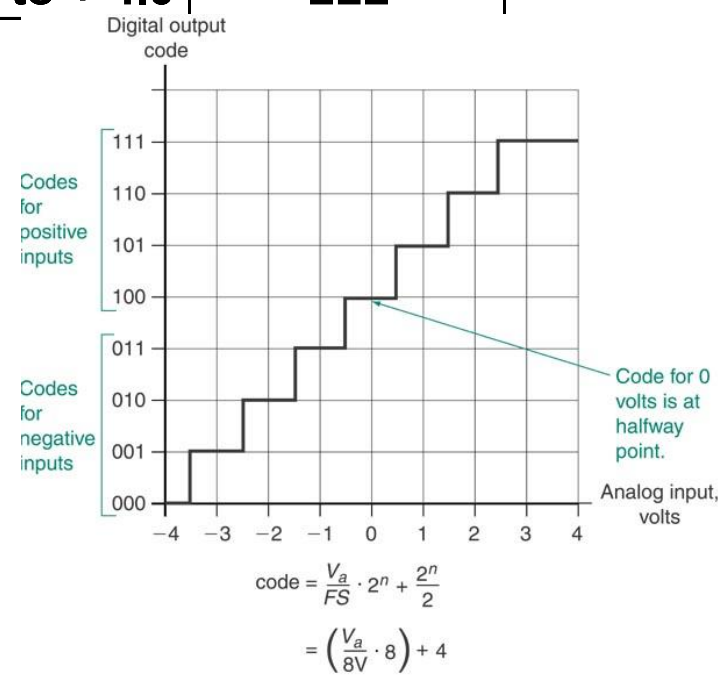


Bipolar ADC Output Codes

- 4.0	- 4.0 to - 3.5	000
- 3.0	- 3.5 to - 2.5	001
- 2.0	- 2.5 to - 1.5	010
- 1.0	- 1.5 to - 0.5	011
0	- 0.5 to + 0.5	100
+ 1.0	+ 0.5 to + 1.5	101
+ 2.0	+ 1.5 to + 2.5	110
+ 3.0	+ 2.5 to + 4.0	111

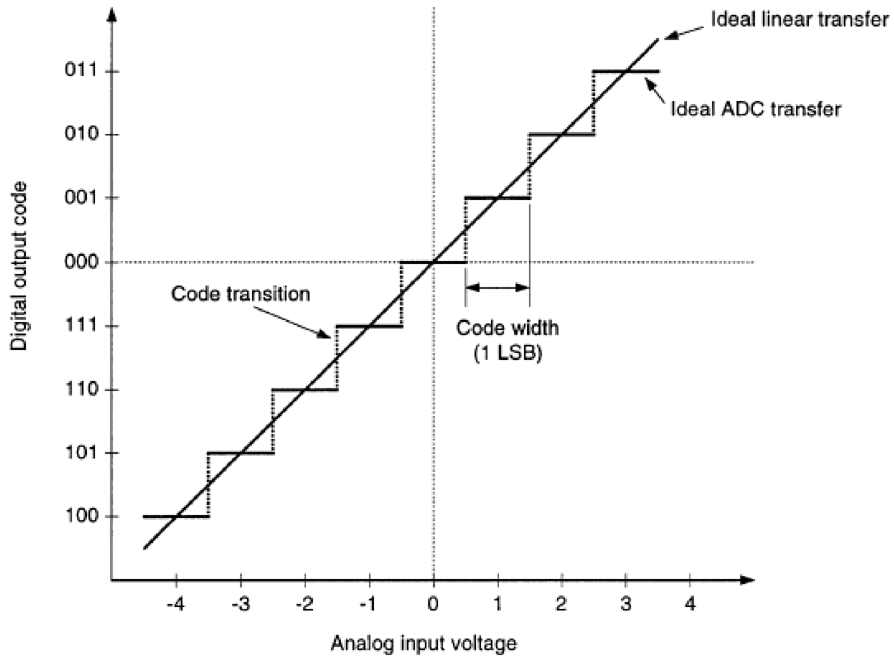
$$\text{code} = \left(\frac{V_a}{V_{FS}} \times 2^n \right) + \text{offset}$$

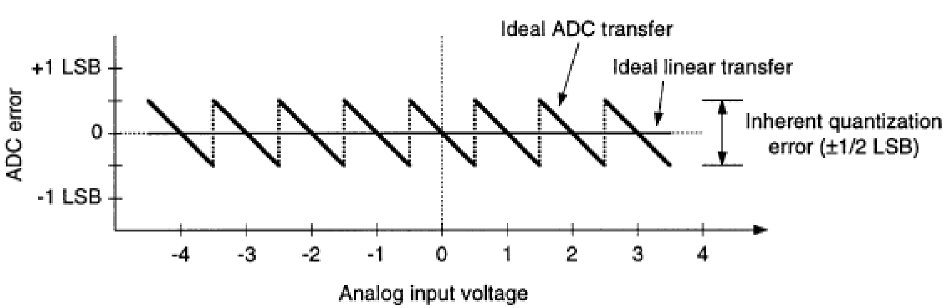
$$= \left(\frac{V_a}{V_{FS}} \times 2^n \right) + \frac{2^n}{2}$$



- # Accuracy: ADC has several sources of error

- A) Quantization error $\Delta_e = \mp \frac{1}{2} LSB$



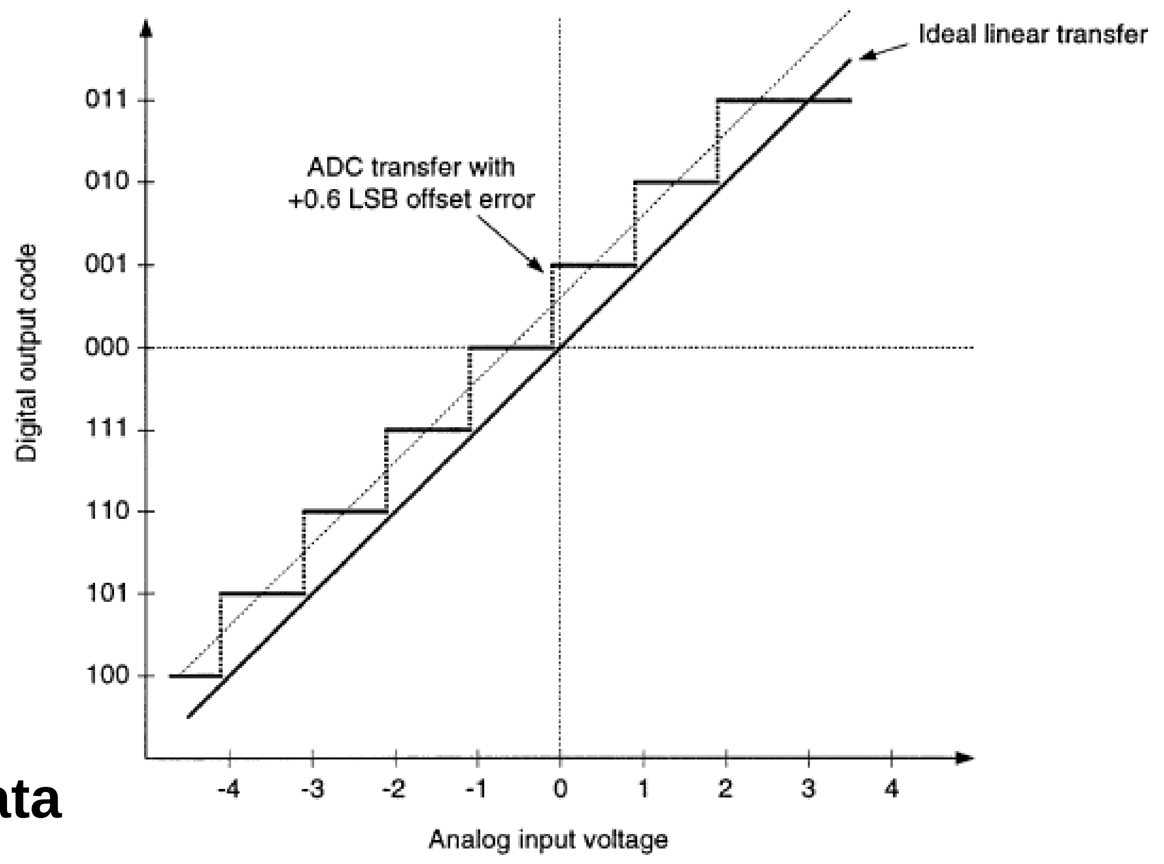


- This is a random error and can be represented by an rms noise source $e_{rms} = \frac{LSB}{\sqrt{12}} = 0.289LSB$
- This places a limit on Dynamic Range
- $DR = 20log\frac{S}{N}$
- $DR = 6.026n + 1.7609$
- $ENOB = \frac{DR-1.7609}{6.026}$
- For an ADC with DR=92dB
- ENOB= $\frac{92-1.7609}{6.026}$=14.988 bits

- B) Linear Errors:

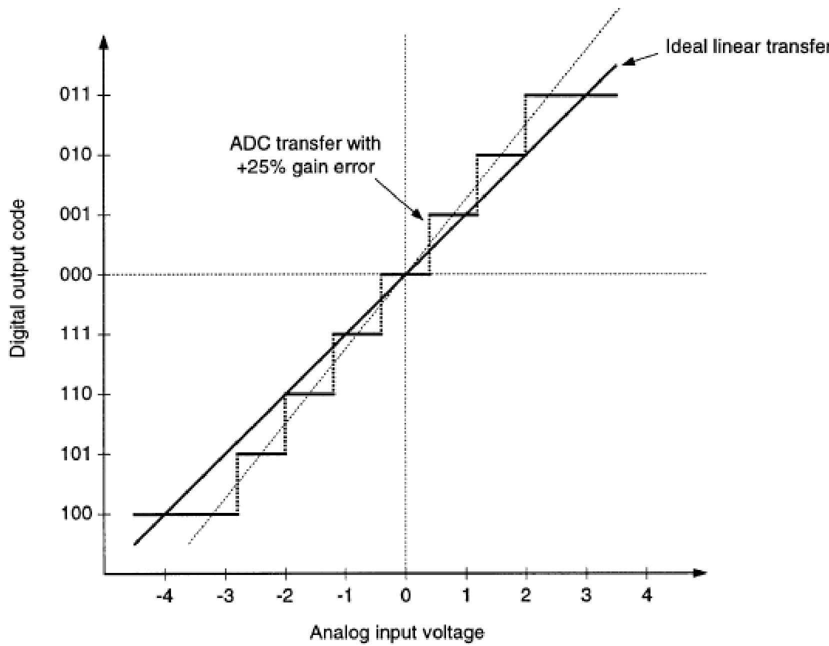
- Linear errors are the largest and most common errors in an ADC and are easily corrected by simple calibrations or by additions with and multiplications by correction constants.
- Linear errors do not distort the transfer function; they only change somewhat the input range over which the ADC operates.
- Figure shows the tran with some *offset error* the code transitions is bottom graph shows tl

Offset errors can be compensated for simply by adding a correcting voltage in the analog circuitry or by adding a constant to the digital data



• B) Linear Errors:

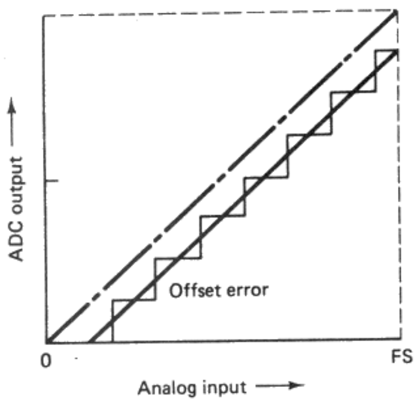
- Figure shows an ideal three-bit ADC with a +25% *gain error* . The slope of the line through the code transitions is 1.25 times the ideal slope of 1.00. If the slope of the line were 0.75 instead, the gain error would be –25%. The bottom graph shows the error resulting from excessive gain.



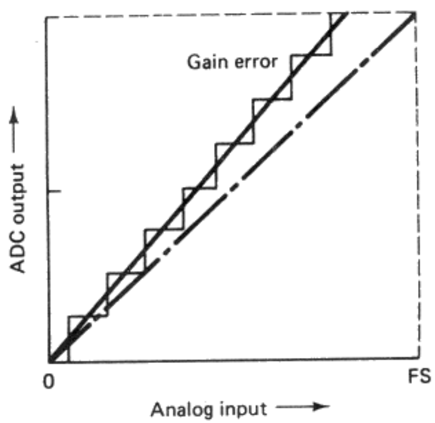
- Gain errors can be corrected by analog circuitry like potentiometers or voltage-controlled amplifiers or by multiplying the digital data by a correction constant.

Summary of Other ADC Errors

- Offset Error

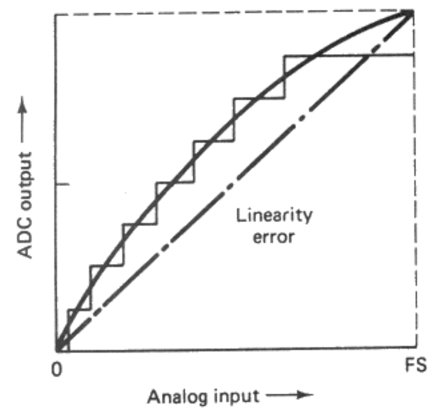


- Gain Error

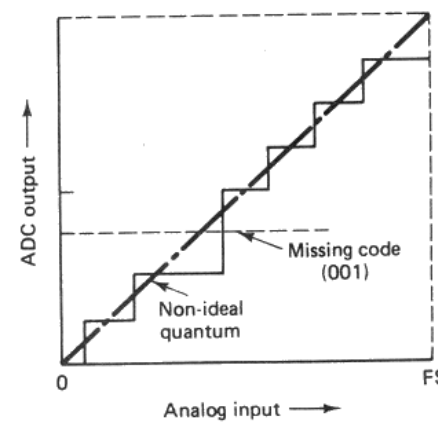


- Can be eliminated by initial adjustments

- Integral Linearity Error



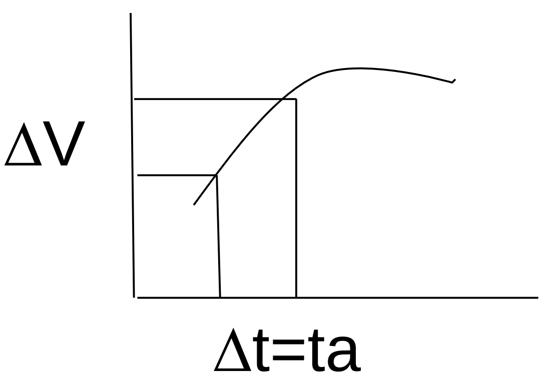
- Differential Linearity Error



- Nonlinear Error
  - Hard to remove

Aperture Error

- ADC conversion takes time (τ_c) which might be fixed or variable depending of ADC type
- If analog input is changing during conversion(this can also be due to clock jitter), then the converted signal will be in error known as Aperture Error
- To avoid error in digitized output, this change must be small and less than ½ Δ



Actual Sampling time uncertainty due to changing signal or clock jitter

Consider A sine wave

- Vin=Vref Sin ωot
- $\left(\frac{\Delta V}{\Delta t}\right)_{max} = V_{REF}\omega_0 \Longrightarrow \Delta t = \frac{\Delta V}{V_{REF}\omega_0}$

$$let\ \Delta V = \frac{1}{2} LSB = \frac{V_{REF}}{2.2^n}$$

$$\Delta t = \frac{\frac{V_{REF}}{2.2^n}}{V_{REF}\omega_0} = \frac{1}{2.2^n\omega_0}$$

Make sure that τ_c is less than ta

Conversion Time (τ_c)

- The time the ADC takes to convert a a single analog input voltage value to corresponding digital value
- During conversion process the input must remain constant, or if it is allowed to change, this change should be restricted to a value : $\frac{dV_{in}}{dt} < \frac{V_{FSR}}{2^n \tau_c}$

- 10 bit ADC with τ_c=20 μs , what is the maximum allowable rate of change (frequency) of a sinusoidal input voltage to be converted using this ADC
- Solution: $\frac{dV_{in}}{dt} < \frac{V_{FSR}}{2^n \tau_c}$
- $A\omega_o < \frac{V_{FSR}}{2^n \tau_c}$, let A=V_{FSR}

$$\omega_o < \frac{1}{2^n \tau_c}$$

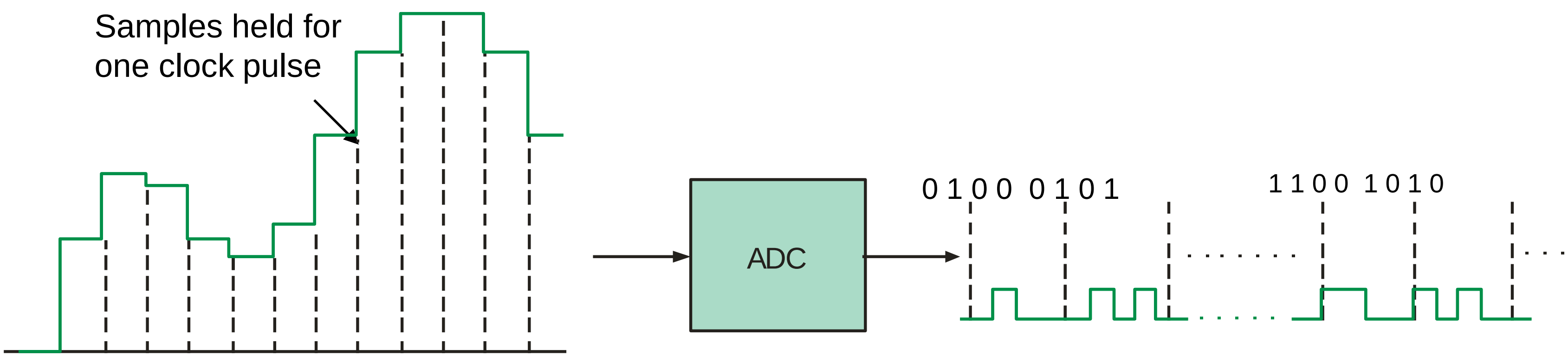
$$f_o < \frac{1}{2\pi . 2^{10} 20 \mu s} = 7.75\ Hz$$

This is the maximum frequency of input to be used with this ADC>>>>> If higher frequency needed , increase n or reduce τ_c

Sample-and-Hold and ADC

Following the anti-aliasing filter, is the sample-and-hold circuit and the analog-to-digital converter.

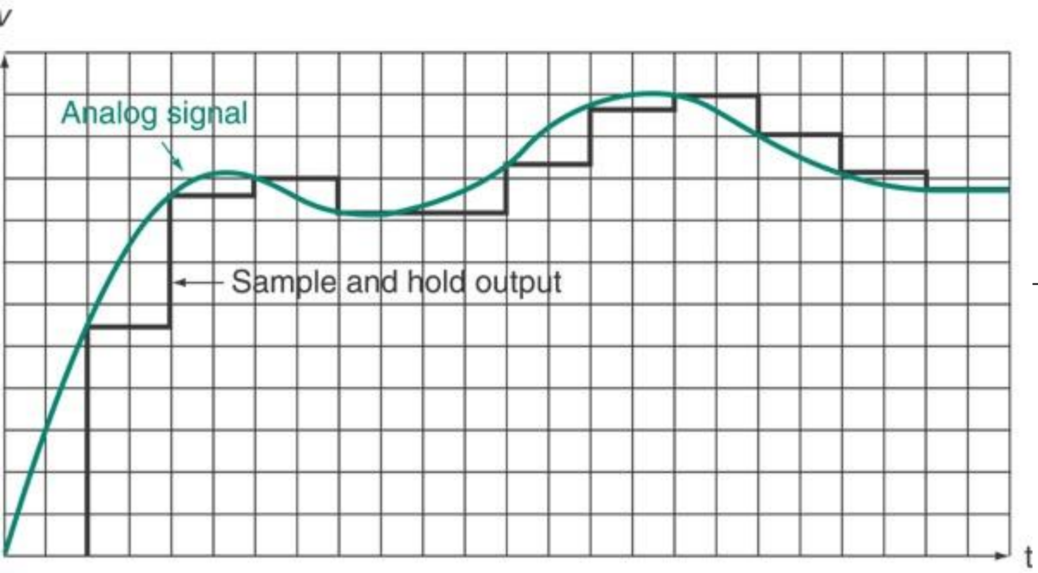
At this point, the original analog signal has been converted to a digital signal.

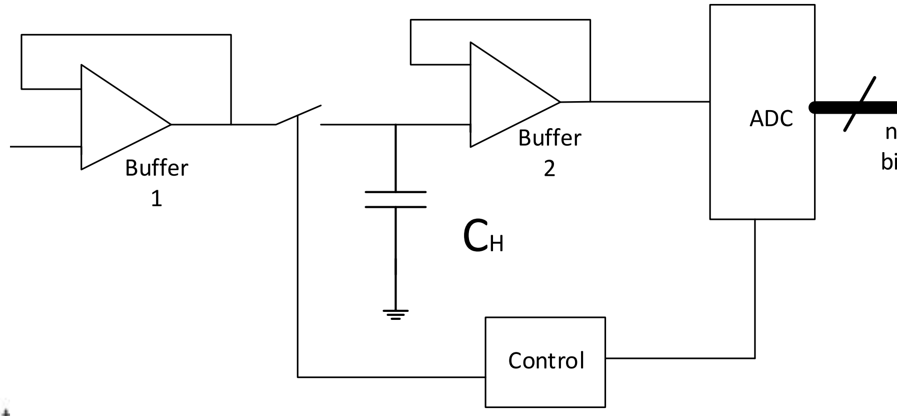


Many ICs can perform both functions on a single chip and include two or more channels. For audio applications, the AD1871 is an example of a stereo audio ADC.

