Xi'an Jiaotong-Liverpool University
西交利物浦大学

EEE220 Instrumentation and Control System

2018-19 Semester 2

Dr. Qing Liu

Email: qing.liu@xjtlu.edu.cn

Office: EE516

Department of Electrical and Electronic Engineering

28 Feb, 2019

Lecture 4

Outline

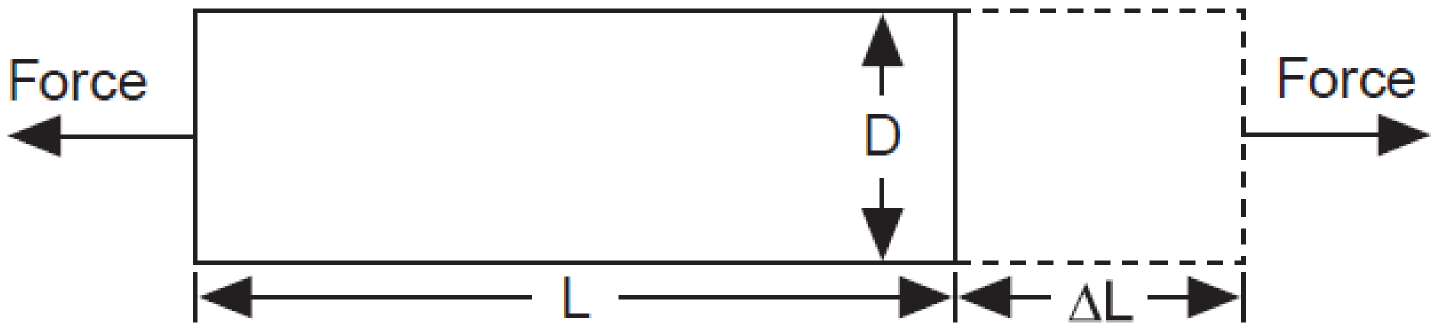
Sensors & Transducers

- **Strain Sensors**
  - Strain gauge
- **Position and Displacement Sensors**
  - Potentiometer
  - Capacitive element
  - Optical encoder

What is Strain?

Strain is the amount of deformation of a body due to an applied force. More specifically, strain (ε) is defined as the fractional change in length, as shown in Figure below.

Strain can be positive (tensile) or negative (compressive).



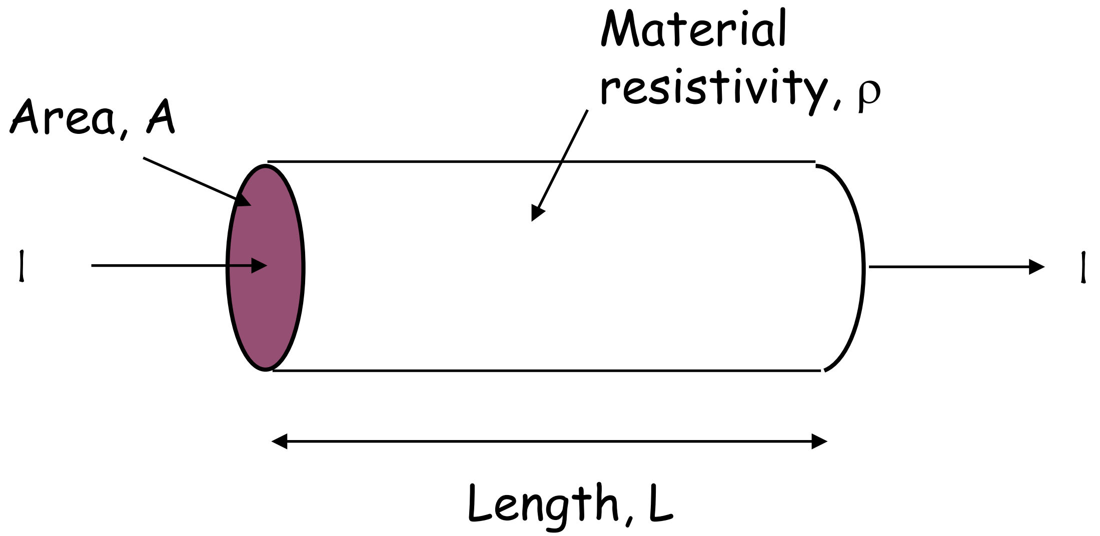
$$\varepsilon = \frac{\Delta L}{L}$$

Measurement of Strain

Resistance gauges are normally used. The resistance value of a conductor is given by:

$$R = \rho L / A$$

where ρ = resistivity,
L= length of conductor
A = cross-sectional area through which the current flows.