Sample and Hold Circuit

- Sample and Hold (S& H) reduces Δt
- S&H is placed at the input of ADC, it holds the input signal at a constant level during conversion
- S&H is used to avoid errors if variations of the measurand were allowed to pass to the ADC
- Reduce uncertainty error in the converted output when input changes are fast compared to the conversion time
- Sample mode: output follows input
- Hold: Output is held constant until sample mode is resumed



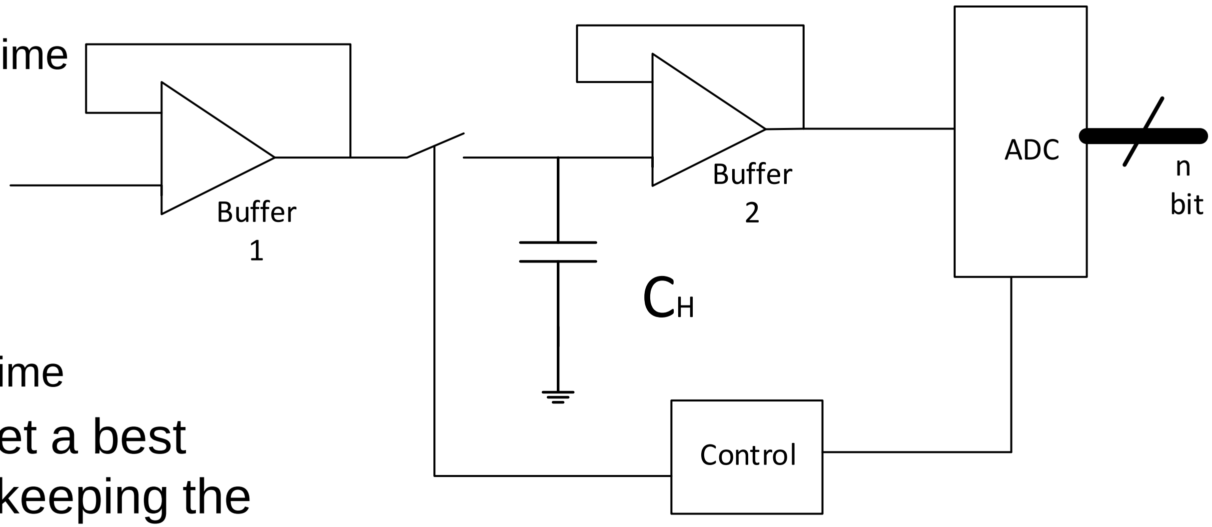


- This is low pass filter with fc as high as possible in order not to disturb the signal

$$f_c = \frac{1}{2\pi(\sum R)C_H}$$

➢ Care in selecting hold capacitor C_H
- Low Value
  - Increases BW
  - Reduces acquisition time
  - Increase Droop
- High Value
  - Reduces BW
  - Minimize Droop
  - Increase acquisition time
- Choose capacitor to get a best acquisition time while keeping the droop per conversion below 1 LSB

➢ In Multi-channel system S&H used
- To hold a sample from one channel while multiplexer proceed to sample next one
- Simultaneous sampling of two signal

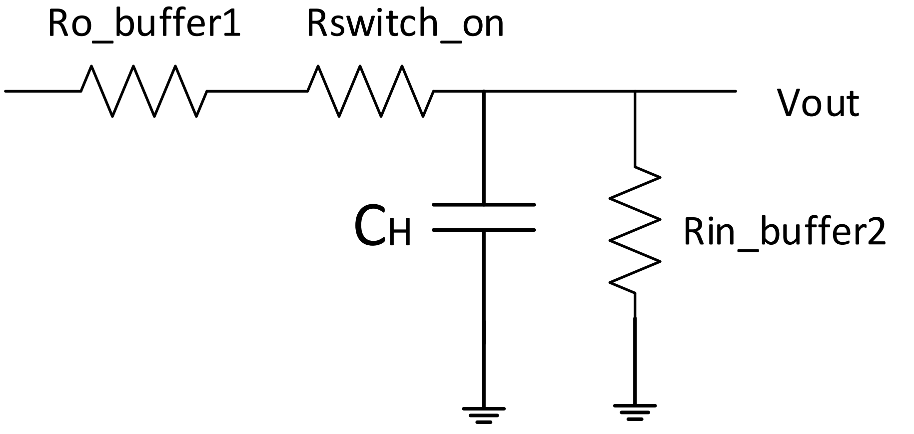


➢ Care in selecting hold capacitor C_H

Choose capacitor to get a best acquisition time while keeping the droop per conversion below 1 LSB

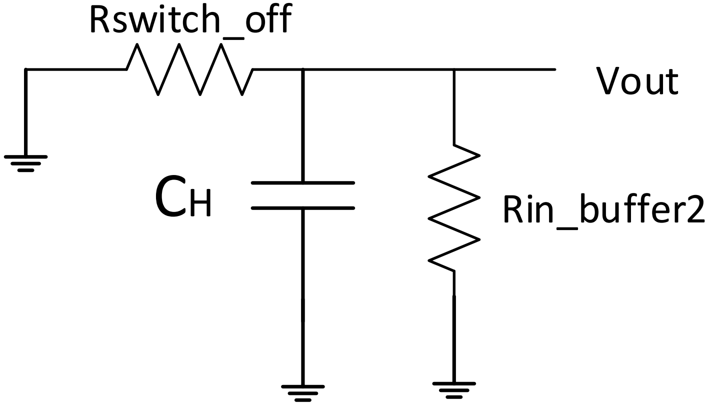
Sample/Track Mode

For High fc , C_H must be low



Hold Mode

C_H must be low to minimize discharge of Capacitor (Droop)

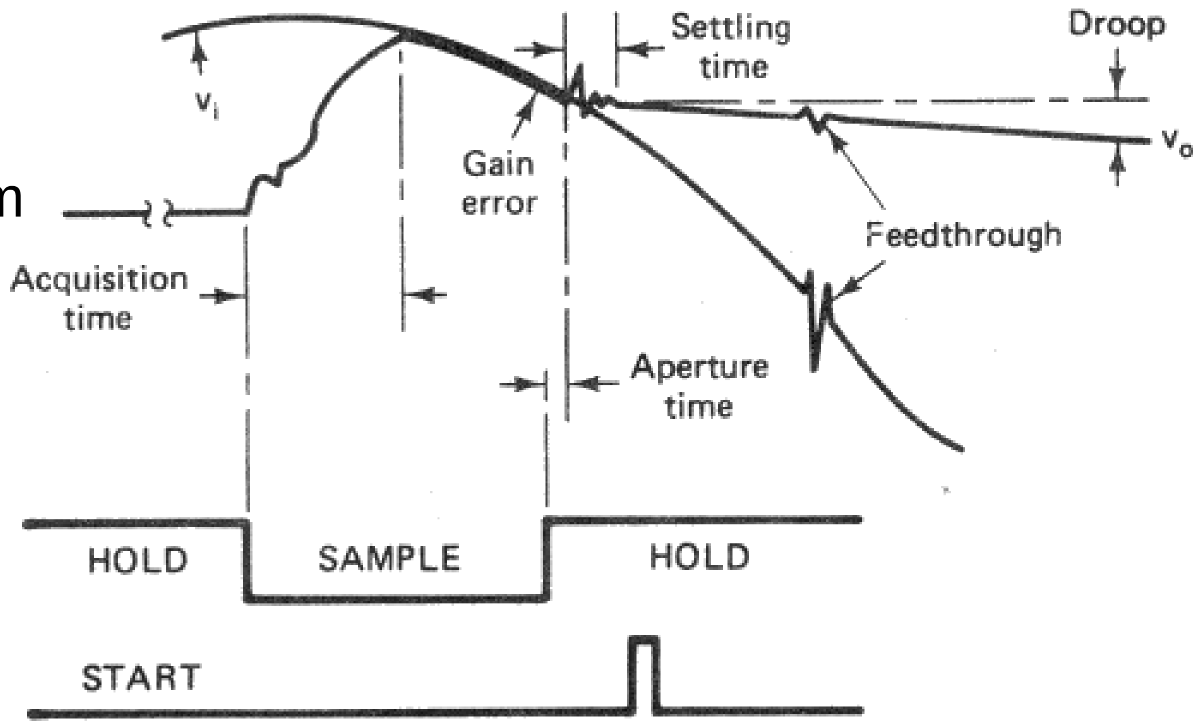


Sample and Hold Circuits

τ_{acq} – time required for the S&H circuit to acquire signal when changing from the hold mode to sample mode

τ_{ap} – aperture time, time required for switch from sample to hold state (time when output stops following the input)

or time between when the hold command is received to actual transition to actual hold mode



Converter Throughput Rate/ Frequency

- It is defined as the number of times the input signal can be sampled maintaining full accuracy
- It is calculated as the inverse of total time required for one successful conversion
- 1) For ADC's without S&H

$$f = throughput = \frac{1}{\tau_c}$$

- 2) For ADC's with S&H: other delays affect the throughput

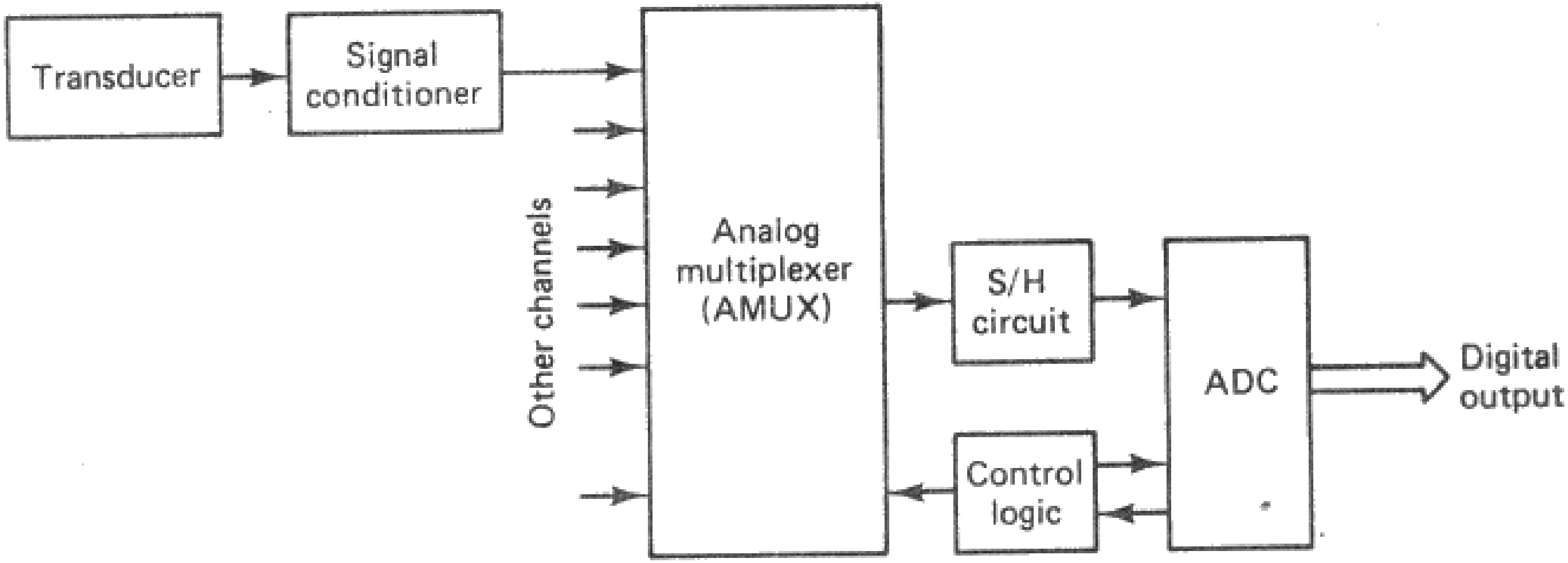
$$f = throughput = \frac{1}{\sum \tau}$$

where $\sum \tau = \tau_c + \tau_{acq} + \tau_{ap}$

Commercially Available S/H

Device type	Manufacturers	Acquisition time	Aperature time	Settling time	Features	Price (100s)
AD582	Analog Devices	6 μs to 0.1% 25 μs to 0.01%	150 ns	0.5 μs	Monolithic, general purpose	$ 8
AD583	Analog Devices	4 μs to 0.1% 5 μs to 0.01%	50 ns	—	Monolithic, faster	16
LF398	National	4 μs to 0.1% 6 μs to 0.01%	150 ns	0.8 μs	Monolithic, general purpose	3
SHC298	Burr-Brown	9 μs to 0.1% 10 μs to 0.01%	200 ns	1.5 μs	Monolithic, general purpose	7
AD346	Analog Devices	2 μs to 0.01%	60 ns	0.5 μs	Hybrid, internal hold capacitor	—
SHC85	Analog Devices, Datel-Intersil, Burr-Brown	4 μs to 0.01%	25 ns	0.5 μs	Hybrid, internal hold capacitor, low droop rate	70
HTS0025	Analog Devices	20 ns to 0.01%	20 ns	30 ns	Hybrid, very fast	187

Multi-channel DAQ System



TYPES of ADC

Flash

Integrating

SAR

Sigma-Delta

Pipeline

Why Different Types of ADC?

- Various ADC Types exist as a result of different requirements imposed instrumentation, control, audio and video applications
- Obviously speed / conversion rate is not critical in dc or slowly changing measurands
- However, resolution might be important

Types of ADCs

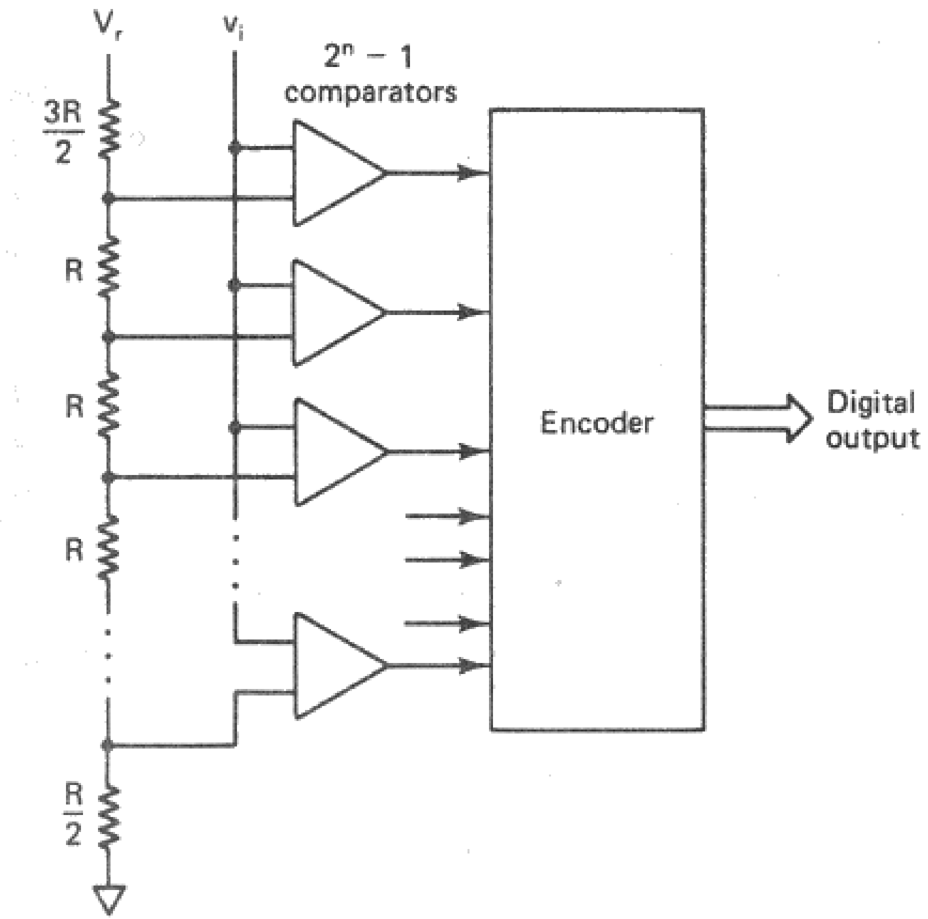
- Most ADC types have the following two blocks in common:
- Comparator ==> Vo= logic “1” if V(+) > V(-)
- Vo= logic “0” if V(+) < V(-)
- i.e. comparator is a 1 bit ADC
- Precise and stable voltage reference

Direct Conversion//Flash//Parallel ADC

- Very High speed of conversion with sampling rate up to 1 GS/s
- For an ADC $\tau_c = \dfrac{1}{1\ GS/s}$=1 ns
- Resolution is limited to 8 bits due to increased number of comparators (2^n -1) and resistors (2^n)

Parallel or Flash ADC

- Very High speed conversion
  - Up to 1GHz and 8 bit resolution
  - Video, Radar, Digital Oscilloscope
- <u>**Single Step Conversion**</u>
- $2^n - 1$ comparator
- 2^n Precision Resistive Network
- Priority Encoder
- Resolution is limited
  - Large number of comparator and resistors in IC ==> bigger die and higher cost



Parallel or Flash ADC

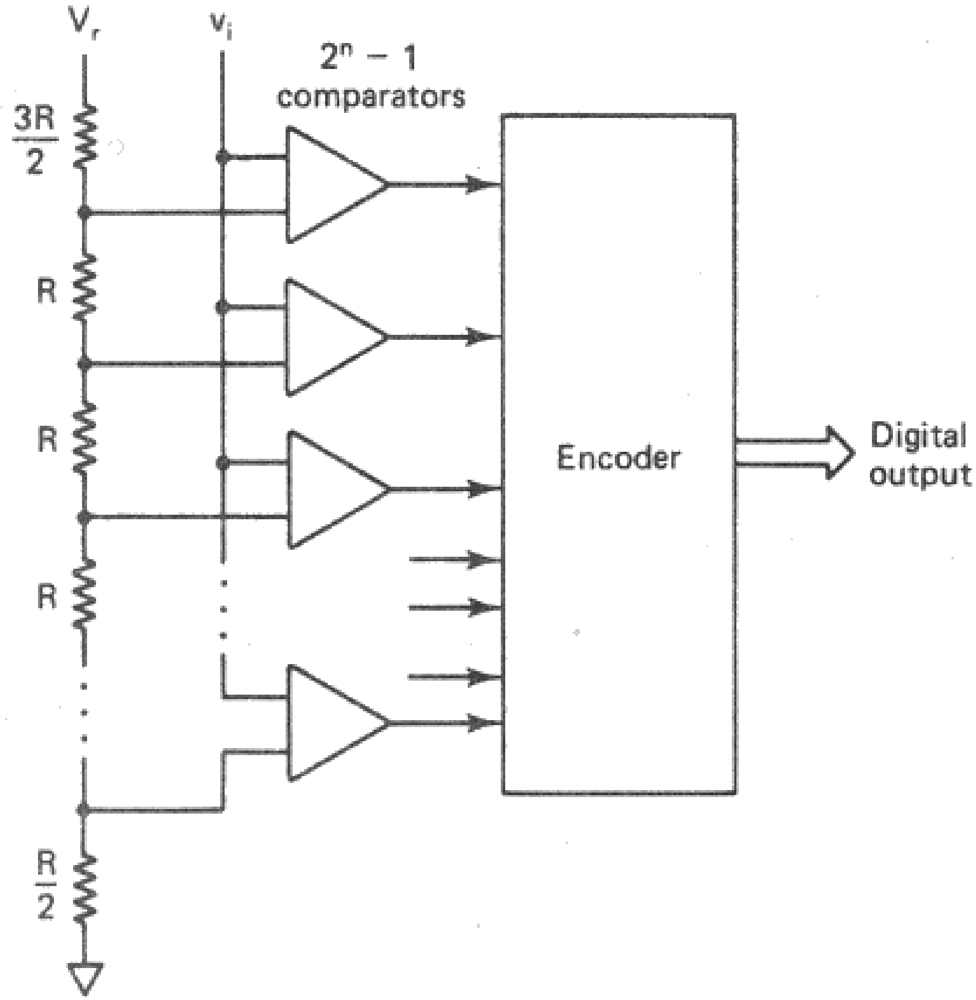
2 bit ADC

Δ=1/4

3 comparators

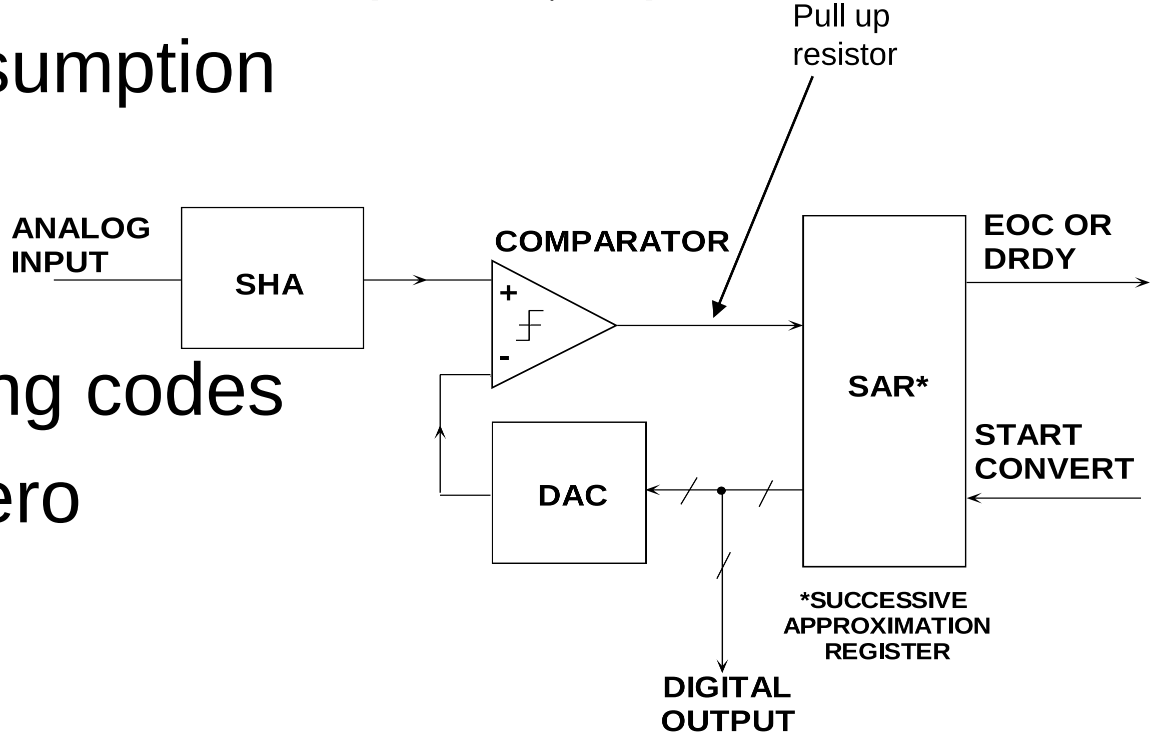
4 Resistors

D3	D2	D1	b2	b1
0	0	0	0	0
0	0	1	0	1
0	1	1	1	0
1	1	1	1	1

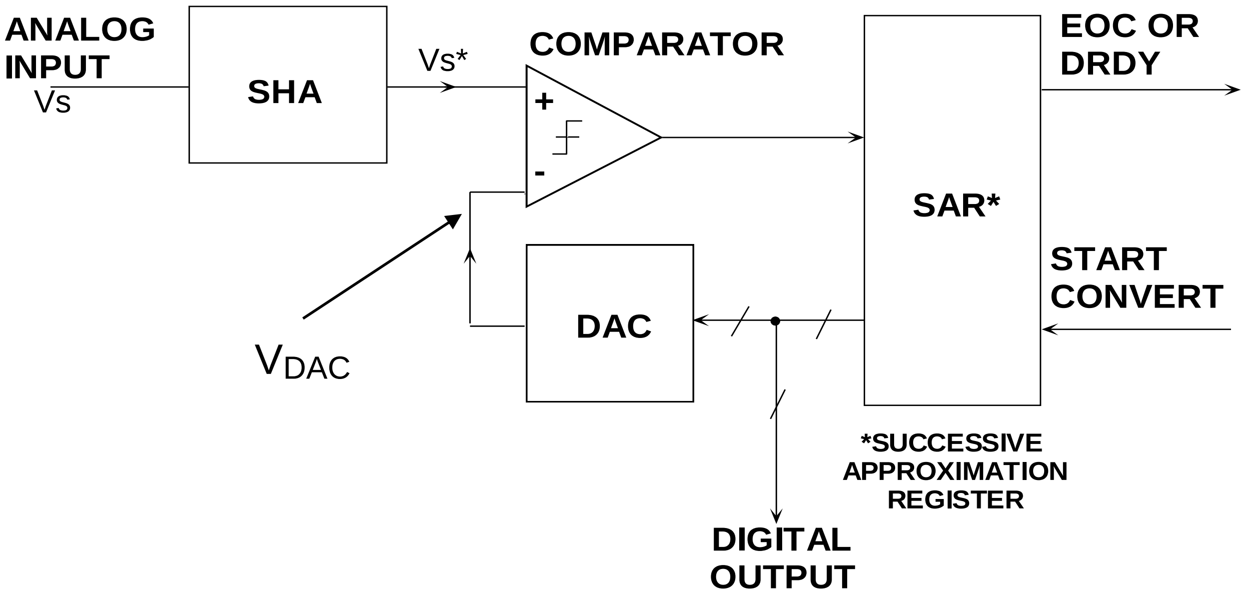


SAR ADC

- SAR – successive approximation register
- SAR ADC are probably the most widely used
- 8-16 bits ;
- Moderate speed ~ 1 MHz (τ_C=1 μs)
- Low power consumption
- Low cost
- Require S&H
- Can have missing codes
- simple to autozero



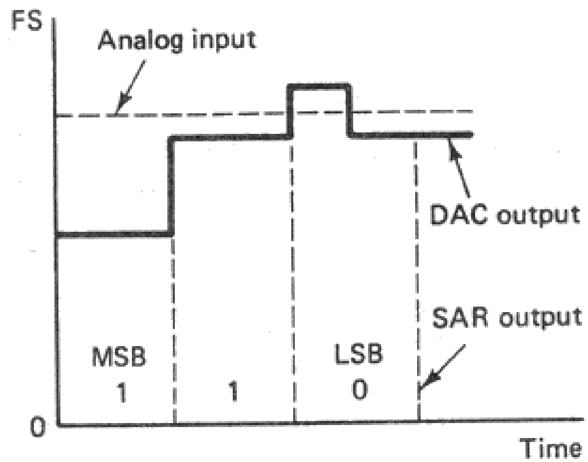
SAR ADC



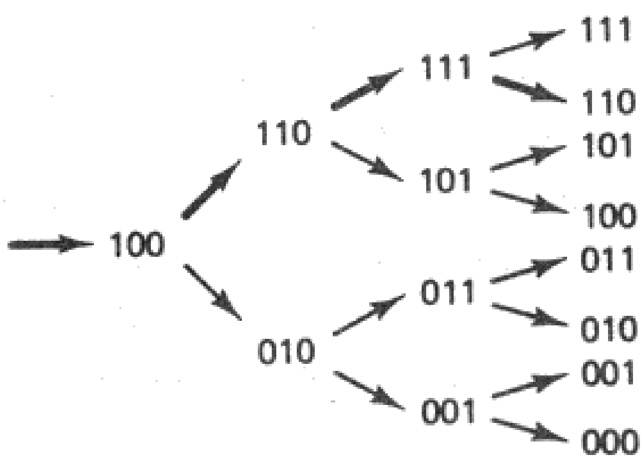
- Based on SAR Register
- DAC output “V_{DAC}” is used as a reference
- Comparator to compare Vs with VDAC
- Final result is reached after n-steps,
- In each step 1 bit conversion is done
- Each step takes one clock cycle