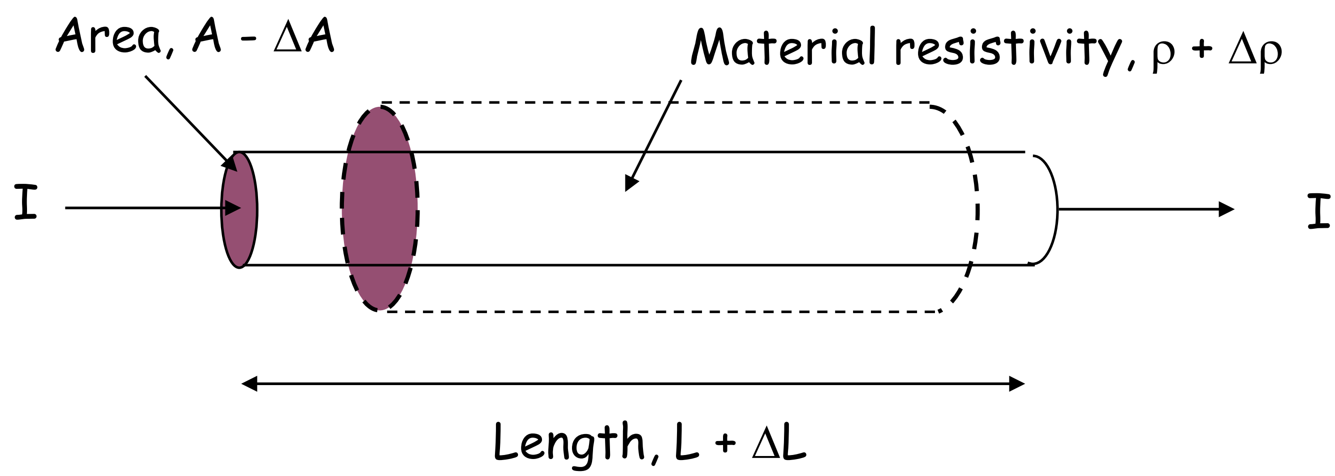


When stretched by the application of tensile forces, all of these factors change: ρ increases, L increases and A decreases. Thus the fractional change in resistance is greater than the strain applied (i.e. the fractional change in length) by a factor of (typically) between 2 and 3.

This is known as the '**gauge factor**': **G.** Thus

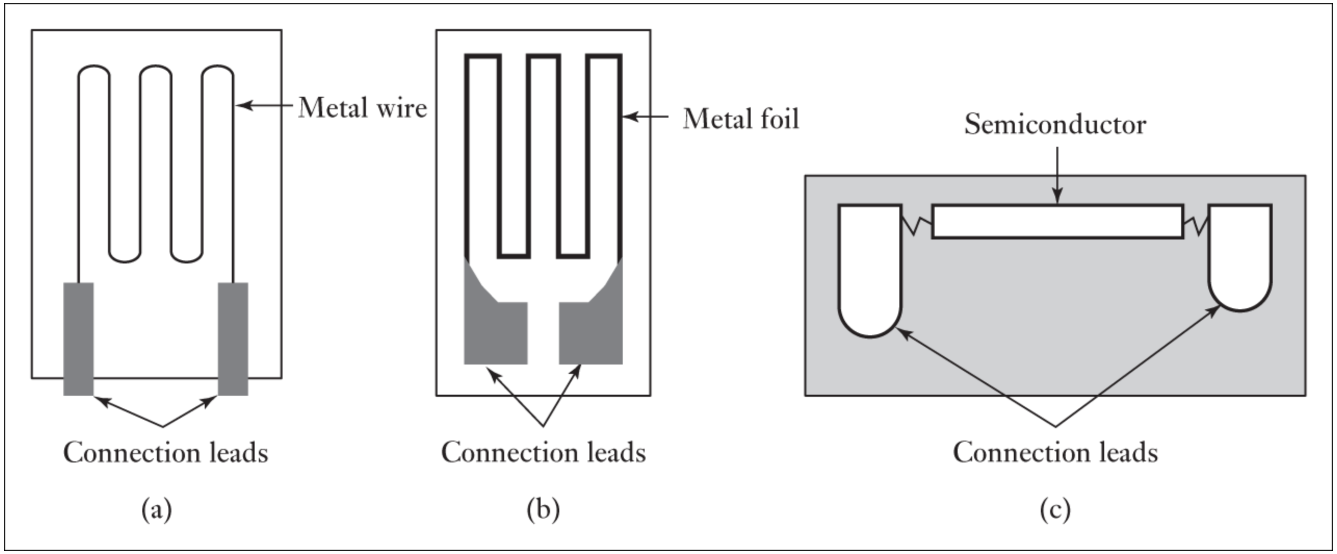
$$\frac{\Delta R}{R} = G\varepsilon$$

where ε = strain = $\Delta L/L$.