Successive Approximation ADC

- Circuit waveform



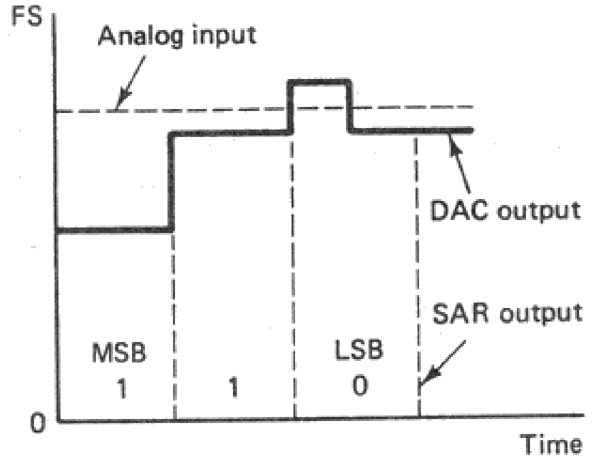
- Logic Flow (decision Tree)



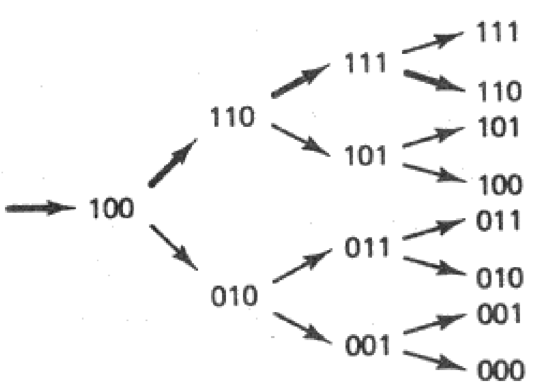
- **Conversion Steps**
- 1. initially SAR provides an output corresponding to have the range (100..0)
- 2. DAC outputs an analog voltage V_{DAC} which if found greater than Vs , then MSB is set to "1", otherwise MSB=0
- 3. IF MSB is reset to 0, next bit is tried until V_{DAC} =Vs
- 4. n -conversion steps, each takes a clock period

Successive Approximation ADC

- Circuit waveform



- Logic Flow (binary search)



- Conversion Time
  - n clock for n-bit ADC
  - Fixed conversion time
- Serial Output is easily generated
  - Bit decision are made in serial order

■ τc= n Tclock

▪ Tclock=1/fclock

Typical Applications

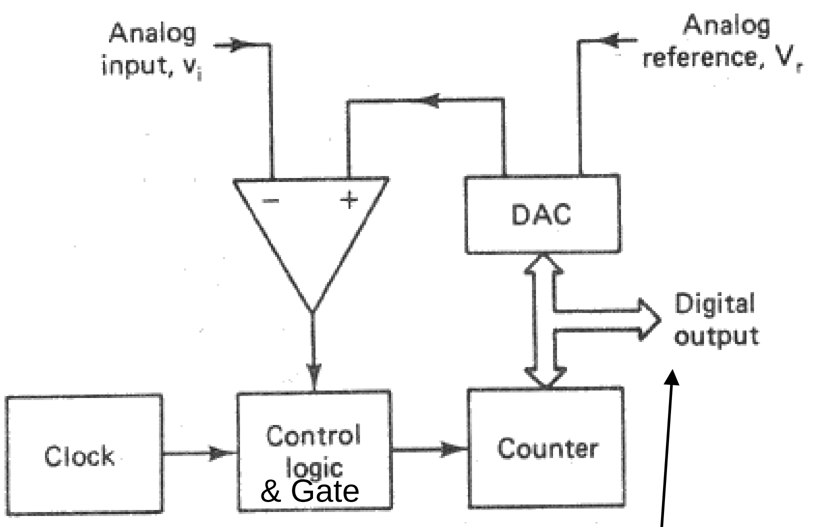
- Instrumentation
- Industrial control
- Data acquisition

Example

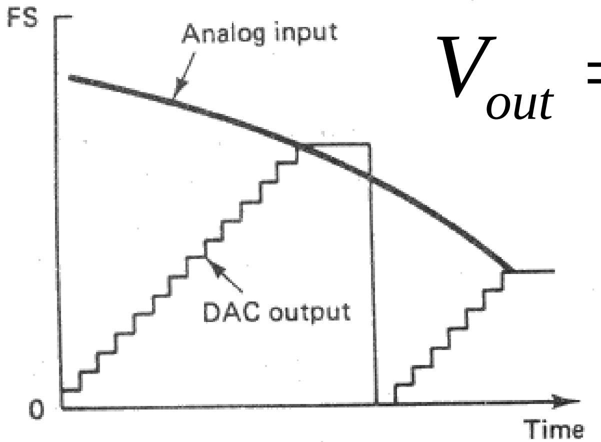
- VFSR=5V, 4 bit, SAR ADC, Vs=Vin=3.127 V, explain how conversion is done?
- Solution:
- Suppose Output is $b_1b_2b_3b_4$
- (1) let b1=1, b2=b3=b4=0
- 1000 ==> VDAC=8/2^4*VREF=2.5V
- Check VDAC > Vs ? (2.5 > 3.127? ==> NO ==> set **b1=1**
- (2) set b2=1, b3=b4=0
- 1100 ==> VDAC=10/2^4*VREF=3.75V
- Check VDAC > Vs ? (3.75 > 3.127? ==> Yes ==> Reset **b2=0**
- (3) set b3=1, b4=0
- 1010 ==> VDAC=10/2^4*VREF=3.1255V
- Check VDAC > Vs ? (3.125 > 3.127? ==> No ==> set **b3=1**
- (4) set b4=1, 1011 ==> VDAC=11/2^4*VREF=3.4375V
- Check VDAC > Vs ? (3.4375 > 3.127? ==> Yes ==> Reset **b4=0**
- **Final Result: 1010**

Counter Type ADC

- Block diagram



- Waveform

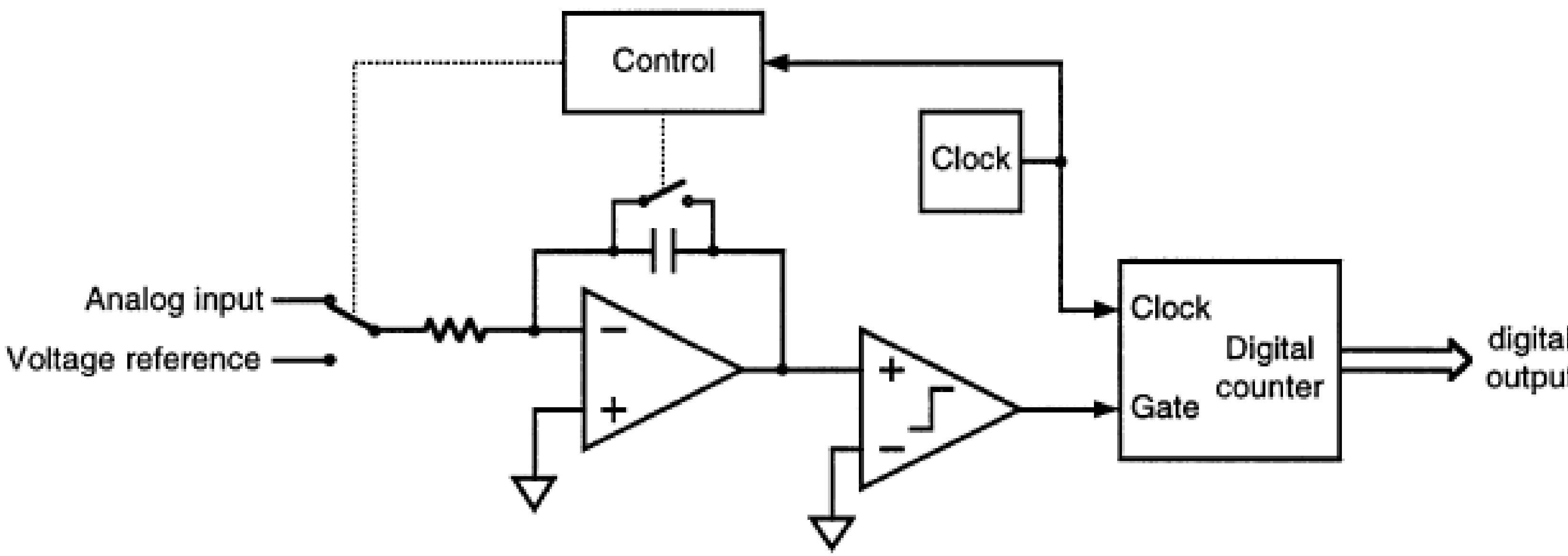


$$V_{out} = \frac{N}{2^n} \times V_{FSR}$$

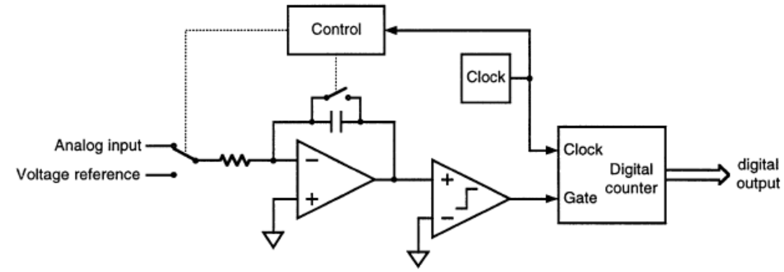
- Operation
- Reset and Start Counter
  - DAC convert Digital output of Counter to Analog signal
  - Compare Analog input and Output of DAC
    - $V_i < V_{DAC}$
      - Continue counting
    - $V_i >= V_{DAC}$
      - Stop counting
  - Digital Output = Output of Counter
- Disadvantage
  - Conversion time is varied
    - 2^n Clock Period for Full Scale input

Dual Slope Integrating ADC

- *Integrating* converters are used for low-speed, high-resolution applications such as voltmeters.
- They are conceptually simple, consisting of an integrating amplifier, a comparator, a digital counter, and a very stable capacitor for accumulating charge
- The most common integrating ADC in use is the dual-slope ADC



Dual Slope Integrating ADC



- Initially, the capacitor is discharged and so has no voltage across it.
- At time 0, the input to the integrator is switched to the analog input and the capacitor is allowed to charge for an amount of time, T1, which is fixed.
- Its rate of charging and thus its voltage at T1 are proportional to the input voltage.
- At time T1 the input switch flips over to the voltage reference, which has a negative value so that the capacitor will begin to discharge at a rate proportional to the reference.
- The counter measures how long it takes to discharge the capacitor completely.

- If the capacitor is of high quality, the ratio of the discharge time to the charge time is proportional to the ratio of the input voltage to the voltage reference, and so the counter output represents the analog input voltage.

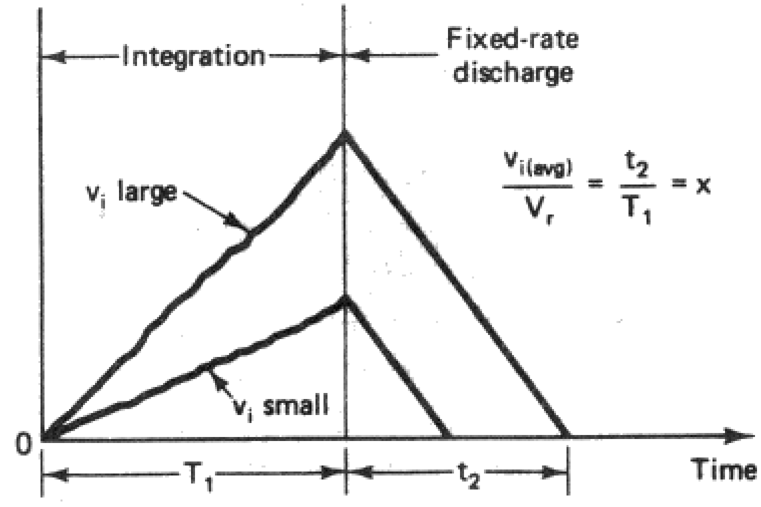
- t2/T1=Vi(avg)/VREF

- Operation
  - – Integrate $\int_0^{T_1} v_i dt$
  - – Reset and integrate $\int_0^{t_2} V_r dt$
  - – Thus $T_1 v_{i(AVG)} = t_2 V_r$
  - – → $v_{i(AVG)} = V_r \frac{t_2}{T_1}$

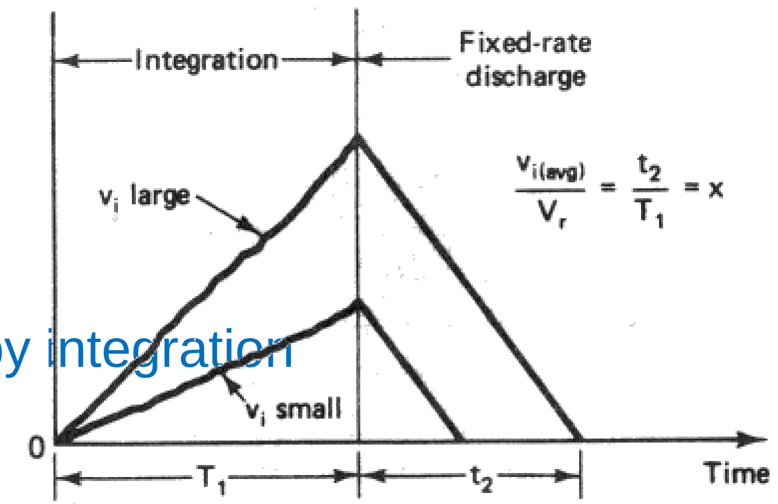
$$t_2 = Count * Tclock$$

- Applications

  DMM(Digital Multimeter)

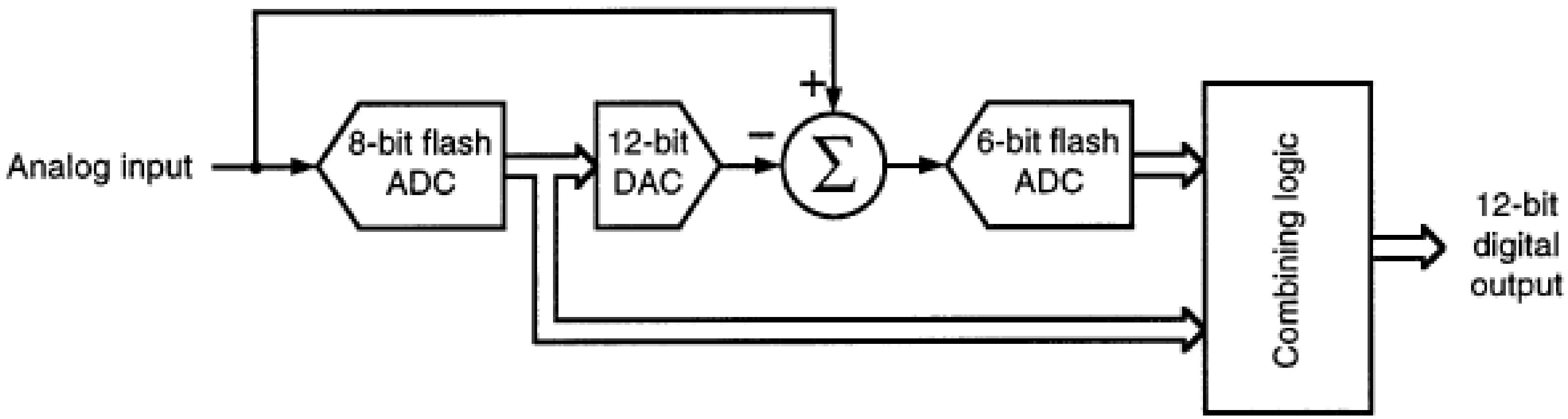


- Integrating converters do not sample the voltage itself; they *average* the voltage over the integration period and *then* they sample the average that is accumulated on the capacitor.
- This tends to reject noise that conventional sampling cannot, especially periodic noises. Most integrating ADCs operate with an integration period that is a multiple of one AC line period (1/60 or 1/50 s) so that any potential interference from stray electric or magnetic fields caused by the power system is canceled.
- Low speed
- High resolution and low cost
- Very stable
- Excellent Noise Rejection
  - High frequency noise cancelled out by integration
  - Proper T_1 eliminates line noise
  - Easy to obtain good resolution

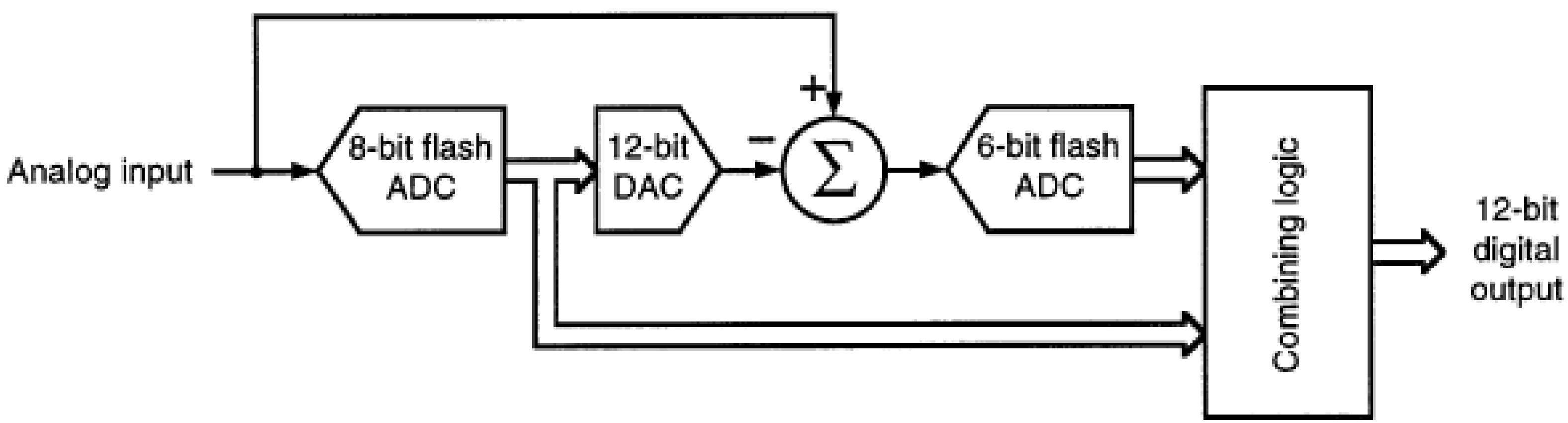


Pipeline “Subranging or Multistage” ADC

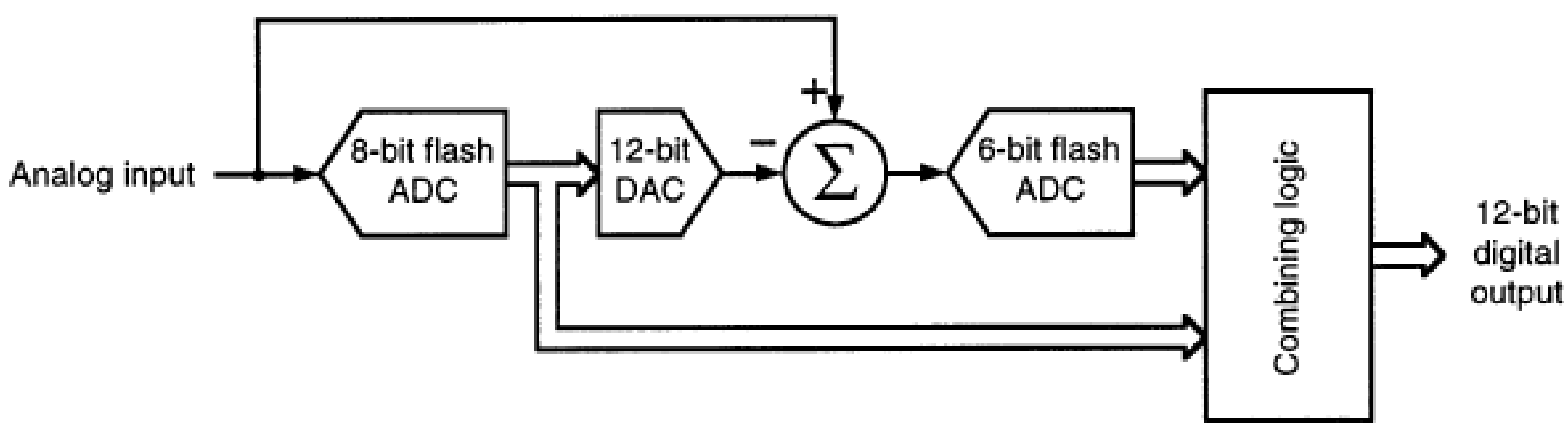
- To achieve higher sample rates than SAR ADCs at resolutions of 10 to 16 bits, *multistage* ADCs (sometimes called *subranging* or *multipass* ADCs) use the iterative approach of SAR ADCs but reduce the number of iterations in a conversion.
- Instead of using just a comparator, the multistage ADC uses low-resolution flash converters (4 to 8 bits) as building blocks.
- An example of a 12-bit two-stage ADC built out of two flash ADCs and a fast DAC.



- The 6-bit flash ADC converts the residual error of the 8-bit flash ADC. The two digital outputs are combined to produce a 12-bit conversion result.
- If each flash ADC has a T/H at its input, then each stage can be converting the residual error from the previous stage while the previous stage is converting the next sample.
- The whole converter then can effectively operate at the sample rate of the slowest stage.
- Without the extra T/Hs, a new conversion cannot start until the residues have propagated through all the stages. This variation of the multistage ADC is called a *pipelined* ADC.

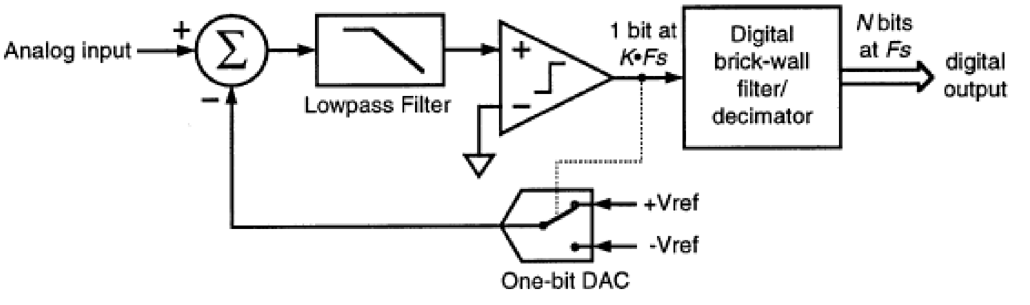


- An example of a 12-bit multistage ADC built out of two flash ADCs and a fast DAC.
- The 8-bit flash ADC takes a first “guess” at the input signal and the 6-bit flash ADC converts the error in the guess, called the “residue.”
- The 12-bit DAC actually needs to have only 8 bits, but it must be accurate to 12 bits.
- If the 8-bit flash ADC were perfect, the second flash ADC would only need 4 bits. But since the first flash actually may have some error, the second flash has 2 bits of “overlap.



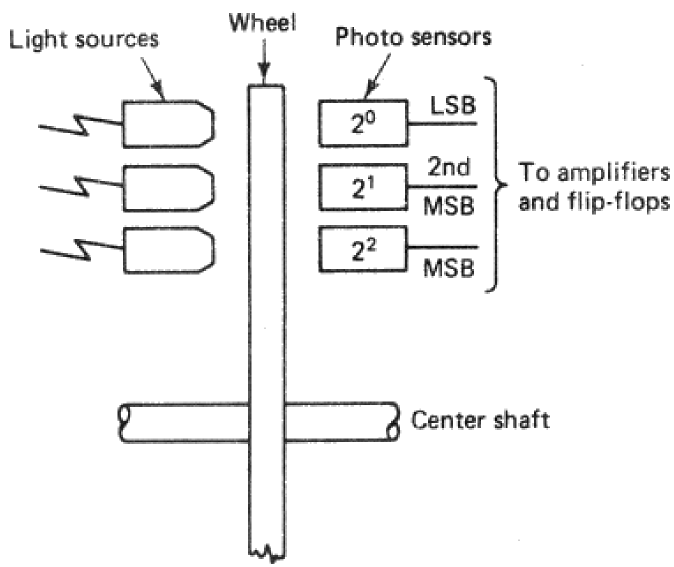
SIGMA-DELTA ($\sum - \Delta$) ADC

- Two major Blocks: DAC & Digital Filter
- Used more and more for audio applications
- Resolution 16-24 bits
- Sample rate around 100 kS/s
- Low noise and low cost

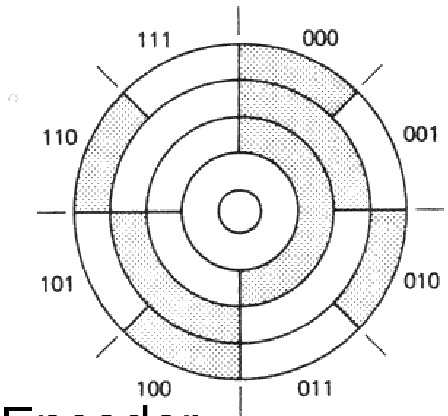


Shaft Encoder

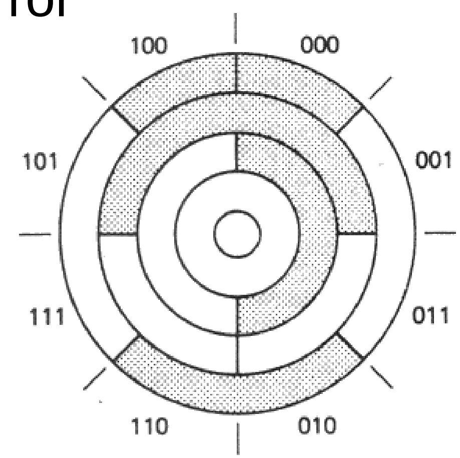
- Electromechanical ADC
  - Convert shaft angle to digital output
- Encoding
  - Optical or Magnetic Sensor
- Applications
  - Machine tools, Industrial robotics, Numerical control



- Binary Encoder
  - Misalignment of mechanism causes large error
    - Ex: 011 → 111 (180deg)



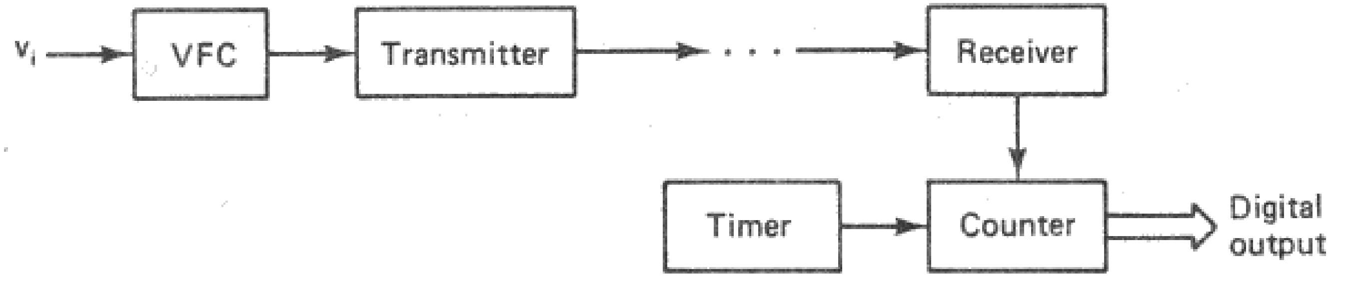
- Gray Encoder
  - Misalignment causes 1 LSB error



Voltage to Frequency ADC

- VFC (Voltage to Frequency Converter)
  – Convert analog input voltage to train of pulses
- Counter
  – Generates Digital output by counting pulses over a fixed interval of time

- Low Speed
- Good Noise Immunity
- High resolution
  – For slow varying signal
  – With long conversion time
- Applicable to remote data sensing in noisy environments
  – Digital transmission over a long distance



ADC Comparison

Characteristic	Flash	Pipeline	SAR	Sigma-Delta	Integrating
Throughput Samples/sec	1	2	3	4	5
Resolution	5	3	4	2	1
Latency Sample to output Tc	1	3	2	4	5
Power consumption	Constant High	Constant Low	Variable Low	Constant Medium	Constant Low

END ADC ==>

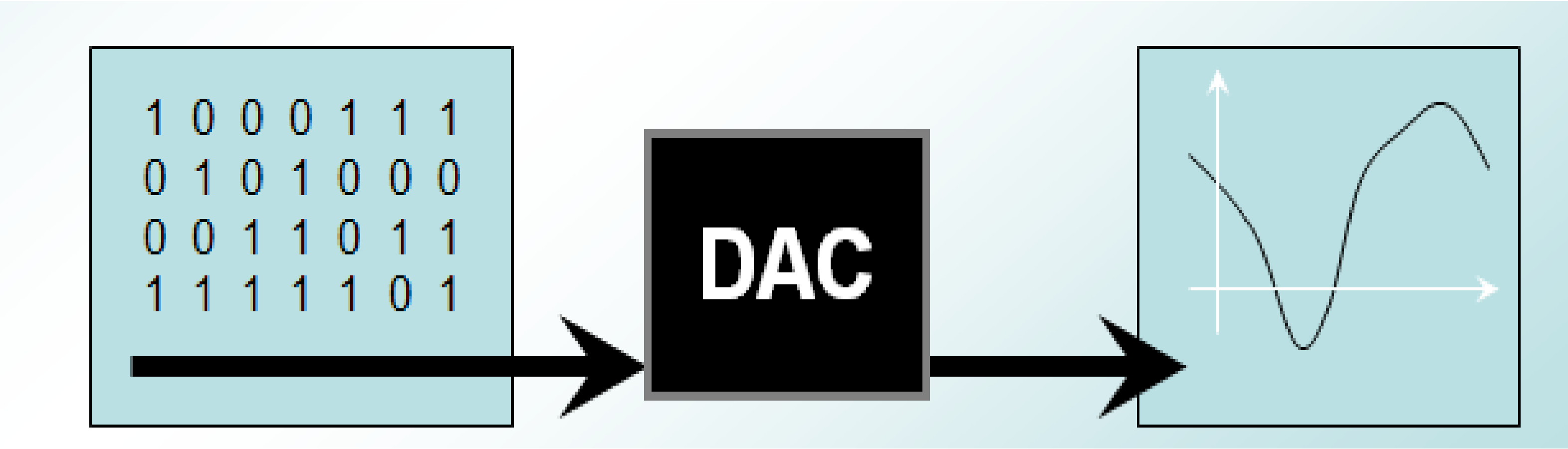
==> START DAC

END ADC ==>

==> START DAC

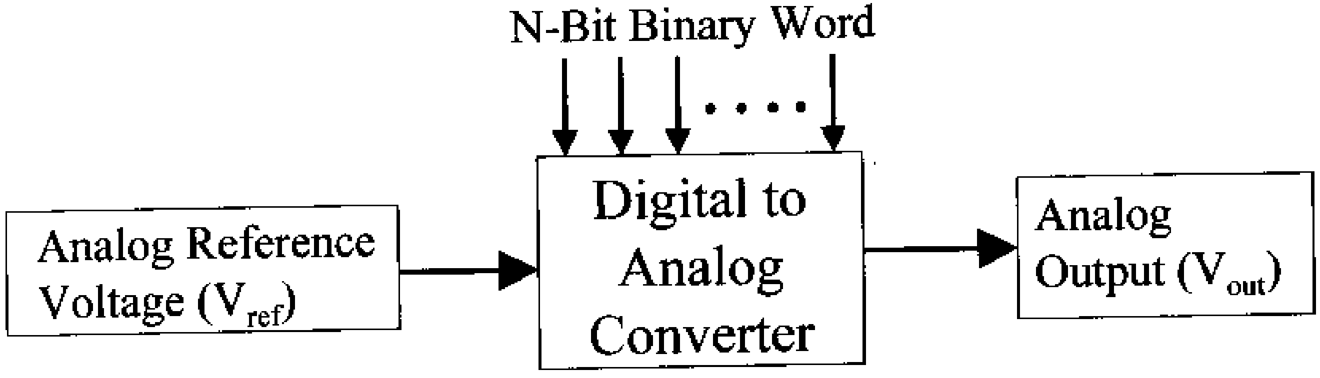
What is a DAC?
(Digital to Analog Converter)

- A digital to analog converter (DAC) is a device that converts n-bit (parallel) digital input into an analog voltage or current output.
- Primary output is a current which can be easily converted to a voltage



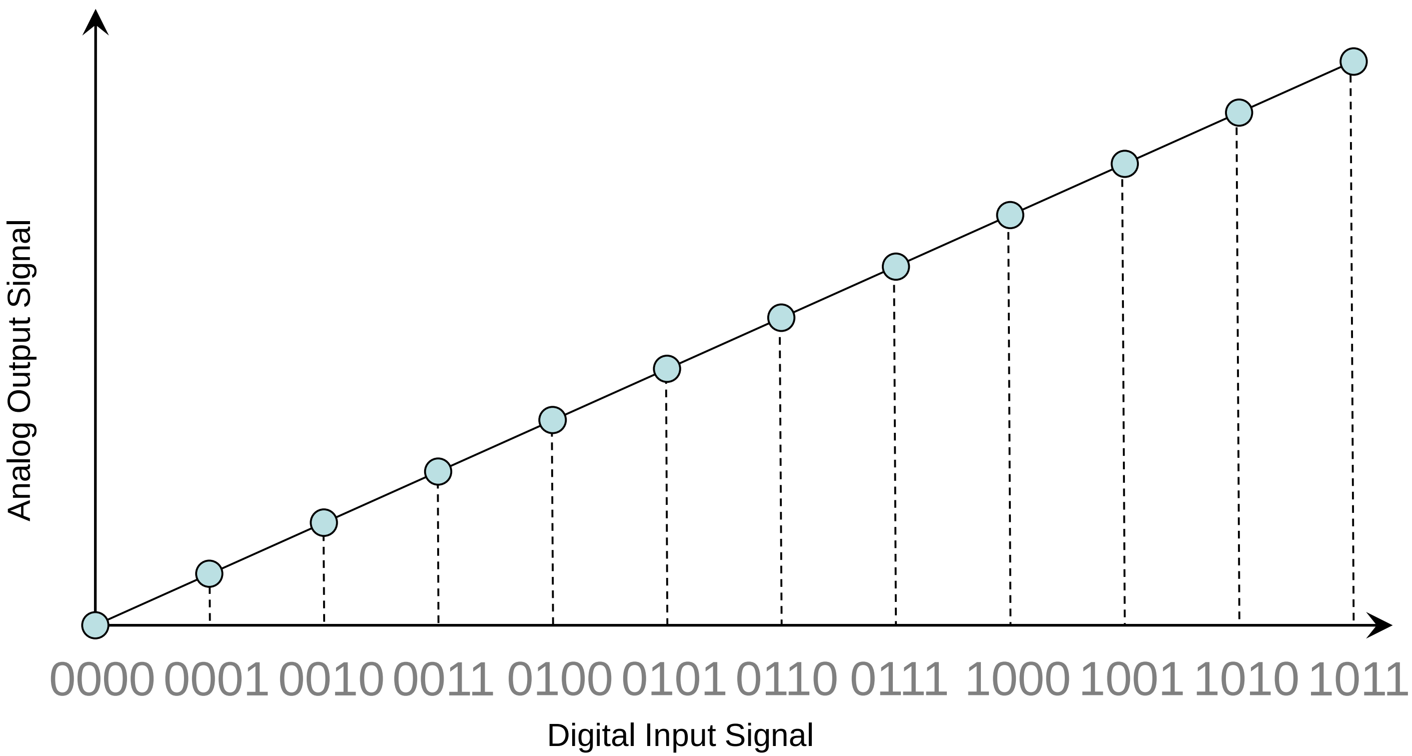
Principal components of DAC

- Consists off:
- Network of analog switches controlled by the input code
- Network of weighted resistors
- The switches control currents or voltages derived from a precise reference voltage
- Output current/voltage represents the ration of the input code to the full scale voltage of the reference source



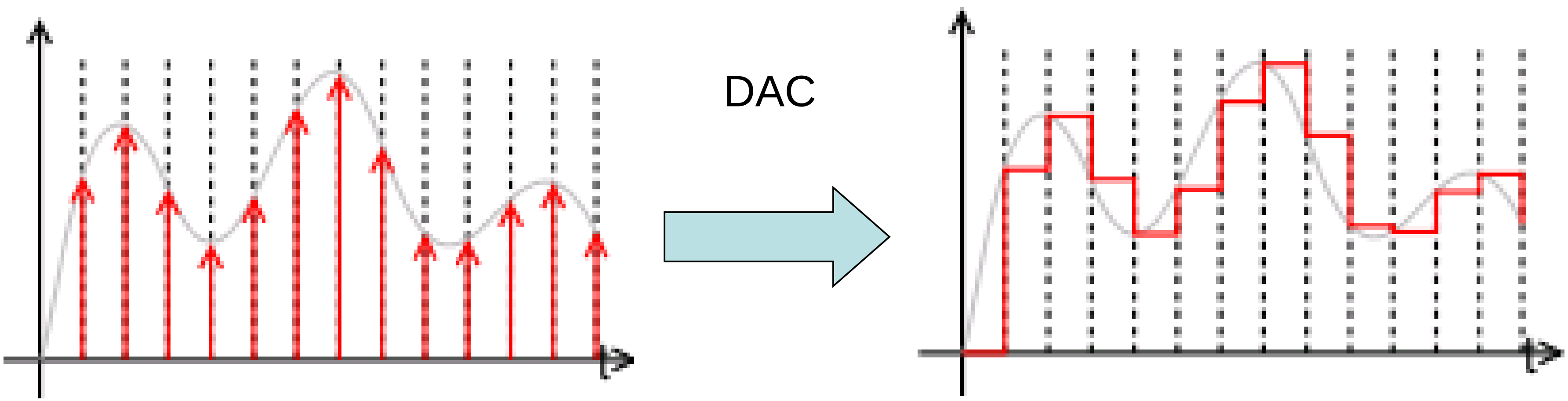
What is a DAC?

- Digital → Analog
- Each binary number sampled by the DAC corresponds to a different output level.



Typical Output

DACs capture and hold a number, convert it to a physical signal, and hold that value for a given sample interval. This is known as a zero-order hold and results in a piecewise constant output.

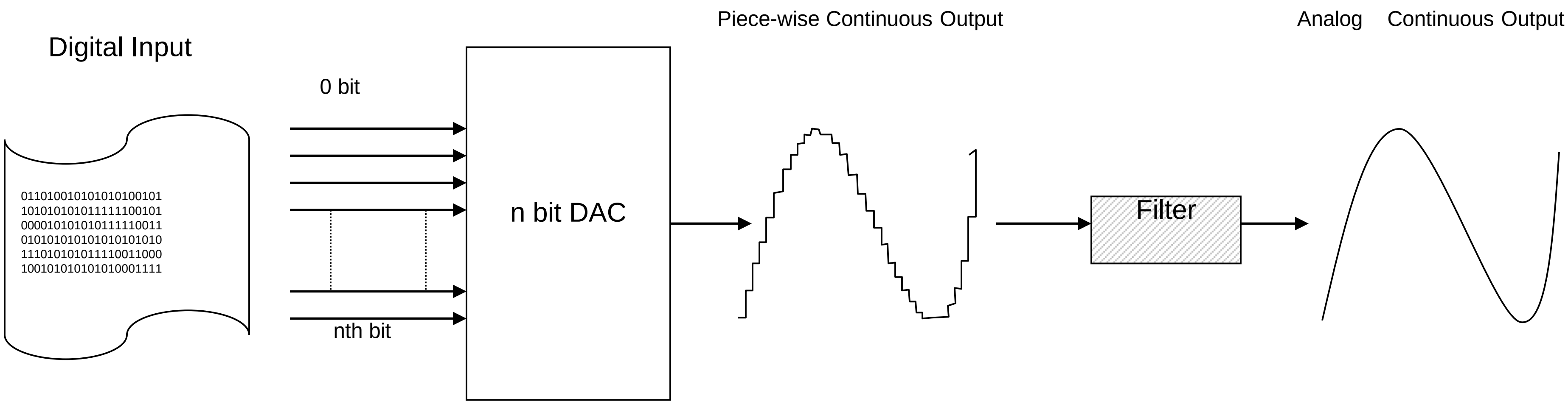


Ideally Sampled Signal

Output typical of a real, practical DAC due to sample & hold

Common Applications

- Used when a continuous analog signal is required.
- Signal from DAC can be smoothed by a Low pass filter



Common Applications:
Function Generators

- Digital Oscilloscopes
  - Digital Input
  - Analog Ouput
- Signal Generators
  - Sine wave generation
  - Square wave generation
  - Triangle wave generation
  - Random noise generation

1

2

Common Applications

Motor Controllers

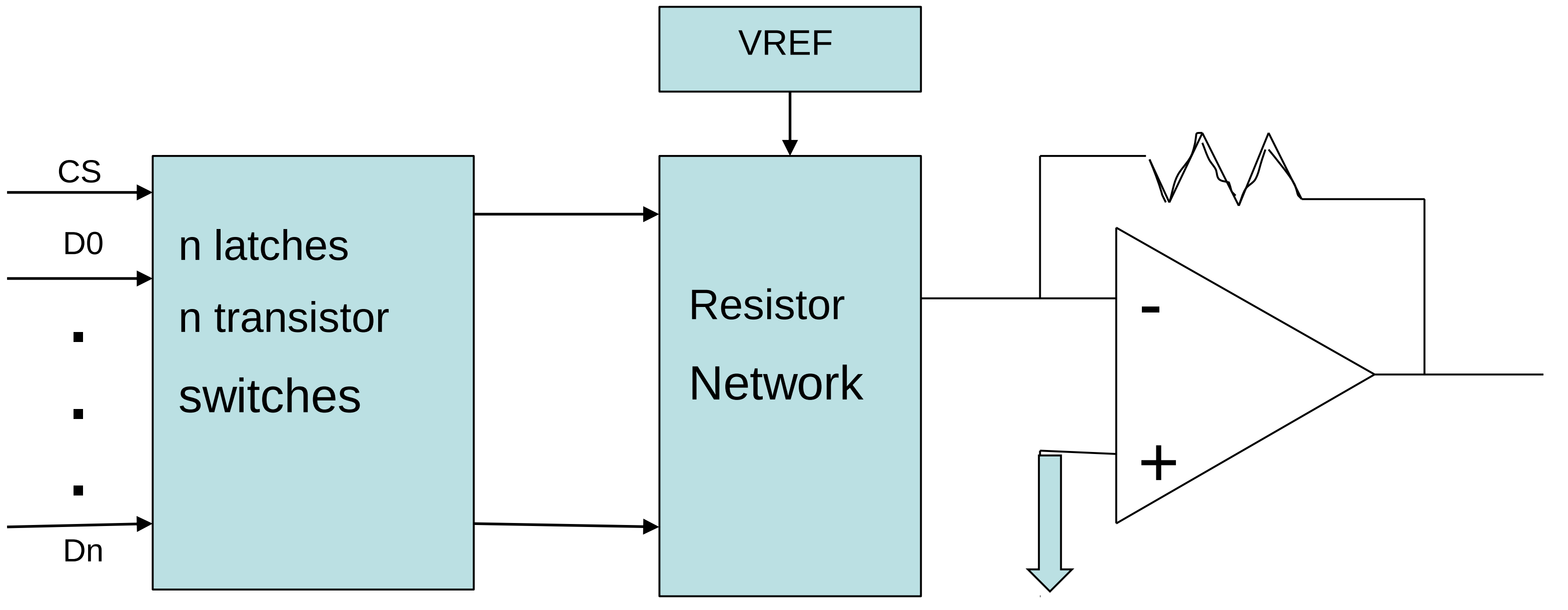
- Cruise Control
- Valve Control
- Motor Control

1

2

3

Typical DAC



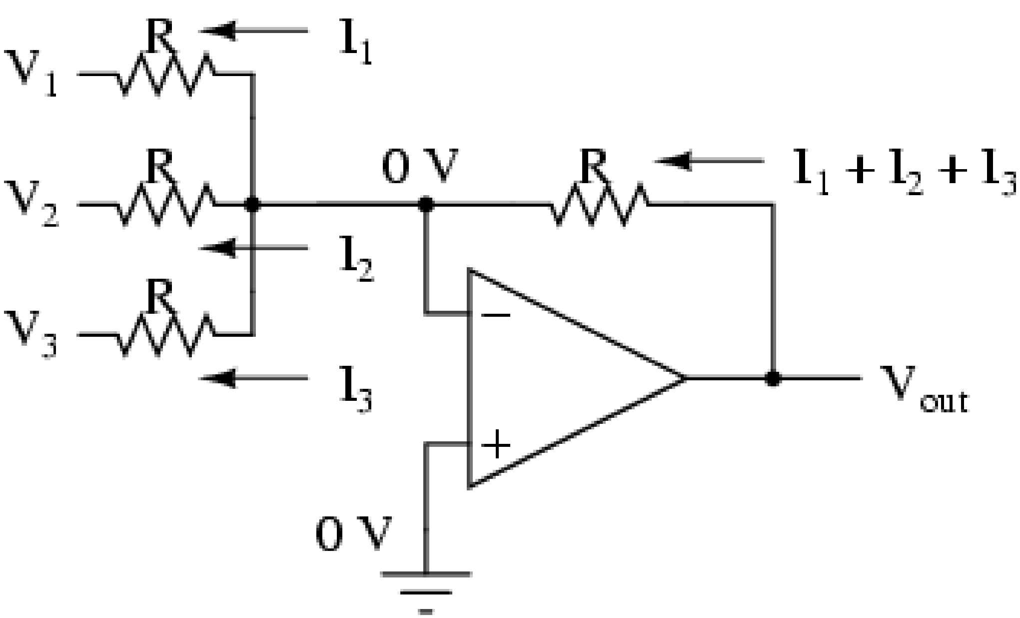
- N latches hold the binary number to be converted
- n transistors controlled by outputs of latches and control a particular resistor each
- VREF precision reference controls output voltage range
- Opamp provides summing function to add together the results of activating multiple switches simultaneously

Types of DAC implementations

- Binary Weighted Resistor
- R-2R Ladder

Binary Weighted Resistor

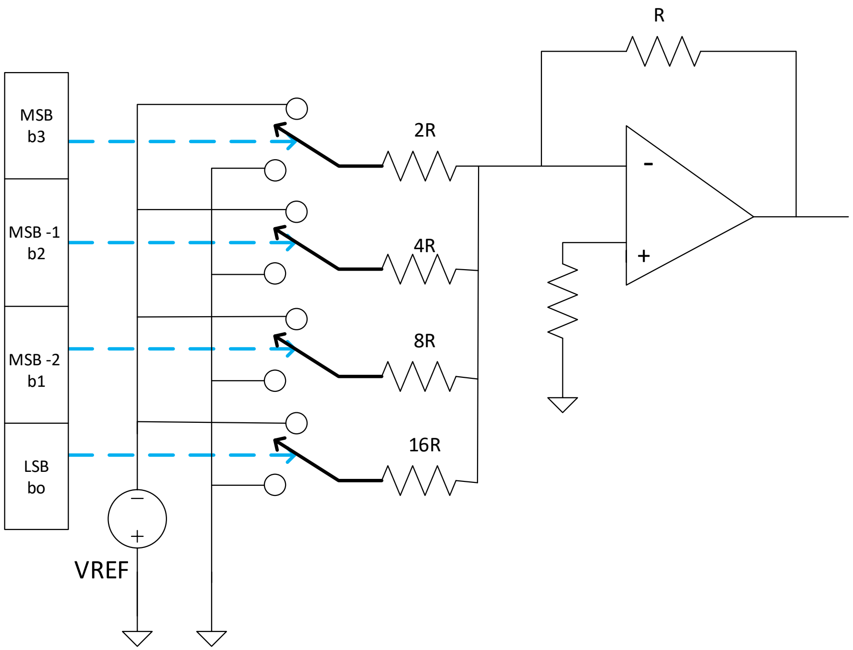
Inverting summer circuit



$$\mathbf{V_{out} = -(V_1 + V_2 + V_3)}$$

- Start with summing op-amp circuit
- Input voltage either high or ground
- Adjust resistor weighting to achieve desired Vout