Strain Gauge

Fig. Three types of strain gauges.



- There are several methods of measuring strain, the most common is with a strain gauge, which is a metal wire, metal foil strip or a strip of semiconductor material which is wafer-like and can be stuck onto surfaces like a postage stamp.

Strain Gauge (cont'd)

- When subject to strain, resistance of the gauge R changes, the fractional change in resistance $\Delta R/R$ being proportional to the strain ε, i.e.,

$$\frac{\Delta R}{R} = G\varepsilon$$

Example 4.1

Consider an electrical resistance strain gauge with a resistance of 100Ω and a gauge factor of 2.0. What is the change in resistance of the gauge when it is subject to a strain of 0.001?

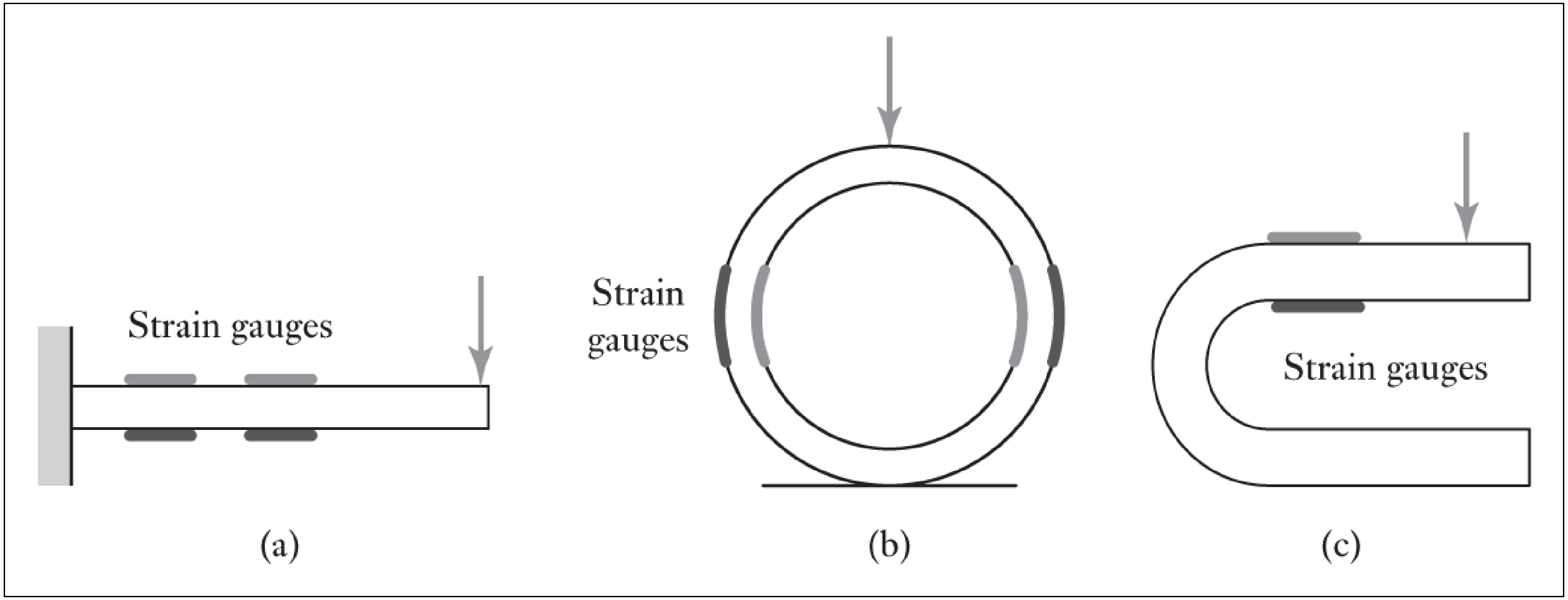
Solutions: the fractional change in resistance is

$$\Delta R = RG\varepsilon = 2.0 \times 0.001 \times 100 = 0.2\Omega$$

Gauge Factor Calibration

- The gauge factor of metal wire or foil strain gauges with the metals generally used in about 2.0 and resistances are generally of the order of about 100Ω;
- Semiconductor strain gauges have gauge factors of about ± 100 and resistances of the order of 1000 to 5000Ω.
- The gauge factor is normally supplied by the manufacturer of the strain gauges from a calibration made of a sample of strain gauges taken from a batch.
- The calibration involves subjecting the sample gauges to known strain and measuring their resistance changes.