Binary Weighted Resistor



- *Details*
  - Use transistors to switch between high and ground
  - Use resistors scaled by two to divide voltage on each branch by a power of two
  - V_1 is MSB, V_4 LSB in this circuit
- *Assumptions:*
  - Ideal Op-Amp
  - No Current into Op-Amp
  - Virtual Ground at Inverting Input

$$I_3 = \frac{\mathrm{V_{REF}}}{2\mathrm{R}} \rightarrow V_{out3} = \frac{\mathrm{V_{REF}}}{2}$$

$$I_2 = \frac{\mathrm{V_{REF}}}{4\mathrm{R}} \rightarrow V_{out2} = \frac{\mathrm{V_{REF}}}{4}$$

$$I_1 = \frac{\mathrm{V_{REF}}}{8\mathrm{R}} \rightarrow V_{out1} = \frac{\mathrm{V_{REF}}}{8}$$

$$I_0 = \frac{\mathrm{V_{REF}}}{16\mathrm{R}} \rightarrow V_{out0} = \frac{\mathrm{V_{REF}}}{16}$$

$$V_{out} = \mathrm{R}\left(I_3 + I_2 + I_1 + I_0\right)$$

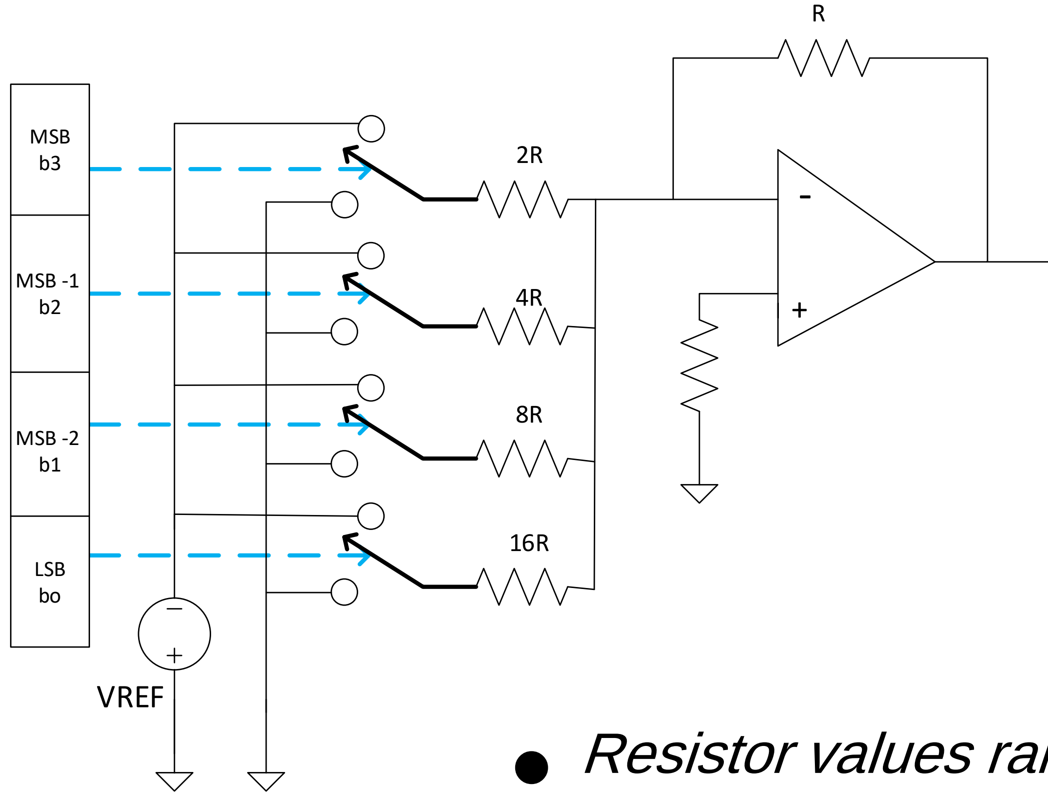
$$= R\left(\frac{\mathrm{V_{REF}}}{2\mathrm{R}} + \frac{\mathrm{V_{REF}}}{4\mathrm{R}} + \frac{\mathrm{V_{REF}}}{8\mathrm{R}} + \frac{\mathrm{V_{REF}}}{16\mathrm{R}}\right)$$

$$= \mathrm{V_{REF}}\left(b_3.\frac{1}{2} + b_2.\frac{1}{4} + b_1.\frac{1}{8} + b_0.\frac{1}{16}\right)$$

$$= \mathrm{V_{REF}}\left(b_3.2^{-1} + b_2.2^{-2} + b_1.2^{-3} + b_0.2^{-4}\right)$$

Ken Marek

Binary Weighted Resistor



For a 12 bit DAC

$$R = 5k\Omega$$

$$2^n R = 20.48M\Omega$$

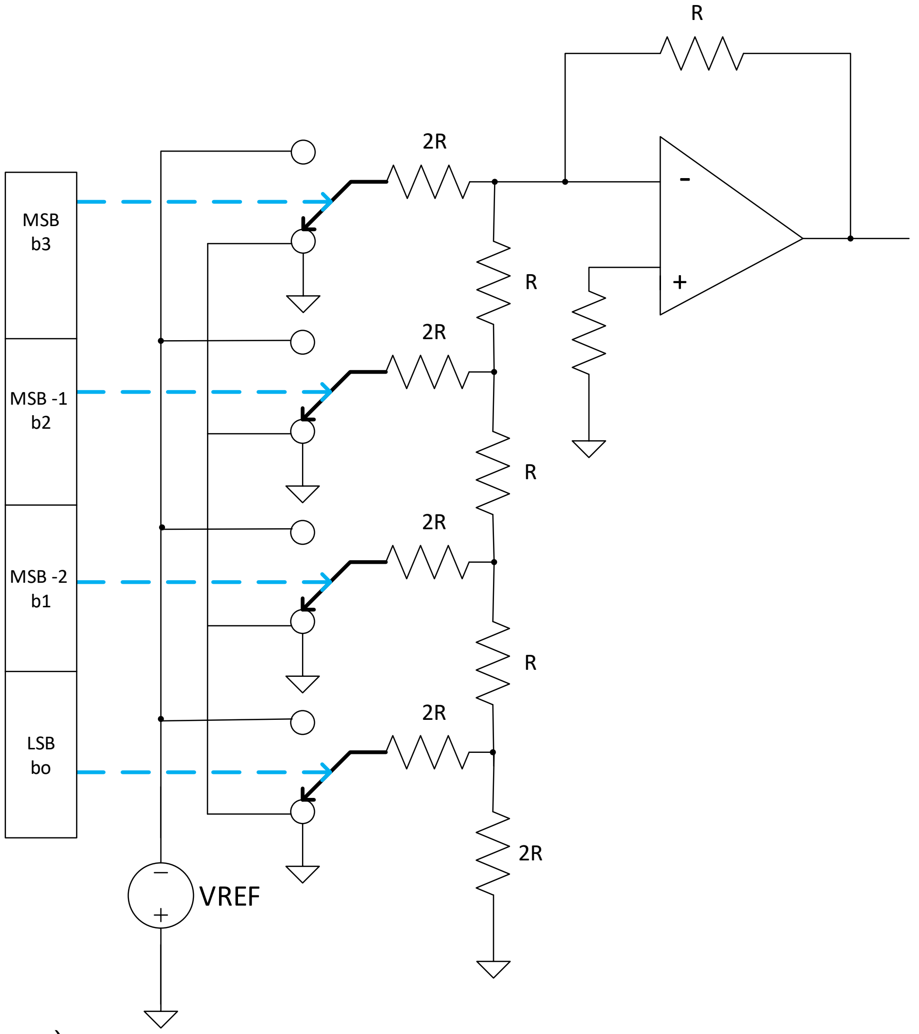
- *Resistor values range from R to 2^n*R which must be matched*
- *High value of resistance requires more silicon die area*
- *This results in higher cost*

Binary Weighted Resistor

- Advantages
  - Simple
  - Fast
- Disadvantages
  - Need large range of resistor values (2048:1 for 12-bit) with high precision in low resistor values
  - Need very small switch resistances
  - Op-amp may have trouble producing low currents at the low range of a high precision DAC

R-2R Ladder

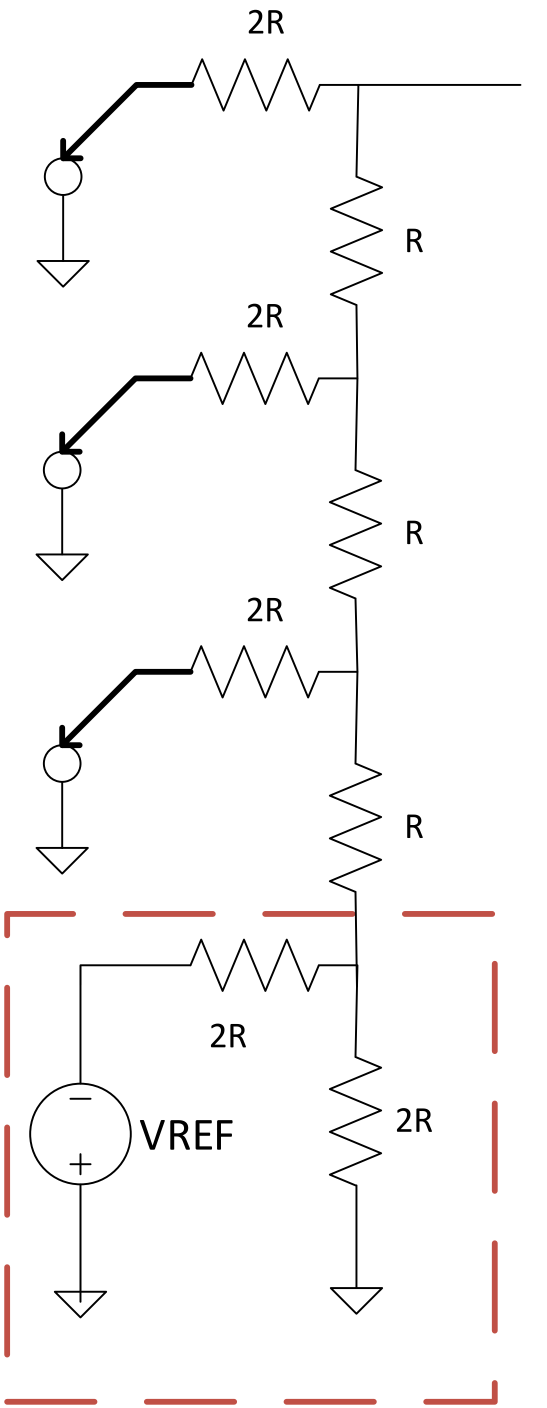
- Each bit corresponds to a switch:
  - If the bit is high "1", the corresponding switch is connected to the reference voltage
  - If the bit is low "0" , the corresponding switch is connected to ground.

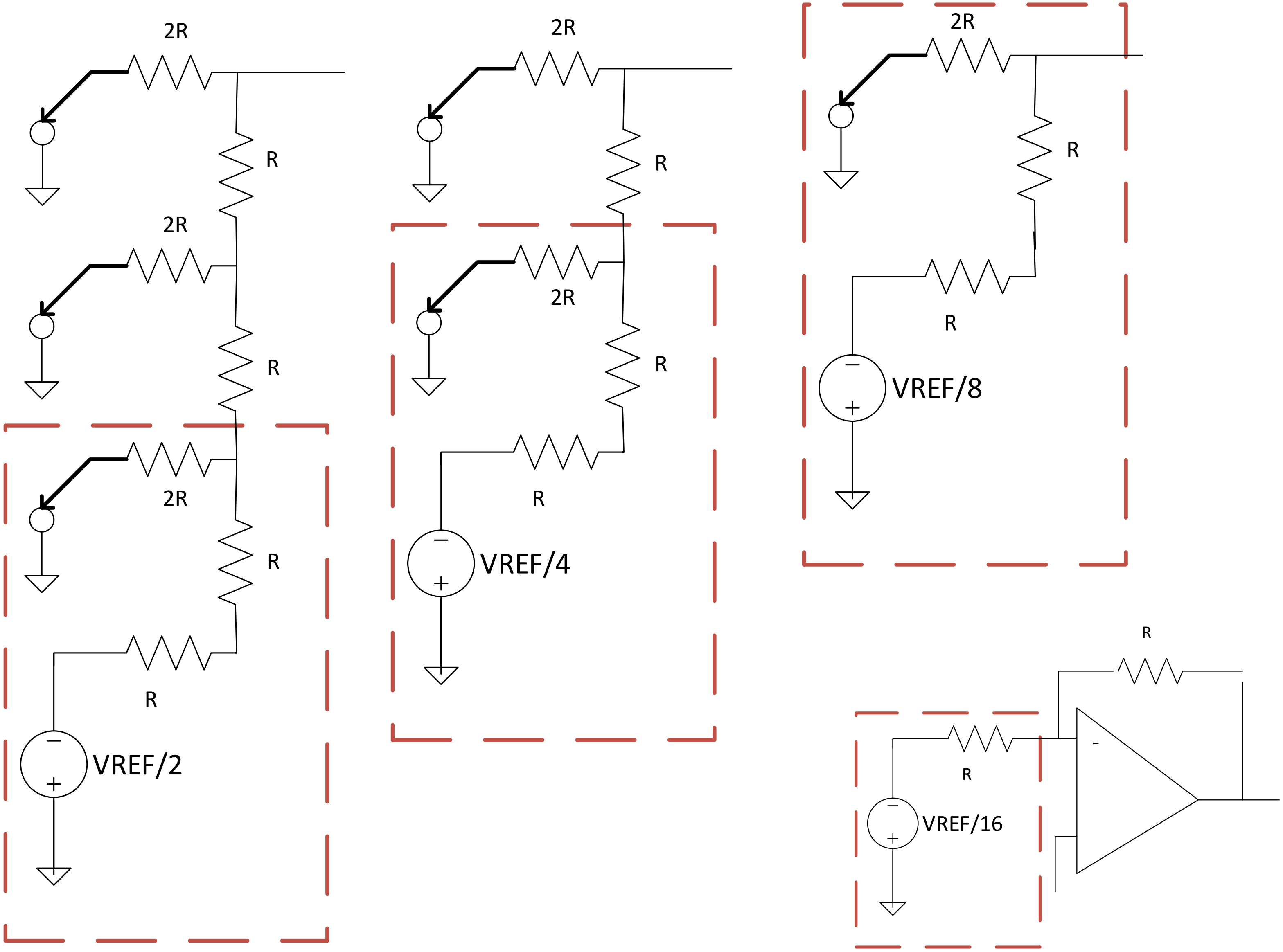


$$V_{out} = \mathrm{V_{REF}}\left(b_3.2^{-1} + b_2.2^{-2} + b_1.2^{-3} + b_0.2^{-4}\right)$$

R-2R Ladder

- Circuit may be analyzed using Thevenin's theorem and superposition by considering one bit high at a time (replace network with equivalent voltage source and resistance)
- Consider input =0001





$$V_{out} = \mathrm{V_{REF}}\left(0.2^{-1} + 0.2^{-2} + 0.2^{-3} + 1.2^{-4}\right) = \frac{\mathrm{V_{REF}}}{16}$$

- Contribution of each input bit can be found in a similar fashion , by setting its value to 1 while all other bits are set to zero
- R-2R DAC resistor values are limited to two values only R or 2R which is less expensive
- Number of resistors is less: 2n+1 and lower precision is acceptable
- Conversion speed is lower

- Example: an 8 bit DAC with 5V reference has an input 10100111, what is the output?

$$V_{out} = \frac{167}{256} * 5 = 3.2617\,\mathrm{V}$$

- Example: a 10 bit DAC with 10V reference, what input is required to get 6.5V output?

$$V_{out} = \frac{(\mathrm{N})_{10}}{2^{10}} * 10 = 6.5\,\mathrm{V}$$

$$(\mathrm{N})_{10} = \frac{6.5 * 2^{10}}{10} = 665.6$$

$$\text{if } \mathrm{N} = 665 ==> \mathrm{V} = 6.494$$

$$\text{if } \mathrm{N} = 666 ==> \mathrm{V} = 6.504 \text{ (closer to required value)}$$

- Highest value of N:
- Unipolar DAC:

$$V_{o\max} = \frac{(\mathrm{Nmax})_{10}}{2^n} * V_{FSR}; \text{where } \ \mathrm{Nmax} = 2^{\mathrm{n}} - 1$$

$$V_{o\max} = \frac{2^{\mathrm{n}} - 1}{2^n} * V_{FSR}$$

- For Bipolar DAC:

$$V_o = \frac{(\mathrm{N})_{10}}{2^n} * V_{FSR} - \frac{V_{FSR}}{2};$$

$$V_{o\max} = \frac{2^{\mathrm{n}} - 1}{2^n} * V_{FSR} - \frac{V_{FSR}}{2}$$

$$V_{o\min} = -\frac{V_{FSR}}{2}$$

Examples

- A bipolar 10 bit DAC has V_{FSR}=5V and a hexadecimal input 2A4, what is the output? And at what input the output will be zero?
- Solution: 2A4 = 10 1010 0100 ==> $(512+128+32+4)_{10}=676_{10}$

$$V_o = \frac{676}{1024}*5-\frac{5}{2} = -\ 0.8\ \text{V}$$

- For Vo=0

$$0 = \frac{(\mathrm{N})_{10}}{1024}*5-\frac{5}{2} ==>$$

$$N = 512$$

$$0010\,0000\,0000 ==> (200)_{\mathrm{H}}$$

- Determine how many bits a DAC should have to provide an output voltage increment of 0.04V if V_{FSR}=10V?

$$\Delta = \frac{V_{FSR}}{2^n} = 0.04$$

$$2^{\mathrm{n}} = \frac{10}{0.04} = 250$$

$$n \ln n = \ln 250$$

$$n = \frac{\ln 250}{\ln 2} = 7.966 ==> n = 8$$

General comments

- Circuits as shown produce only unipolar output
- Replacing ground with $-V_{ref}$ will allow V_{out} to be positive or negative

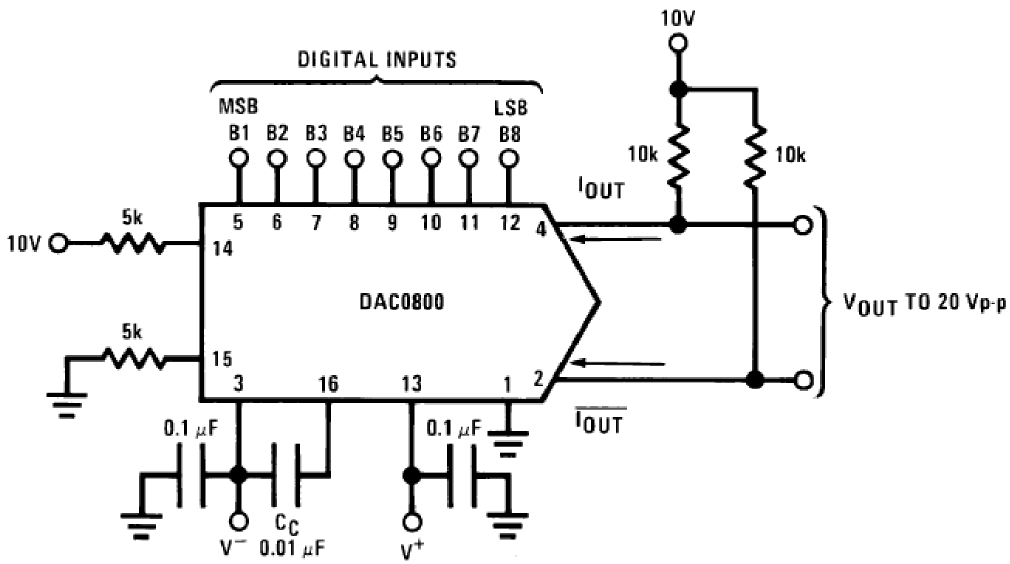
Other Types of DAC

A) DAC’s with current output (DAC0800)

- Used in many applications
- Can be used in applications requiring voltage output by converting current to voltage using any of the known techniques

DAC080x

- A popular all-purpose 8-bit D to A converter IC is the DAC080x series.
- The settling time is in the order of 100 ns.

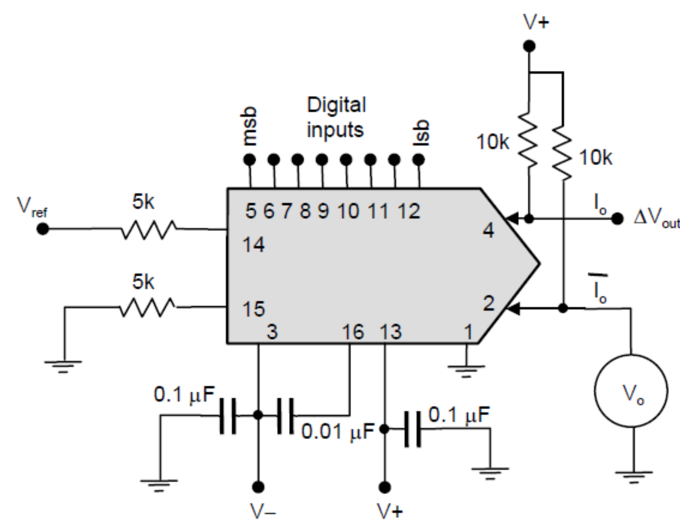


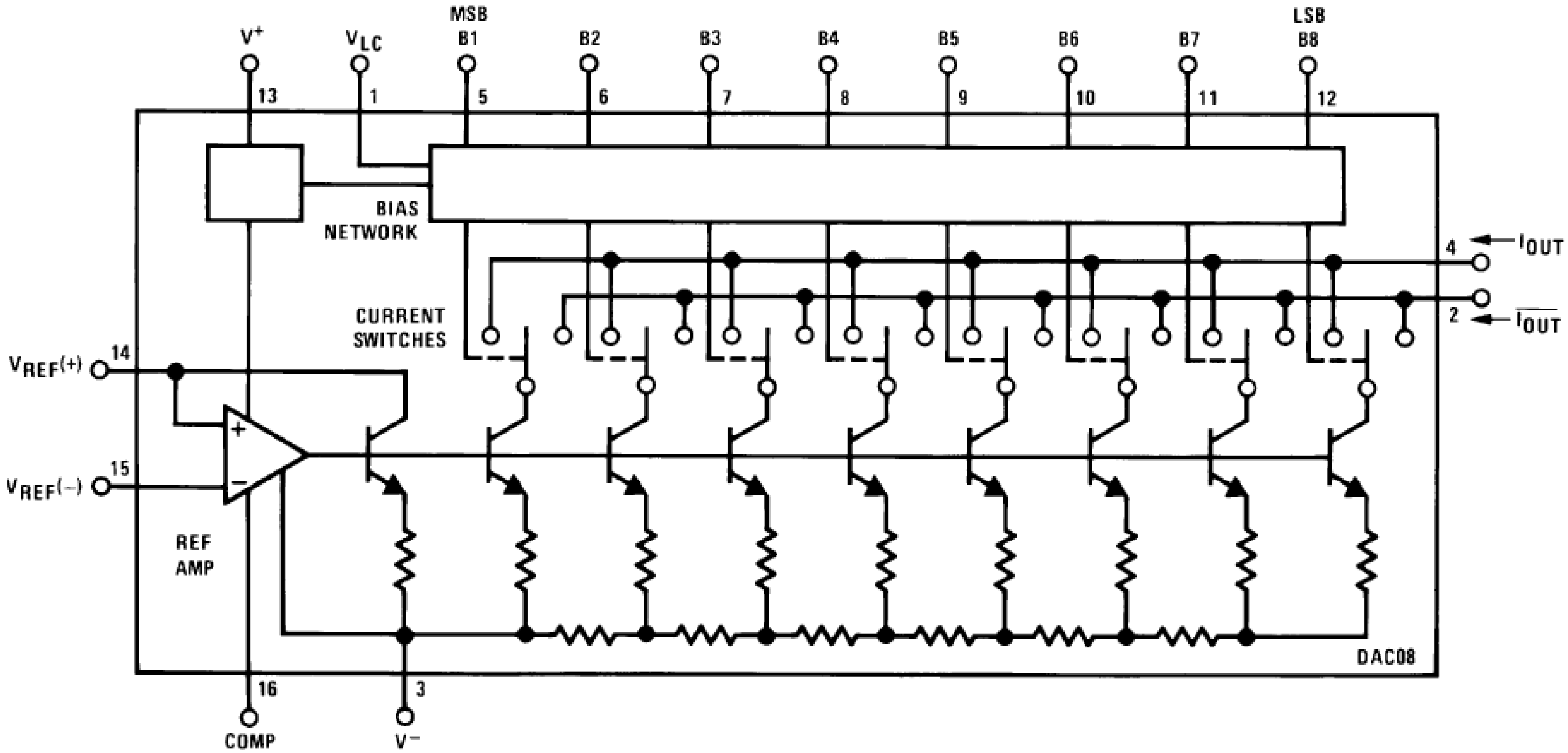
- The output for this IC is in the form of two **complementary currents** I_o and I_o'.
- In the diagram above, these current outputs are connected to a V+ supply through two 10K resistors

DAC080x

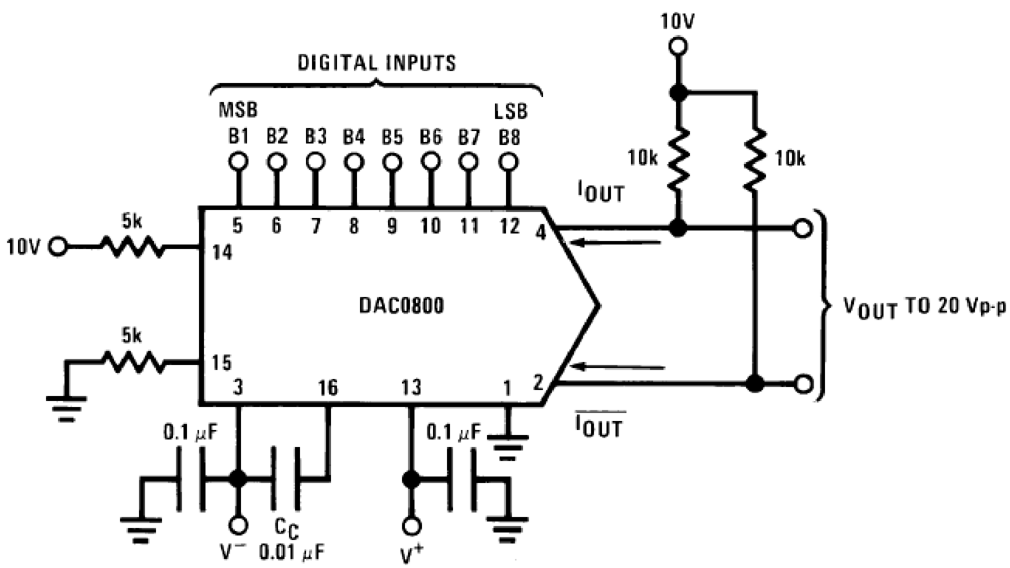
- A voltage output can be obtained by measuring the voltage between the two output terminals or measuring the voltage of one of the outputs with respect to ground.
- As the binary value of the digital inputs increases, Io increases and Io’ decreases. A decrease in Io’ means an decrease in the voltage drop across the 10k resistor and an increase in Vo measured w.r.t. ground.
- Vref provides a current reference. Setting Vref to V+ makes Vo swing positive and negative.
- Setting Vo to V+/2 gives

  a 0 to V+ analog output.

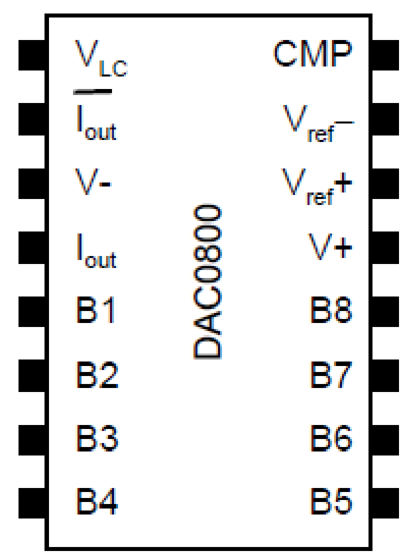




V+
VLC
MSB
B1
B2
B3
B4
B5
B6
B7
LSB
B8
13
1
5
6
7
8
9
10
11
12
BIAS
NETWORK
CURRENT
SWITCHES
4
IOUT
2
IOUT
VREF(+)
14
VREF(−)
15
REF
AMP
DAC08
16
COMP
3
V−

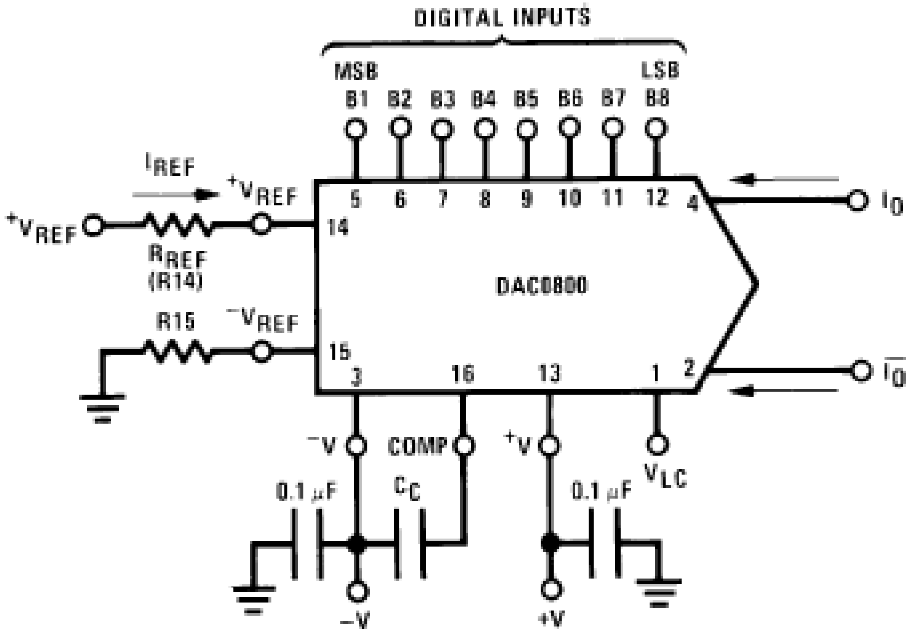


DIGITAL INPUTS
MSB
B1 B2 B3 B4 B5 B6 B7 B8
LSB
10V
5k
14
5k
15
5 6 7 8 9 10 11 12 4
DAC0800
3 16 13 1 2
10V
10k
10k
IOUT
IOUT
VOUT TO 20 Vp-p
0.1 μF
0.1 μF
V−
CC
0.01 μF
V+



VLC
CMP
Iout
Vref−
V-
Vref+
Iout
V+
B1
B8
B2
B7
B3
B6
B4
B5
DAC0800

Positive Reference Operation



$$I_{FS} \approx \frac{+V_{REF}}{R_{REF}} \times \frac{255}{256}$$

$I_O + \overline{I}_O = I_{FS}$ for all logic states

For fixed reference, TTL operation, typical values are:

V_{REF} = 10.000V

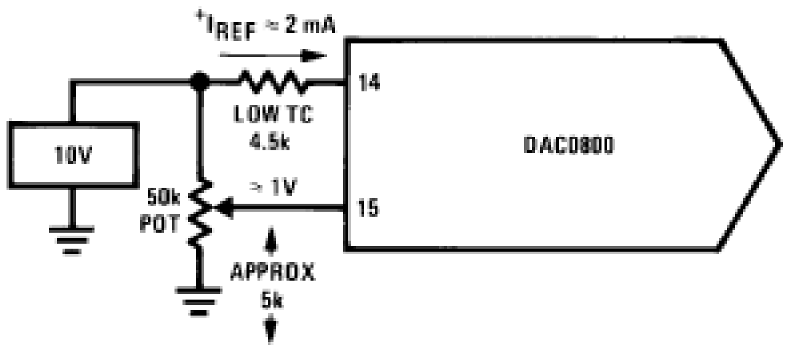
R_{REF} = 5.000k

R15 ≈ R_{REF}

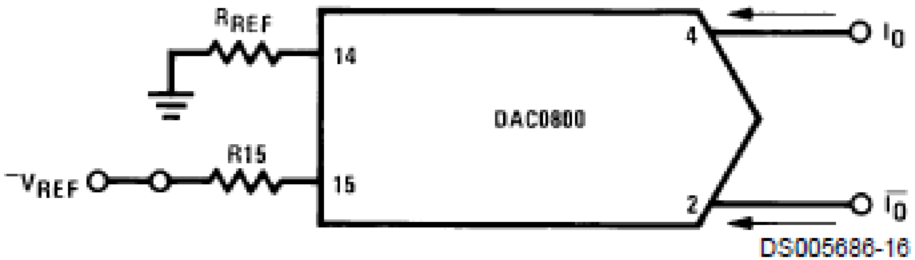
C_C = 0.01 μF

V_{LC} = 0V (Ground)

Recommended Full Scale Adjustment Circuit

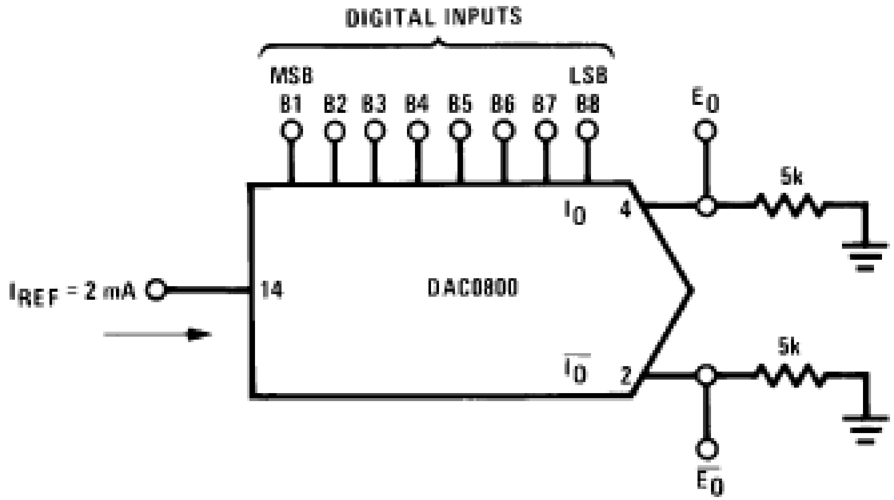


Basic Negative Reference Operation



$$I_{FS} \approx \frac{-V_{REF}}{R_{REF}} \times \frac{255}{256}$$

Note. R_{REF} sets I_{FS}; R15 is for bias current cancellation



	B1	B2	B3	B4	B5	B6	B7	B8	I_O mA	$\bar{I}_O$mA	E_O	$\bar{E}_O$
Full Scale	1	1	1	1	1	1	1	1	1.992	0.000	−9.960	0.000
Full Scale−LSB	1	1	1	1	1	1	1	0	1.984	0.008	−9.920	−0.040
Half Scale+LSB	1	0	0	0	0	0	0	1	1.008	0.984	−5.040	−4.920
Half Scale	1	0	0	0	0	0	0	0	1.000	0.992	−5.000	−4.960
Half Scale−LSB	0	1	1	1	1	1	1	1	0.992	1.000	−4.960	−5.000
Zero Scale+LSB	0	0	0	0	0	0	0	1	0.008	1.984	−0.040	−9.920
Zero Scale	0	0	0	0	0	0	0	0	0.000	1.992	0.000	−9.960

Basic Unipolar Negative Operation

B) Frequency to voltage converter (LM2917)

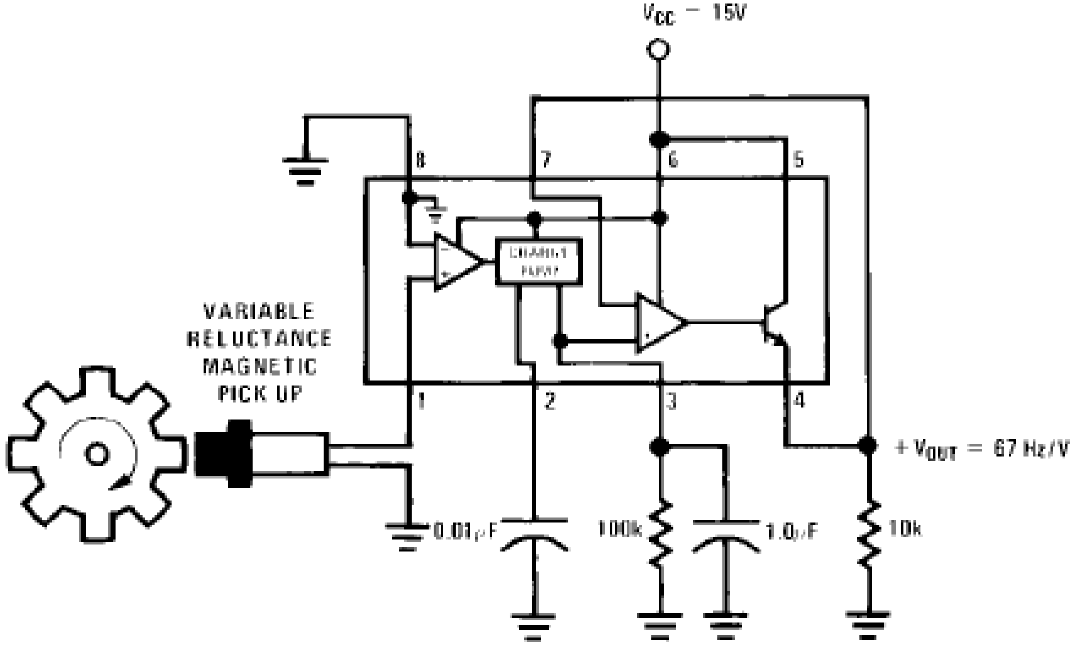
Accepts a signal and converts its frequency to a corresponding analog voltage level as an alternative of counting pulses for certain time , then converting the count via D/A methods

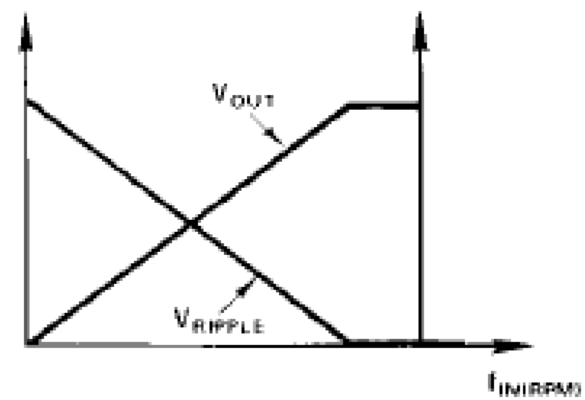
- The LM2907, LM2917 series are monolithic frequency to voltage converters with a high gain op amp/comparator designed to operate a relay, lamp, or other load when the input frequency reaches or exceeds a selected rate.
- The tachometer uses a charge pump technique and offers frequency doubling for low ripple, full input protection in two versions (LM2907-8, LM2917-8) and its output swings to ground for a zero frequency input.

Advantages

- Output swings to ground for zero frequency input
- Easy to use; $V_{OUT} = f_{IN} \times V_{CC} \times R_1 \times C_1$
- Only one RC network provides frequency doubling
- Zener regulator on chip allows accurate and stable frequency to voltage or current conversion (LM2917)

Minimum Component Tachometer





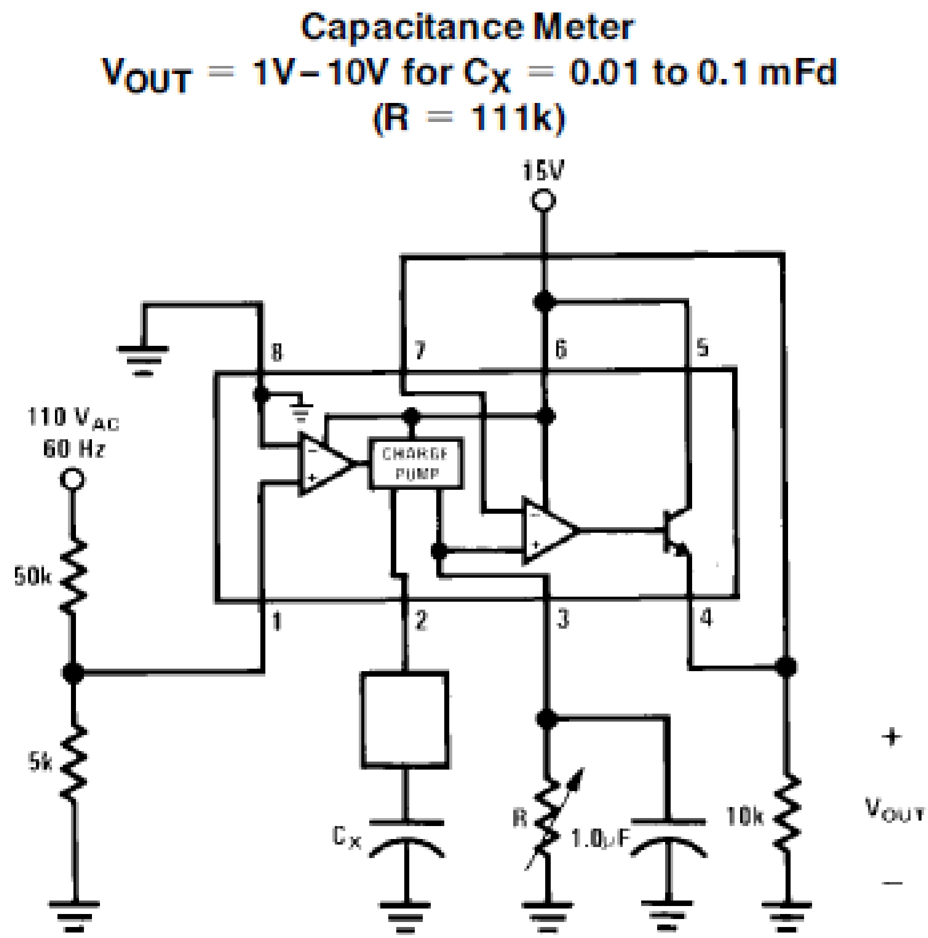
- Following the input stage is the charge pump where the input frequency is converted to a dc voltage. To do this requires one timing capacitor, one output resistor, and an integrating or filter capacitor.
- When the input stage changes state (due to a suitable zero crossing or differential voltage on the input) the timing capacitor is either charged or discharged linearly between two voltages whose difference is VCC/2
- Then in one half cycle of the input frequency or a time equal to 1/2 f_{IN} the change in charge on the timing capacitor is equal to VCC/2 x C1.

- The average amount of current pumped into or out of the capacitor then is:

$$\frac{\Delta Q}{T} = i_{c(AVG)} = C1 \times \frac{V_{CC}}{2} \times (2f_{IN}) = V_{CC} \times f_{IN} \times C1$$

- The output circuit mirrors this current very accurately into the load resistor R1, connected to ground, such that if the pulses of current are integrated with a filter capacitor, then
- V_O = ic x R1, and the total conversion equation becomes: $V_O = V_{CC} \times f_{IN} \times C1 \times R1 \times K$
- Where K is the gain constant - typically 1.0

Capacitance Meter



- C) Pulse width modulation
- The digital input code is used to generate a train of pulses of fixed frequency and variable width proportional to the input count, LPF is used to generate an output proportional to the average time spent in the high state, i.e. proportional to the input code
- D) Multiplying DACs (AD7541,7548,7845 and DAC 1230) : in these DACs , the output equal to the product of an input (voltage or current) and the input digital code

Types of DAC

- Multiplying DAC*
  – Reference source external to DAC package

- Nonmultiplying DAC
  – Reference source inside DAC package

*Multiplying DAC is advantageous considering the external reference.

- These DACs open the possibility for ratiometric measurements and conversions
- If a sensor is powered from the reference voltage that supplies the DAC or ADC , then variations in this voltage will not affect the measurement which relaxes requirements on references and power supplies

Data Acquisition

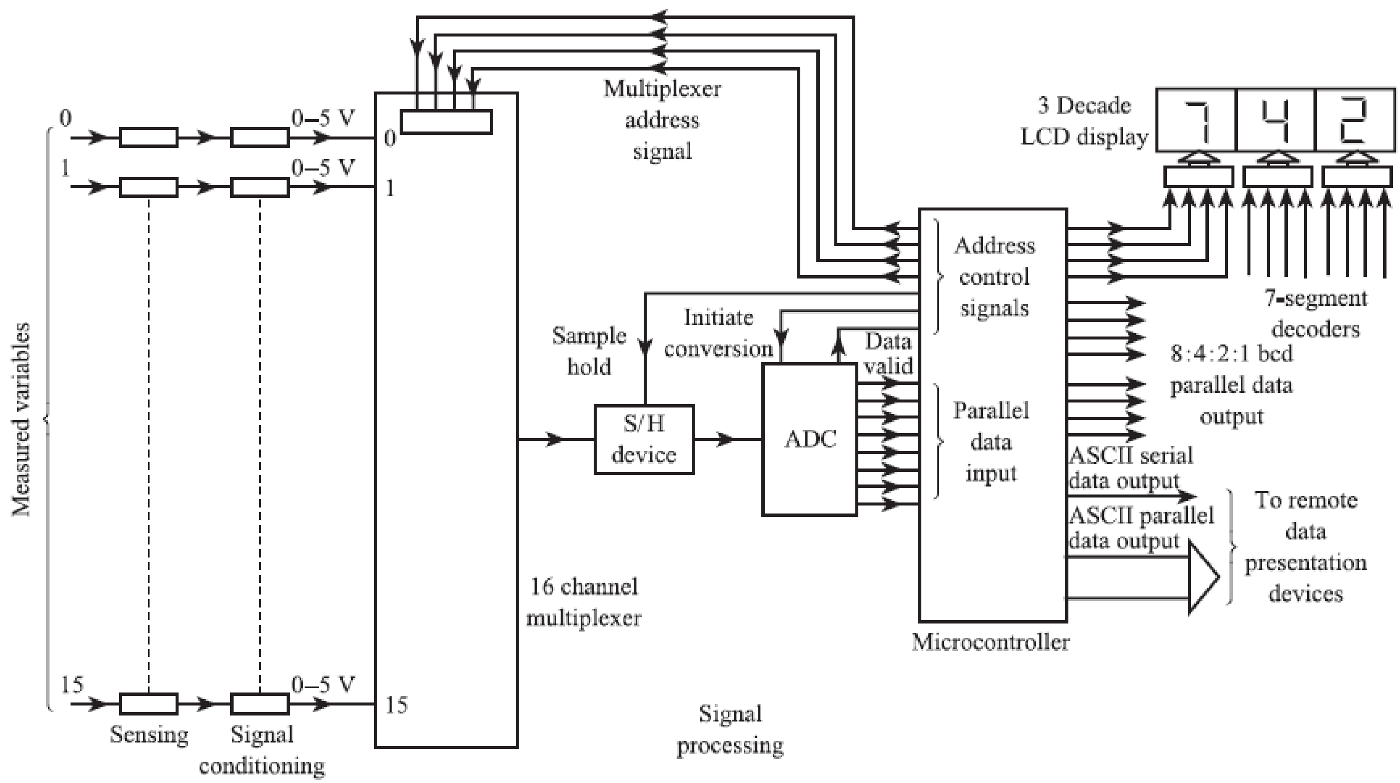
Need For Data Acquisition

- There are many applications where it is necessary to know, simultaneously, the measured values of several variables associated with a particular process, machine or situation.
- Examples are measurements of temperature measurements at different points in a nuclear reactor core, and components of velocity and acceleration for an aircraft.

- It would be extremely uneconomic to have several completely independent systems,and a single multi-input/multi-output **data acquisition system** is used.
- Here several elements are ‘time shared’ amongst the different measured variable inputs.