Strain Gauge Arrangement



One form of displacement sensor has strain gauges attached to flexible elements in the form od cantilevers (a), rings (b) or U-shapes (c).

Such arrangements are typically used for linear displacements of the order of 1 to 30mm and have a non-linearity error of about $\pm 1\%$ of full range.

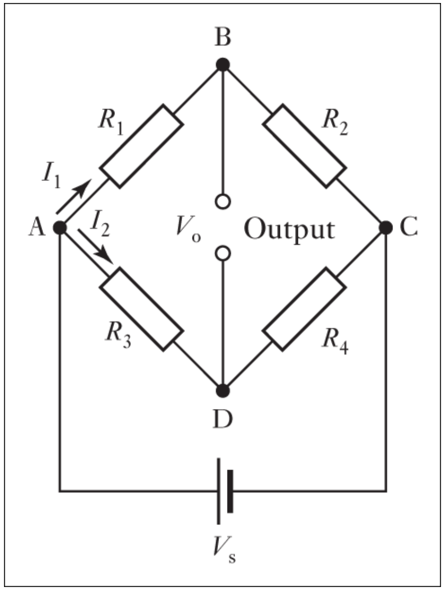
Problem of Strain Gauge

A problem of all strain gauges is that, their resistance changes not only with stain, but also with temperature.

Especially for semiconductor strain gauges, which have a much greater sensitivity to temperature than metal strain gauges.

- A way of eliminating the temperature effect is to use a specific sensor arrangement and circuit configuration which is called

Wheatstone Bridge



We'll discuss more later in the course.

Measurement of Displacement & Position

Displacement are concerned with the measurement of the amount by which some object has been moved. Position sensors are concerned with the determination of the position of some object in relation to some reference point.

For measuring position and displacement, basically we can use resistive, capacitive, inductive/magnetic, optical and acoustic elements.

Here we'll focus on three of them:

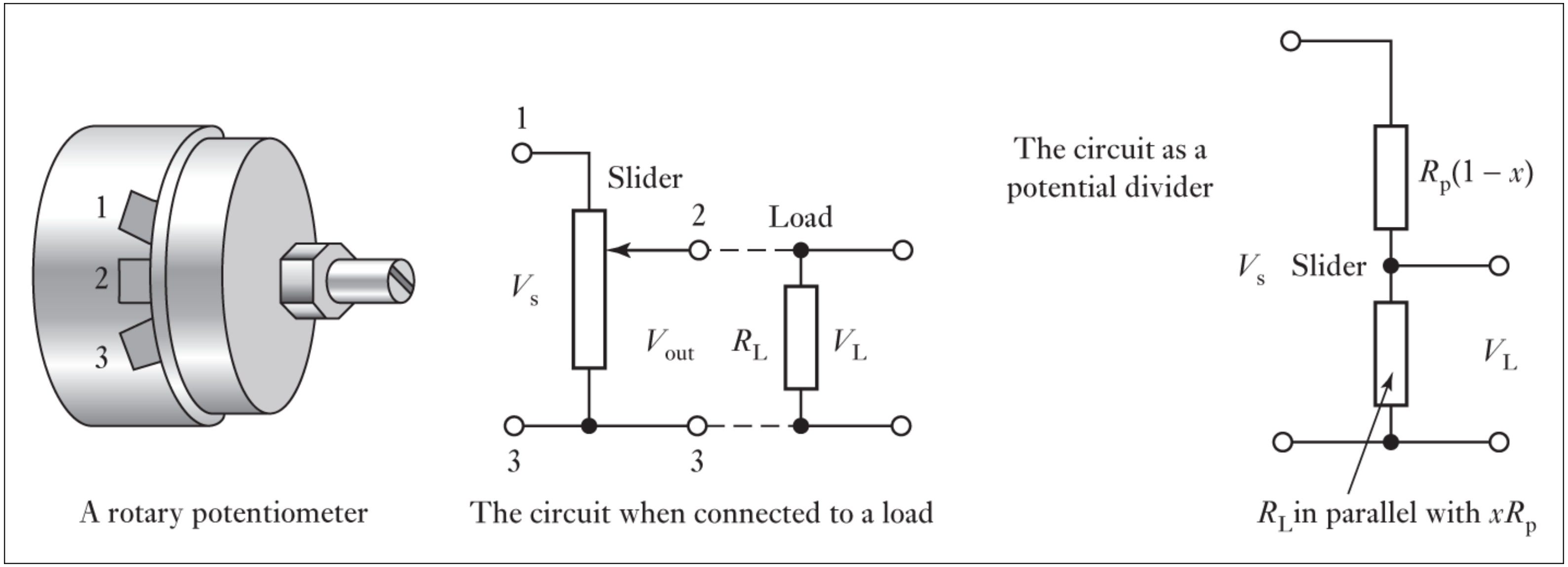
- *Potentiometer sensor (Resistive element)*
- *Capacitive element*
- *Optical encoder*

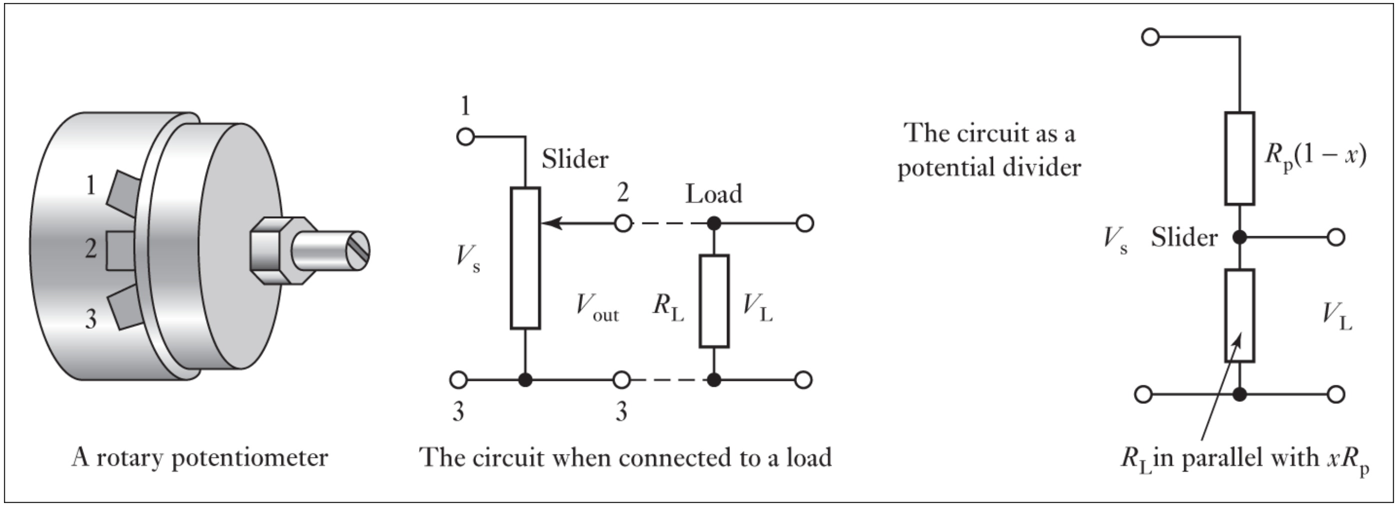
Potentiometer Sensor

A **potentiometer** consists of a resistance element with a sliding contact which can be moved over the length of the element.

Such element can be adopted to measure linear, or rotary displacement.

The displacement will be converted into a potential difference.





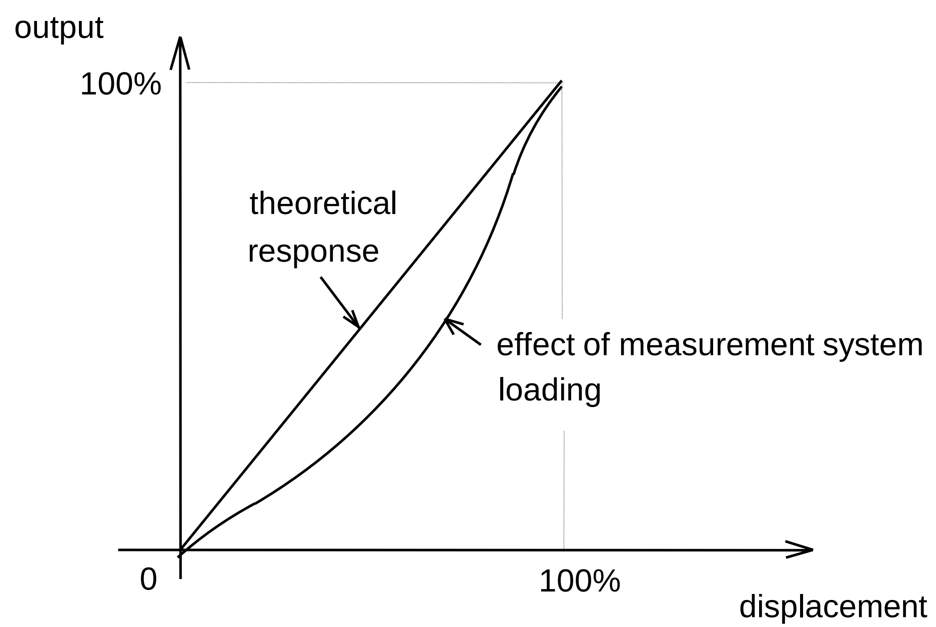
- V_s: input voltage (supply voltage); V_L: output voltage;
- R_p: total resistance of the potentiometer; R_L: resistance of the load;
- x: fraction of displacement.