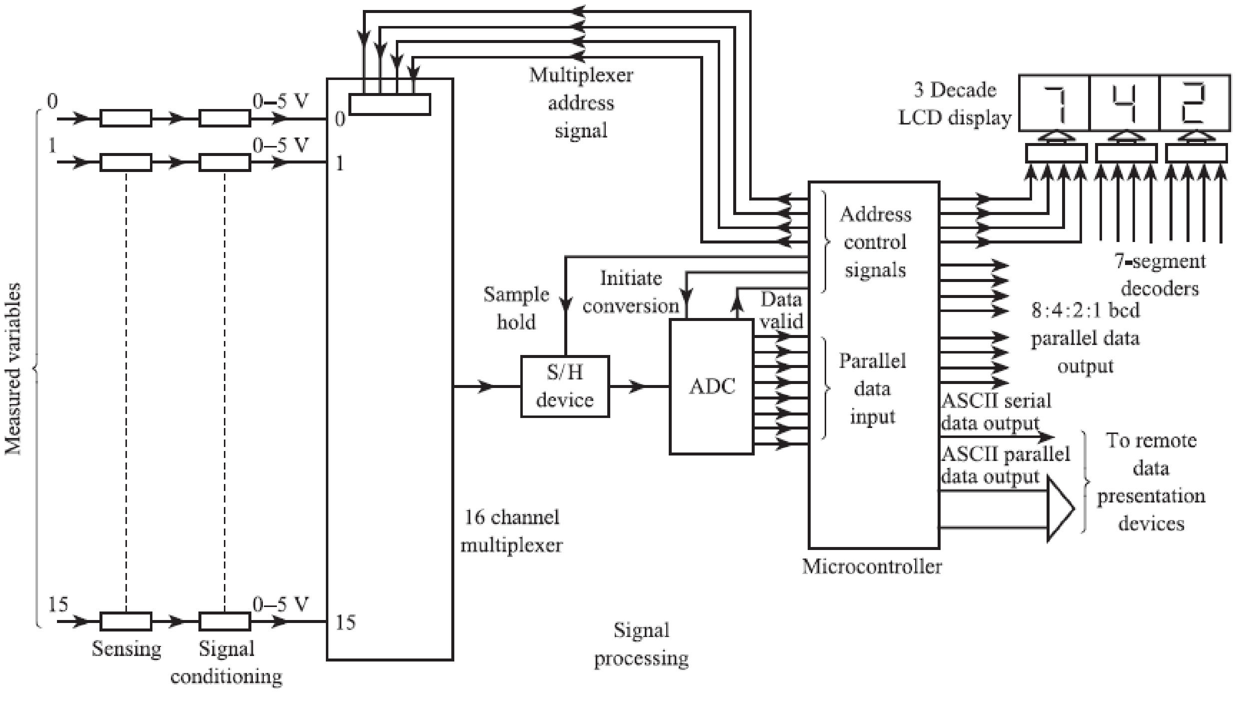
microcontroller-based data acquisition system

- a typical microcontroller-based data acquisition system is shown.
- The signal conditioning elements are necessary to convert sensor outputs to a common signal range, typically 0 to 5 V;
- The voltage signals are input to a 16- channel time division multiplexer, and the multiplexed signal is passed to a single sample/hold device and analogue-to-digital converter

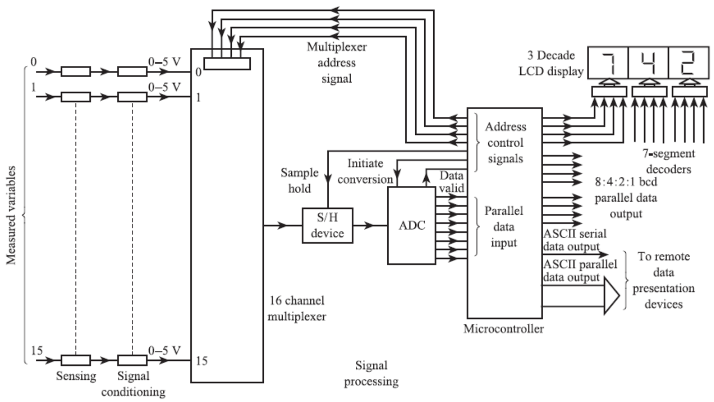


microcontroller-based data acquisition system

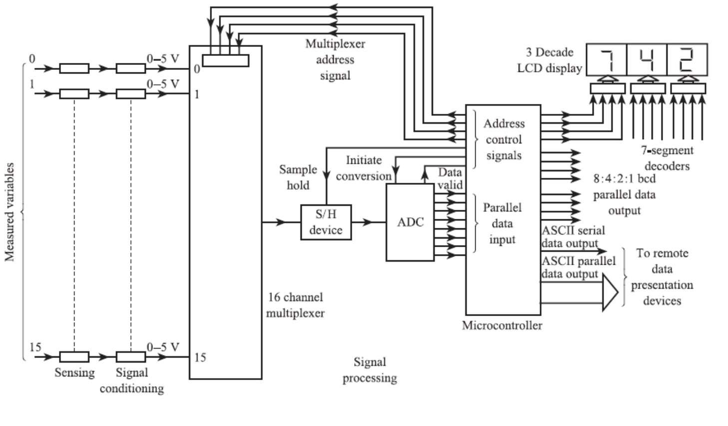
- In cases where all the sensors are of an identical type, for example 16 thermocouples, it is more economical to multiplex the sensor output signals.
- Here the multiplexed sensor signal is input to a single signal conditioning element, such as the reference junction circuit and instrumentation amplifier, before passing to the sample/hold and ADC.



- The ADC gives a parallel digital output signal which passes to one of the parallel input interfaces of the microcontroller.
- Another parallel input/output (I/O) interface provides the address and control signals necessary for the control of multiplexer, sample/hold and ADC.
- These are a four-bit multiplexer address signal, a **sample/ hold** control signal, an **initiate conversion** signal to the ADC, and a **data valid** signal from the ADC.
- The microcontroller performs whatever calculations (on the input data) are necessary to establish the measured value of the variable.
- A common example is the solution of the non-linear equation relating thermocouple e.m.f. and temperature



- The computer converts the measured value from hexadecimal into binary coded decimal form .
- This b.c.d. data is written into a computer parallel output interface.
- Each decade is then separately converted into seven-segment code and presented to the observer using a seven-segment LCD display
- The computer also converts each decade of the b.c.d. to ASCII form
- The resulting ASCII code is then written into a serial and/or parallel output interface.
- These can transmit ASCII data in serial and/or parallel form to remote data representation devices such as a monitor, printer or host computer.



Distributed Nature of processes

- The oil, water and gas industries are characterised by complex distribution systems involving the transfer of fluids by long pipelines from producing to consuming areas.
- Similarly, an electricity distribution system involves the transfer of electrical power from power stations to consumers, via a network of high voltage cables.
- These systems also include several items of equipment or plant, e.g. pumping stations, compressors, storage tanks and transformers, each with associated measured variables.
- These plant items are often located several miles from each other, in remote areas. It is essential for the effective supervision of these distribution systems that all relevant network measurement data are transmitted to a central control point.

Common Data Acquisition Hardware

- Several of the most common Data Acquisition Hardware configurations are as follows:
- Computer plug-in I/O.
- Distributed I/O.
- Stand-alone or distributed loggers* and controllers.
- IEEE-488 instruments.

Intelligent stand-alone loggers and controllers

- **Intelligent stand-alone loggers and controllers**, which can be monitored, controlled and configured from the computer via an RS-232 interface, and yet can be left to operate independently of the computer.
- It **can be configured and controlled by the computer, via the IEEE-488 communication interface**.

(for info only)

Computer plug-in I/O

- **Plug-in I/O boards are plugged directly into the computers expansion bus, are generally compact, and also represent the fastest method of acquiring data to the computers memory and/or changing outputs**.
- Along with these advantages, plug-in boards often represent the lowest cost alternative for a complete data acquisition and control system and are therefore a commonly utilized item of DAQ hardware

Distributed I/O ➔ Digital Transmitter

- One of the most commonly implemented forms of distributed I/O is the digital transmitter. These intelligent devices perform all required signal conditioning functions and contain a micro-controller and A/D converter, to perform the digital conversion of the signal within the module itself.
- Converted data is transmitted to the computer via an RS-232 or RS-485 communications interface.
- The use of RS-485 multi-drop networks, as shown in Figure 1.3, reduces the amount of cabling required, since each signal-conditioning module shares the same cable pair. Linking up to 32 modules, communicating over long distances, is possible when using the RS-485 multi-drop network.
- However, since very few computers have built in support for the RS-485 standard, an RS-232 to RS-485 converter is required to allow communications between the computer and the remote modules.

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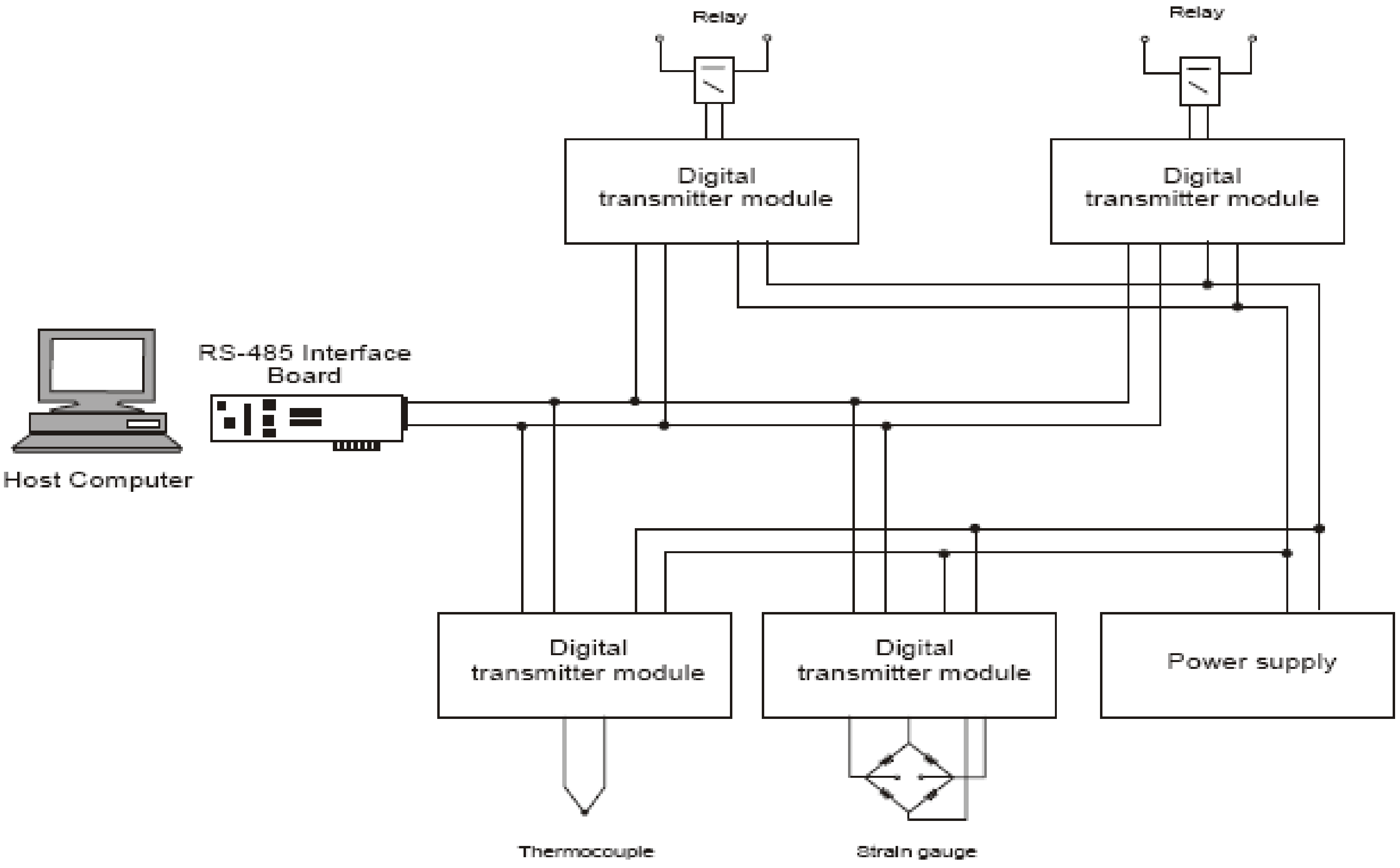


Figure 1.3

Distributed I/O – digital transmitter modules

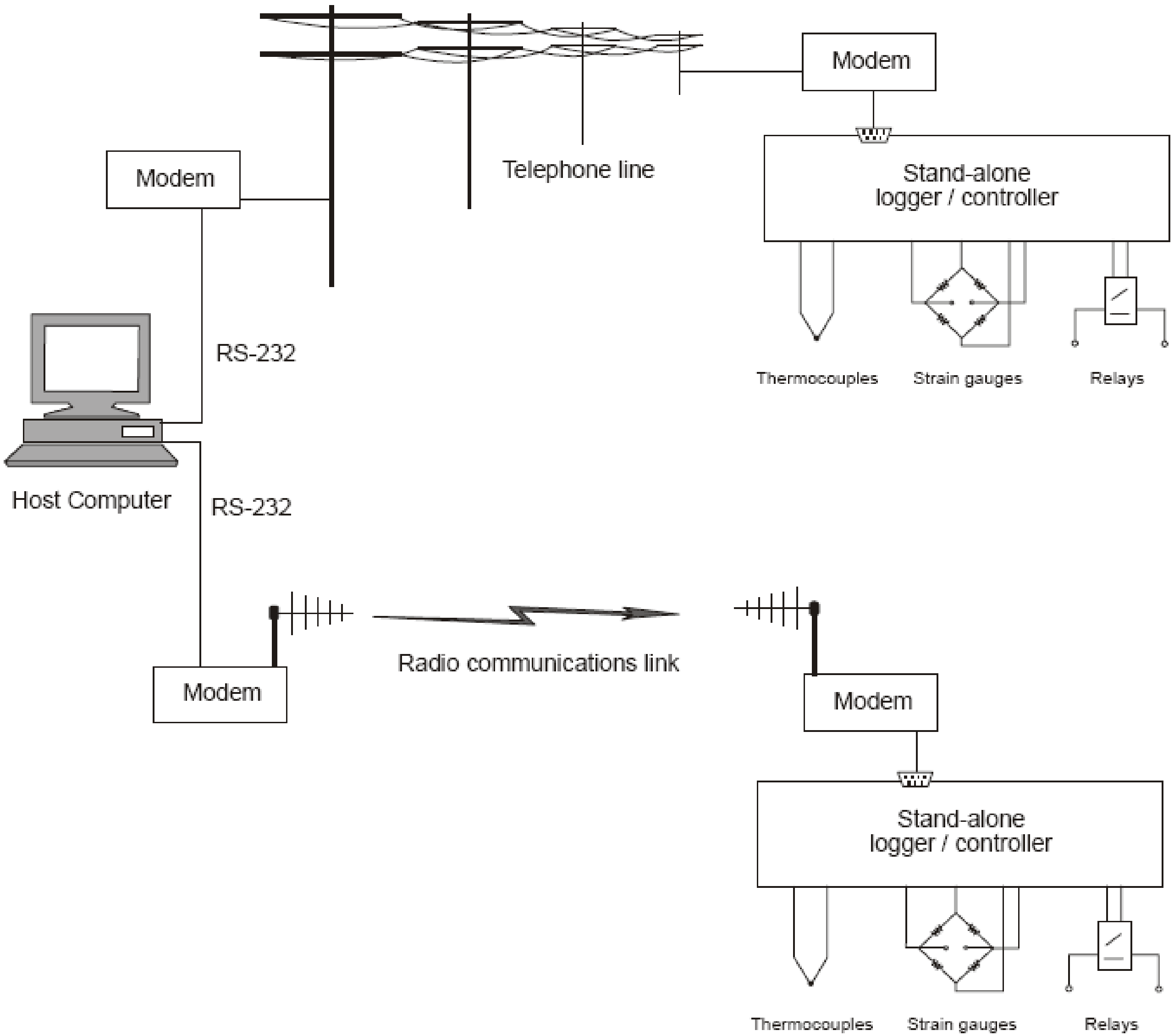


Figure 1.6
Remote connection to a stand-alone logger/controller via a telephone or radio communications network

(for info only)

- Where an application requires more than one logger/controller, each unit is connected within an RS-485 multi-drop network. A signal unit, deemed to be the host unit, can be connected directly to the host computer via the RS-232 serial interface, as shown in Figure 1.7, thus avoiding any requirement for an RS-232 to RS-485 serial interface card.
- The same methods of programming or logging data from each logger/controller are available either via the serial communications network or via using portable and reusable memory cards.

1.3.4 IEEE-488 (GPIB) remote programmable instruments

- The communications standard now known as GPIB (General Purpose Interface Bus), Was originally developed by Hewlett-Packard in 1965 as a digital interface for interconnecting and controlling their programmable test instruments.
- Originally referred to as the Hewlett Packard Interface Bus (HPIB), its speed, flexibility and usefulness in connecting instruments in a laboratory environment led to its widespread acceptance, and finally to its adoption as a world standard (IEEE-488).
- Since then, it has undergone improvements (IEEE-488.2) and SCPI (Standard Commands for Programmable Instruments), to standardize how instruments and their controllers communicate and operate.
- Evolving from the need to collect data from a number of different stand-alone instruments in a laboratory environment**, the GPIB is a high-speed parallel communications interface that allows the simultaneous connection of up to 15 devices or instruments on a short common parallel data communications bus**.
- **Devices must be placed within 3 meters or so of the host controller/ computer**

- A device connected to the bus can send data (bytes) to 14 other devices on the bus
- GPIB allows data to be sent at whatever rate the devices on the bus operate.
- Hardware consideration limit the max speed of data transmission to 250 kbytes/s (= 2 Mbits/s).
- GPIB is used to communicate with a set of instruments with the same interface for setting an automatic measurement and control system by a network of instruments

(for info only)

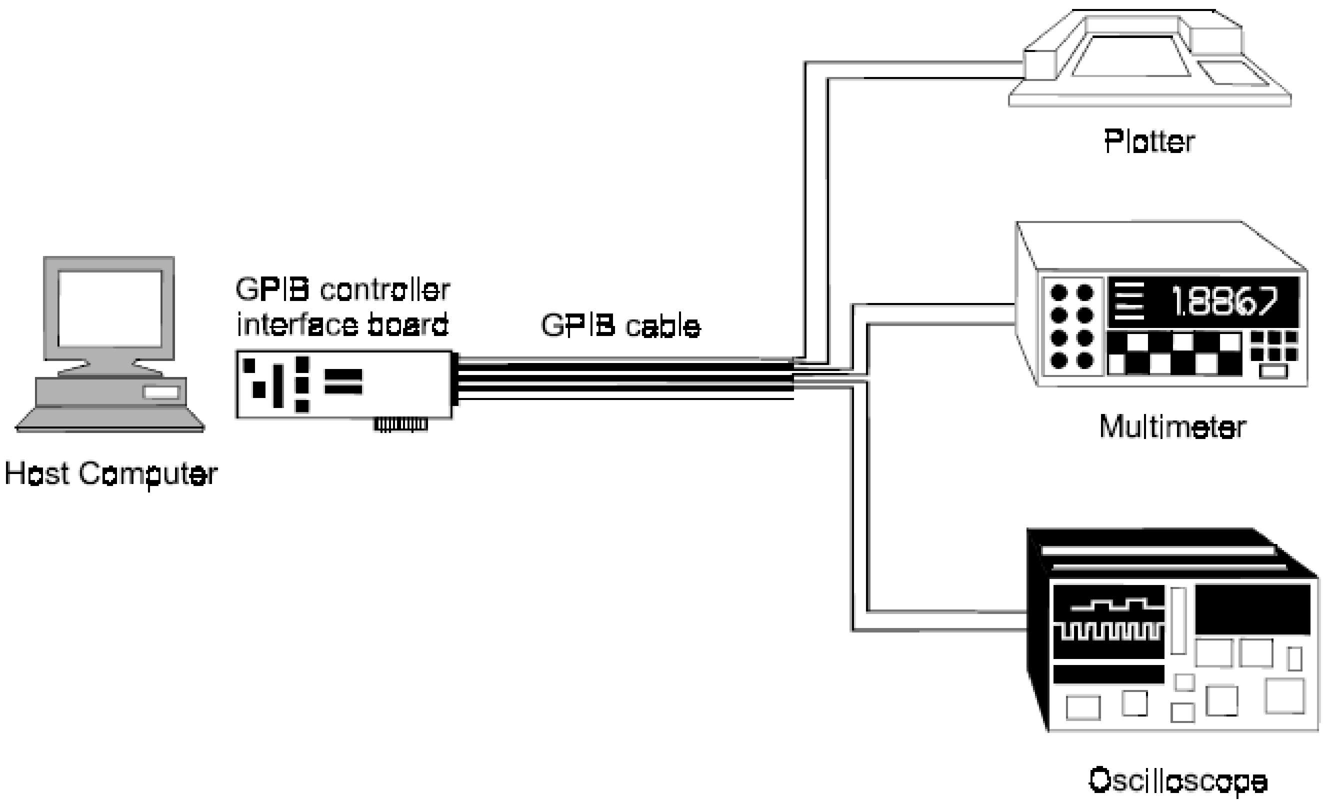
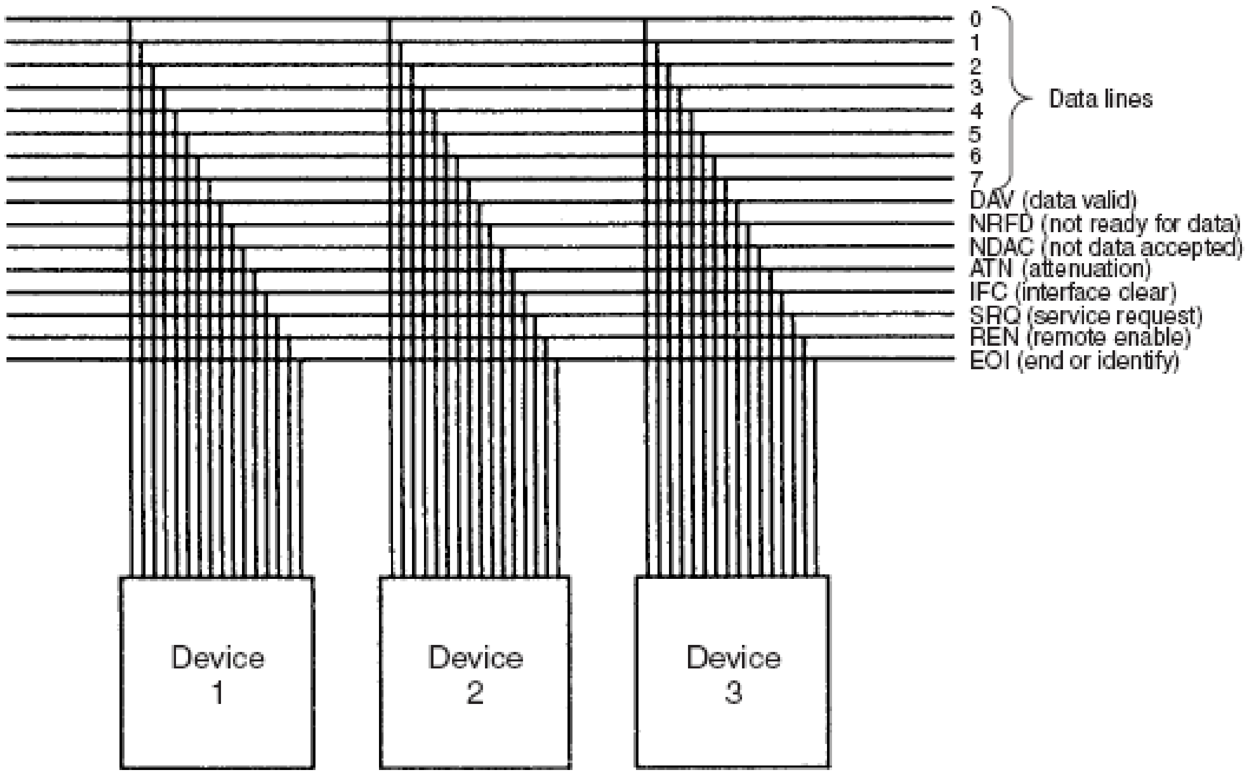


Figure 1.8
A typical GPIB system configuration

GPIB Bus Structure



-16 lines

- 8 carry data (or commands)
- 8 are bus control lines: 3 provide handshaking to coordinate data transfer and 5 are other bus control functions

Device on GPIB

Are classified into:

- Listener: may receive data over the bus
- Talker: may send data over the bus
- Listener/ Talker:
- Controller: at least one device must act as a controller (usually PC that also act as listener and talker)

*Any one device can perform combination of these functions.