Ideally, if the resistance of the loading system is infinite, i.e. $R_L = \infty$, then it has negligible effect on the output voltage. The output voltage will be proportional to the fraction of displacement, i.e.,

$$V_L \propto x$$

Non-linearity Error

However, if the resistance R_L is not negligible, it will cause non-linearity errors. The effect become especially noticeable in the mid-range of the potentiometer travel.



Analysis

The resistance R_L is in parallel of the fraction x of the potentiometer.

The total resistance = $R_p(1-x) + xR_pR_L/(xR_p + R_L)$;

Then we have

$$\frac{V_L}{V_s} = \frac{xR_pR_L/(xR_p + R_L)}{R_p(1-x) + xR_pR_L/(xR_p + R_L)} = \frac{x}{(R_p/R_L)\,x(1-x) + 1}$$

Note if $R_L = \infty$, we have

$$V_L = xV_s$$

If $R_L \neq \infty$, the error introduced is

$$error = xV_s - \frac{xV_s}{(R_p/R_L)\,x(1-x) + 1} = V_s\frac{R_p}{R_L}(x^2 - x^3)$$

Example 4.2

Consider the non-linearity error with a potentiometer of resistance 500Ω, when at a displacement of half its maximum slider travel, which results from there being a load of resistance $10k\Omega$. The supply voltage is 4V.

Solutions:

By using the previous derivations, we have

$$error = 4 \times \frac{500}{10000}(0.5^2 - 0.5^3) = 0.025V$$

As a percentage of the full range, this is

$$\frac{0.025}{4} \times 100\% = 0.625\%.$$

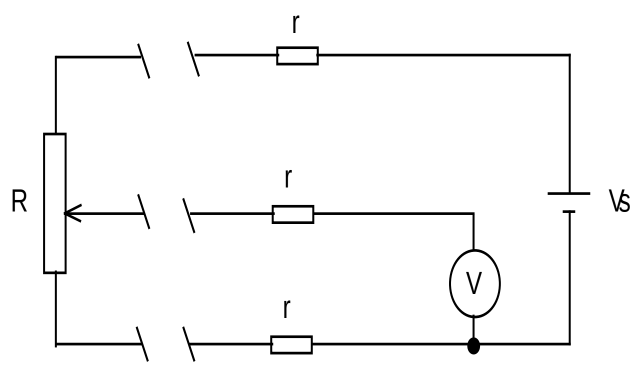
Other Sources of Errors

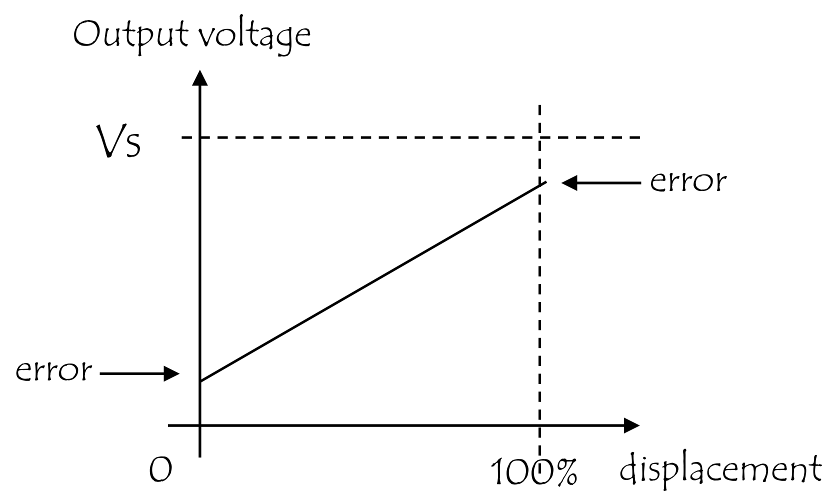
- **Voltage stabilisation**

The measured voltage depends on the stability of the voltage source used to supply the transducer. Variations cause repeatability errors.

- **Parasitic resistances**

This is particularly noticeable if the transducer is a long way from where the power supply is located and if the transducer resistance is small.





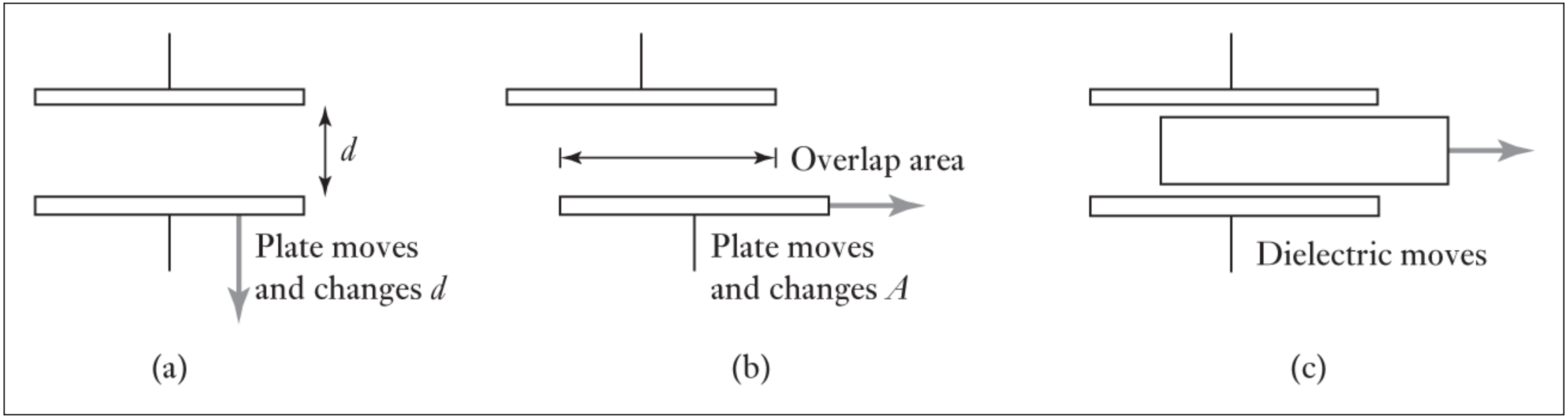
Thus the actual voltage recorded is changed by the addition of the (unintended) parasitic resistances r. Note that if the resistance of the meter is high then the effect of r in series with it is negligible. The values of r cause both zero and sensitivity errors.

Capacitive Element

The capacitance C of a parallel capacitor is given by

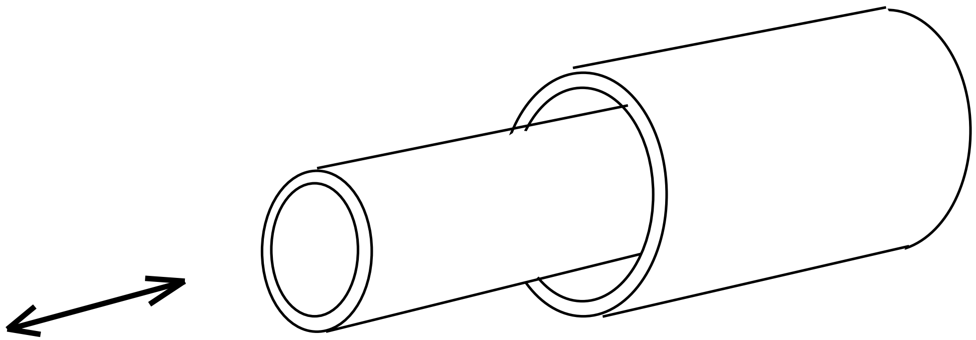
$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

where ε_r is the relative permittivity of the dielectric between the plates, ε_0 a constant called the permittivity of free space, A the overlap between the two plates, and d the plate separation.



Note only variation of ε_r and A give linear responses.

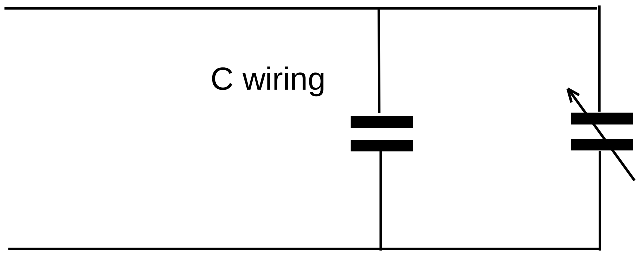
Cylindrical Capacitor Transducer



This is a cylindrical transducer in which the displacement being measured causes the area of electrode overlap (and hence capacitance) to change.