Only 15 devices are allowed on the bus, if more are used, this causes overloading and unreliable operation

- GPIB signal logic:1) TTL voltage levels

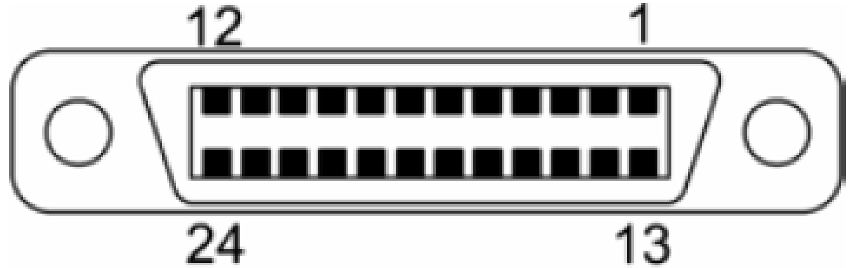
  2) negative logic ➔ < 0.8V (logic 1); > 2.5 (logic 0)

- Lines are driven by open collector drivers

(for info only)

IEEE-488 conne

Pin out



A female IEEE-488 connector

Pin 1	DIO1	Data input/output bit.
Pin 2	DIO2	Data input/output bit.
Pin 3	DIO3	Data input/output bit.
Pin 4	DIO4	Data input/output bit.
Pin 5	EOI	End-or-identify.
Pin 6	DAV	Data valid.
Pin 7	NRFD	Not ready for data.
Pin 8	NDAC	Not data accepted.
Pin 9	IFC	Interface clear.
Pin 10	SRQ	Service request.
Pin 11	ATN	Attention.
Pin 12	SHIELD	
Pin 13	DIO5	Data input/output bit.
Pin 15	DIO7	Data input/output bit.
Pin 16	DIO8	Data input/output bit.
Pin 17	REN	Remote enable.
Pin 18	GND	(wire twisted with DAV)
Pin 19	GND	(wire twisted with NRFD)
Pin 20	GND	(wire twisted with NDAC)
Pin 21	GND	(wire twisted with IFC)
Pin 22	GND	(wire twisted with SRQ)
Pin 23	GND	(wire twisted with ATN)
Pin 24	Logic ground	

Other Interfaces

- GPIB used for managing large measurement systems
- Serial Interface is often used when a single instrument is to be connected to a PC over long distance
- RS232 was originally developed in 1960s and it is slow, not flexible and rarely used on instruments, however it is used for specific applications such as reading in data from remote dc sensors and sending data to loggers
- Other more modern, serial asynchronous data transmission protocols include RS422, RS423, RS449, RS485 and USB
- RS stands for recommended standard

RS-232 Voltage levels/ Important

- The RS-232 standard defines the voltage levels that correspond to logical one and logical zero levels. Valid signals are plus or minus 3 to 15 volts. The range near zero volts is not a valid RS-232 level;
- logic one is defined as a negative voltage, the signal condition is called marking, and has the functional significance of OFF.
- Logic zero is positive, the signal condition is spacing, and has the function ON.
- The standard specifies a maximum open-circuit voltage of 25 volts; signal levels of ±5 V,±10 V,±12 V, and ±15 V are all commonly seen depending on the power supplies available within a device. RS-232 drivers and receivers must be able to withstand indefinite short circuit to ground or to any voltage level up to +/-25 volts.
- The slew rate, or how fast the signal changes between levels, is also controlled.
- Because the voltage levels are higher than logic levels typically used by integrated circuits, **special intervening driver circuits are required to translate logic levels**. These also protect the device's internal circuitry from short circuits or transients that may appear on the RS-232 interface, and provide sufficient current to comply with the slew rate requirements for data transmission.

  (Such as MAX232 that converts TTL to +/-15V)
- Because both ends of the RS-232 circuit depend on the ground pin being zero volts, problems will occur when connecting machinery and computers where the voltage between the ground pin on one end, and the ground pin on the other is not zero. This may also cause a hazardous ground loop (think about using isolation!)
- Unused interface signals terminated to ground will have an undefined logic state. Where it is necessary to permanently set a control signal to a defined state, it must be connected to a voltage source that asserts the logic 1 or logic 0 level. Some devices provide test voltages on their interface connectors for this purpose.

RS232 basic characteristics

- 1 driver, 1 receivers
- ~ 50 Feet
- Rate : 20Kb/s
- Single Ended

RS-422

- 1 driver, 10 receivers
- 4000 Feet
- Rate : 100Kb/s -10Mb/s
- Differential

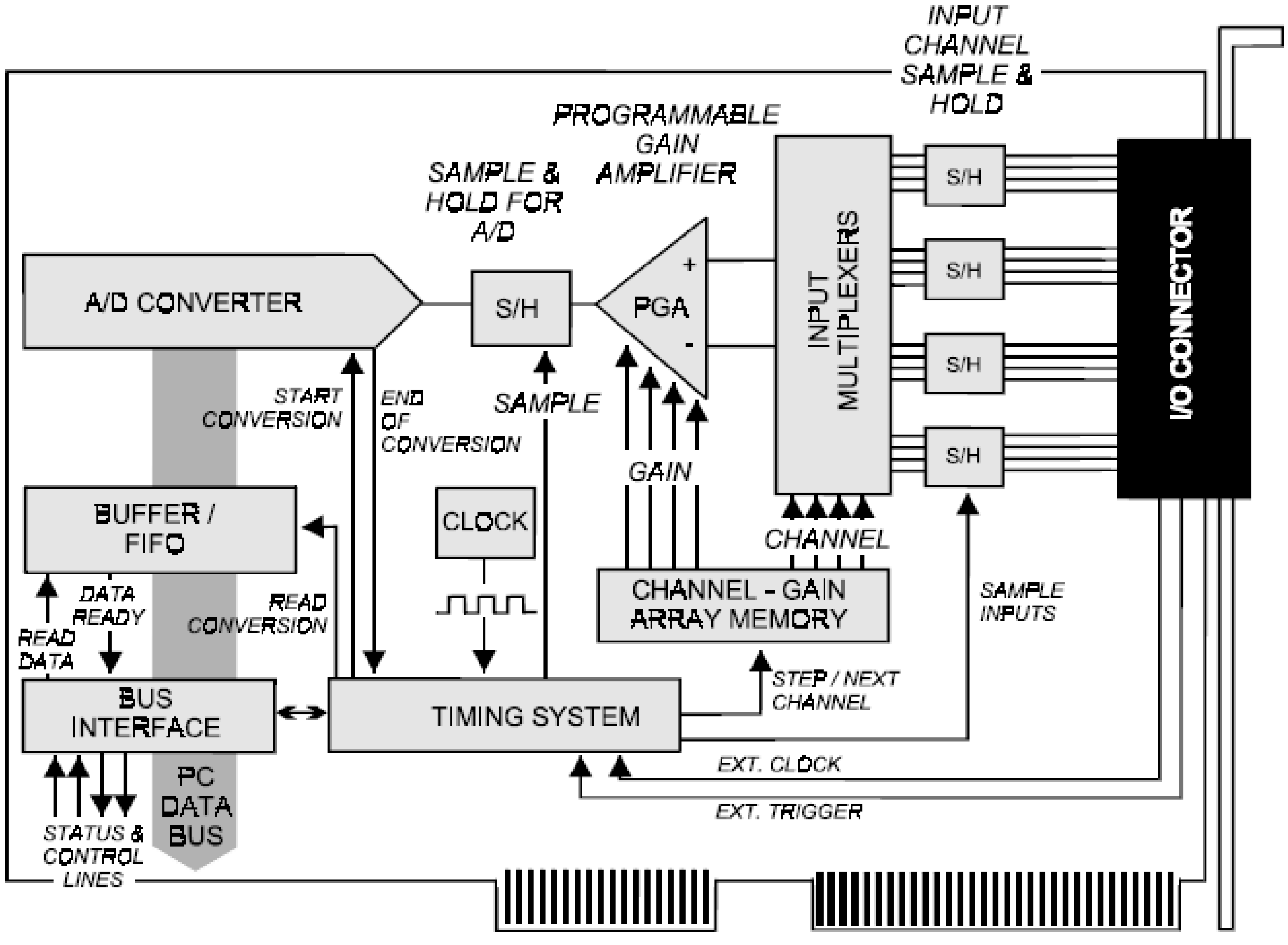
RS-485

- 32 driver, 32 receivers
- 4000 Feet
- Rate : 100Kb/s -10Mb/s
- Differential

(for info only)

SPECIFICATIONS		RS232	RS423	RS422	RS485
Mode of Operation		SINGLE -ENDED	SINGLE -ENDED	DIFFERENTIAL	DIFFERENTIAL
Total Number of Drivers and Receivers on One Line (One driver active at a time for RS485 networks)		1 DRIVER 1 RECVR	1 DRIVER 10 RECVR	1 DRIVER 10 RECVR	32 DRIVER 32 RECVR
Maximum Cable Length		50 FT.	4000 FT.	4000 FT.	4000 FT.
Maximum Data Rate (40ft. - 4000ft. for RS422/RS485)		20kb/s	100kb/s	10Mb/s-100Kb/s	10Mb/s-100Kb/s
Maximum Driver Output Voltage		+/-25V	+/-6V	-0.25V to +6V	-7V to +12V
Driver Output Signal Level (Loaded Min.)	Loaded	+/-5V to +/-15V	+/-3.6V	+/-2.0V	+/-1.5V
Driver Output Signal Level (Unloaded Max)	Unloaded	+/-25V	+/-6V	+/-6V	+/-6V
Driver Load Impedance (Ohms)		3k to 7k	>=450	100	54
Max. Driver Current in High Z State	Power On	N/A	N/A	N/A	+/-100uA
Max. Driver Current in High Z State	Power Off	+/-6mA @ +/-2v	+/-100uA	+/-100uA	+/-100uA
Slew Rate (Max.)		30V/uS	Adjustable	N/A	N/A
Receiver Input Voltage Range		+/-15V	+/-12V	-10V to +10V	-7V to +12V
Receiver Input Sensitivity		+/-3V	+/-200mV	+/-200mV	+/-200mV
Receiver Input Resistance (Ohms), (1 Standard Load for RS485)		3k to 7k	4k min.	4k min.	>=12k

A/D Board


INPUT CHANNEL SAMPLE & HOLD
PROGRAMMABLE GAIN AMPLIFIER
SAMPLE & HOLD FOR A/D
A/D CONVERTER
S/H
PGA
+
-
INPUT MULTIPLEXERS
S/H
S/H
S/H
S/H
I/O CONNECTOR
START CONVERSION
END OF CONVERSION
SAMPLE
GAIN
BUFFER / FIFO
CLOCK
CHANNEL
CHANNEL - GAIN ARRAY MEMORY
SAMPLE INPUTS
DATA READY
READ DATA
READ CONVERSION
BUS INTERFACE
TIMING SYSTEM
STEP / NEXT CHANNEL
EXT. CLOCK
EXT. TRIGGER
PC DATA BUS
STATUS & CONTROL LINES

- Total throughput, for multiple conversions on different channels, is often increased by overlapping parts of this cycle.
- For example:

  While the A/D converter is busy converting the S/H output, the next channel/gain pair can be output to the multiplexer and PGA, so that their settling and delay times are overlapped with the A/D conversion time.
- The timing circuitry may also include a block-sampling mode, which allows blocks of samples to be collected at regular intervals at the A/D board’s maximum sampling rate.

Sampling Techniques

- These techniques are discussed in the following sections:
- **Continuous channel scanning**
- **Simultaneous sampling**
- **Block mode operations**

Continuous channel scanning

- The method of sampling that facilitates the connecting of the required input channel to the A/D converter at a constant rate is known as continuous channel scanning.
- Continuous channel scanning allows channels to be sampled in a pre-determined and arbitrary order (e.g. channel 5, channel 1, channel 11), as well as at different sampling rates.
- An example of this would be the sampling of three channels in the following order (channel 5, channel 1, channel 11, channel 1). Channel 1 is being sampled at twice the rate as channels 5 & 11, which for an A/D board with throughput of 100 kHz represents a sampling rate of 50 kHz.
- Channels 5 & 11 are sampled at 25 kHz.

- There are two methods of continuous channel scanning, either under software control or by on-board hardware control using Channel Gain Array.

- When the input multiplexer switches between channels, a time skew/delay is generated between each channel sampled.
- On an A/D board being sampled at its maximum total throughput of 200 kHz, the minimum channel-to-channel time skew/delay between samples on different channels is 5 μs. Since the skew is additive from channel to channel, the total time skew between the first and last samples, when 16 channels are being sampled, is 80 μs.
- Time skew between signal measurements taken on different channels can lead to an inaccurate portrayal of the events that generated the signals as demonstrated on next slide.

Error due to continuous scanning

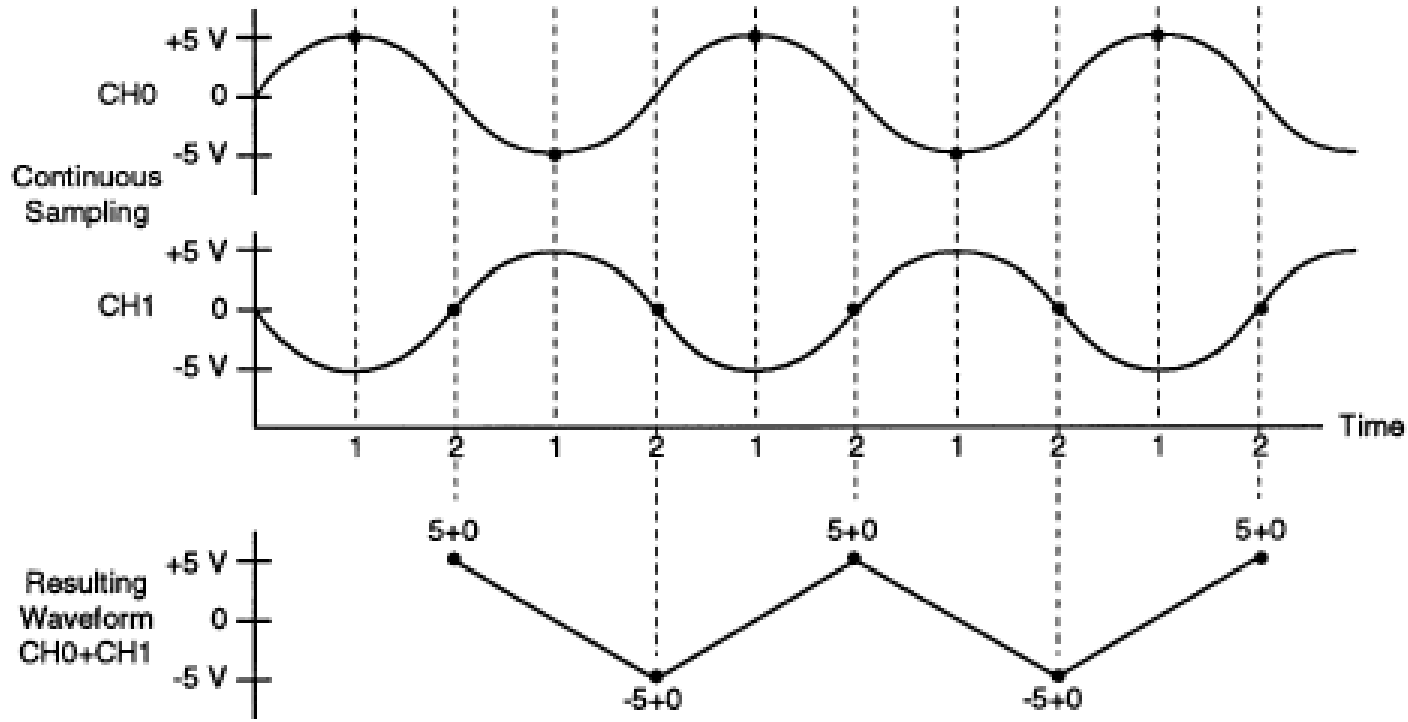


FIGURE 96.9 If the channel skew is large compared with the signal, then erroneous conclusions may result.

Simultaneous Sampling

- **Where the time relationship between each channel sampled is unimportant, or the skew/delay is negligible compared to the speed of the channel scan rate, such delays are not significant**.
- **In many applications, however, such as those dealing with accurate phase measurements or high-speed transient analysis, time skew between channels is unacceptable, since it is crucial to determine the output of several signals on different channels, at precisely the same time.**
- To avoid the timing errors introduced when continuously sampling from one input channel to the next, special applications require A/D boards capable of simultaneous sampling.
- These A/D boards are fitted with **so-called simultaneous sample and hold devices on all input channels**. The sample and hold device on each input channel holds the sampled data until the A/D converter can scan each channel.

Block mode triggering/Sampling / **(for info only)**

- Block mode triggering initiates an A/D conversion on all the required input channels at the maximum sampling rate of the A/D board, every time a sample trigger pulse occurs.
- A second counter is used to trigger the sampling of each of the channels at the maximum sampling rate. The number of samples to be taken in each block is typically stored by software in an on-board buffer, while the channel and gain for each sample in the block is read from the channel/gain array. The scan sequence is repeated at the next sample trigger pulse.
- Consider an example where four channels are being sampled at a total throughput rate of 20 kHz, corresponding to a channel scan rate of 5 kHz. Figure 5.23 shows that in continuous scanning mode, the total scan time is 200 μs, with the samples evenly spaced every 50 μs.
- In block trigger mode, the four samples are taken in a single scan sequence at the maximum throughput of the board. Assuming the board is capable of taking samples at 200 kHz, the time between each of these four samples is 5 μs, while the total time taken for all the samples is 20 μs instead of 200 μs.

FYI

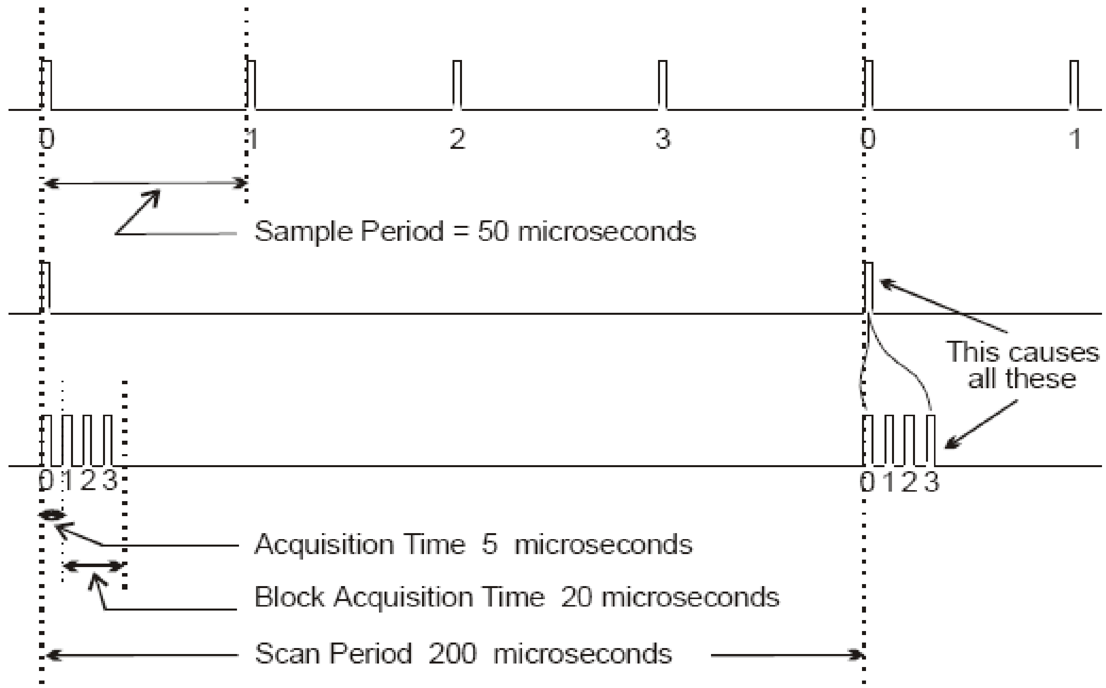


Figure 5.23
Conventional and burst trigger scanning

FYI

- Where the sampling rate remains the same, that is, a sample trigger occurs every 50 μs, the throughput of the board is increased by the number of samples taken in each sample block.
- In this case, the throughput would be increased to 80 kHz.

Important

- Maximum throughput per channel = Total throughput / # of channels
- For example if you wish to sample 4 channels at 50 kHz each, you need a board with throughput of 200 kHz

General Purpose DAQ/DAS

- Example is the AT-MIO-16

(for info only)

AT-MIO-16 (Just for reference)

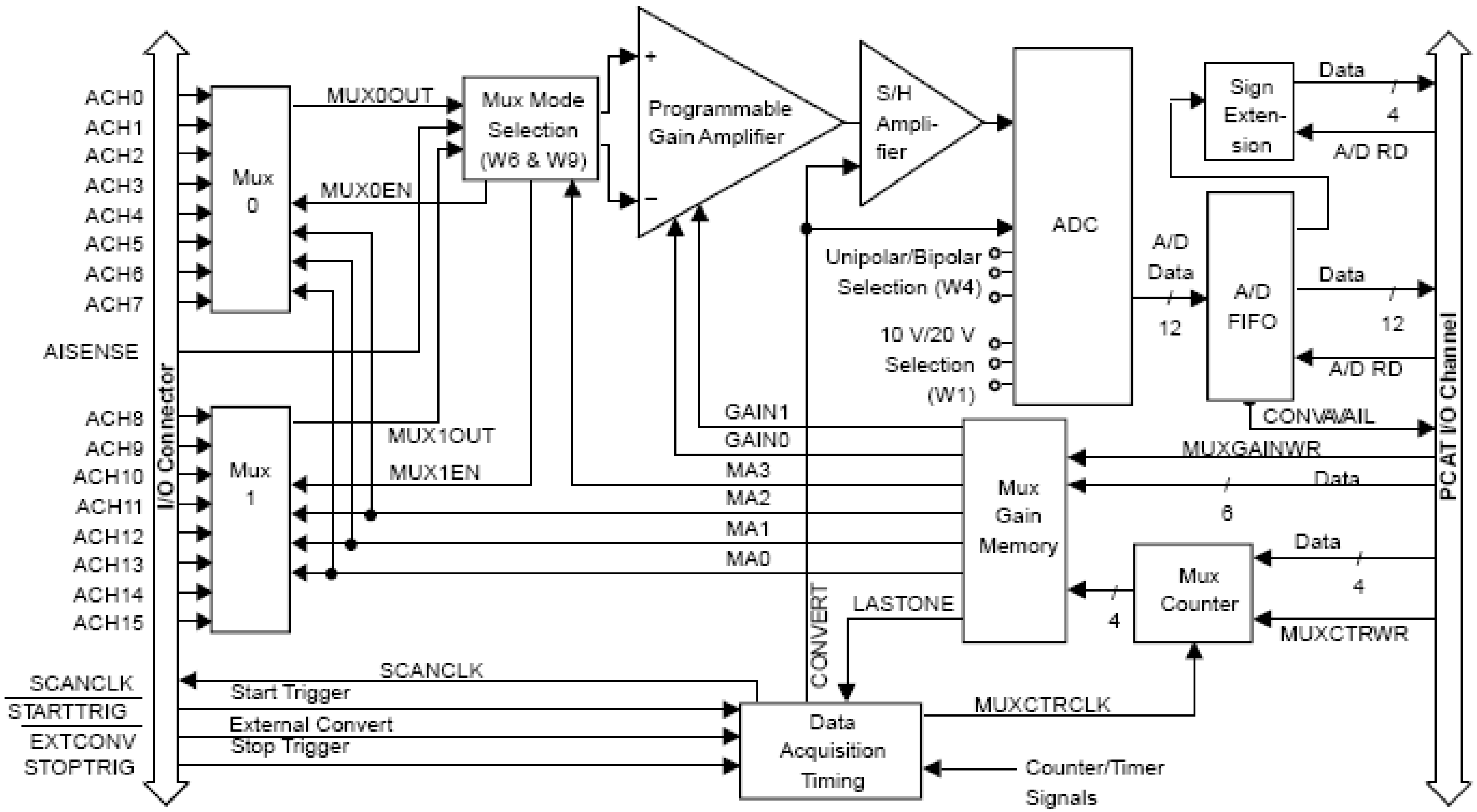


Figure 2-3. Analog Input and Data Acquisition Circuitry Block Diagram

Instrumentation