Problem: Effect of Wiring Capacitance

These systems have the problem that the wiring capacitance also adds to the total capacitance measured (it is in parallel) and this can vary from one installation to another.



Also a small change in capacitance due to small displacements are difficult to resolve when superimposed on that of the wiring.

One solution to this is to use plate separation (d) to measure the displacement instead of area or dielectric permittivity change.

The resulting change in capacitance (ΔC) for a given displacement (Δd) is relatively large, but gives a non-linear response.

For the displacement changing the plate separation, if the separation d is increased by a displacement x, then the capacitance becomes

$$C - \Delta C = \frac{\varepsilon_r \varepsilon_0 A}{d + x}$$

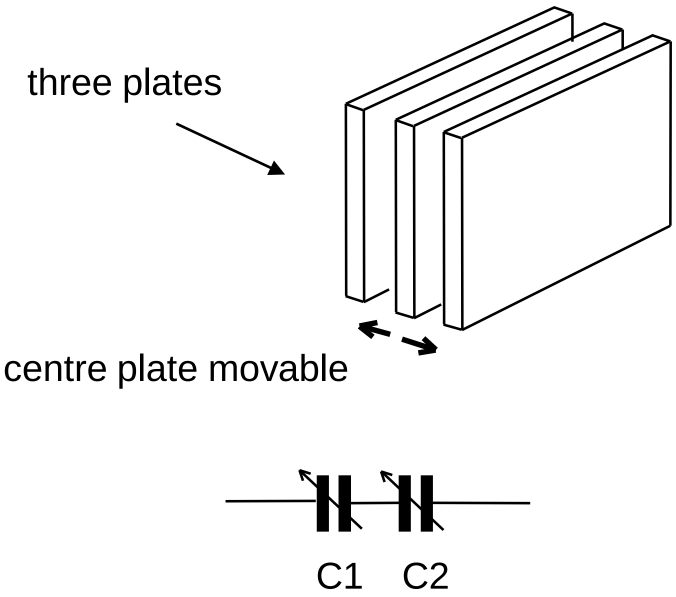
Hence the change in capacitance ΔC as a fraction of the initial capacitance is given by

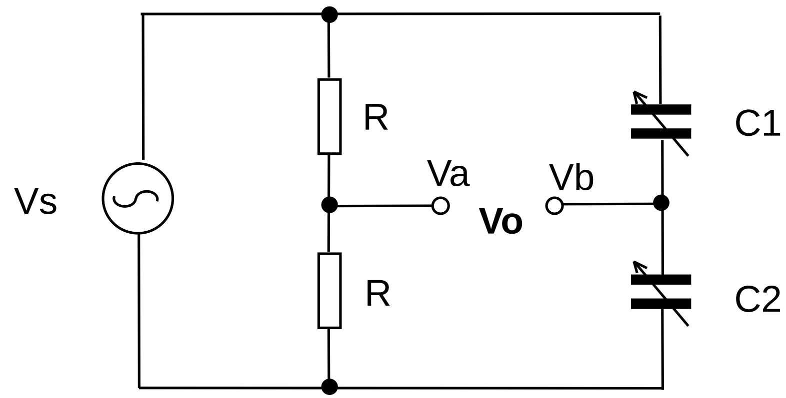
$$\frac{\Delta C}{C} = -\frac{d}{d + x} - 1 = -\frac{x/d}{1 + (x/d)}$$

This is thus non-linear relationship between the change in capacitance ΔC and the displacement x.

This non-linearity can be overcome by using a differential capacitance transducer, what is also termed a push-pull displacement sensor.

The Differential Capacitance Sensor and Bridge





For the parallel plate example, where the central electrode moves:

$$V_o = V_b - V_a = V_s\left(\frac{C_1}{C_1+C_2} - \frac{1}{2}\right)$$

When the movable electrode is in the central position, $C_1 = C_2$ and $V_o = 0$.

When the central electrode is displaced by x, say to the right, then

$$C_1 = \frac{\varepsilon_r \varepsilon_0 A}{d+x}, C_2 = \frac{\varepsilon_r \varepsilon_0 A}{d-x}$$

So the output voltage becomes:

$$V_o = V_s \left(\frac{\frac{\varepsilon_r \varepsilon_0 A}{d+x}}{\frac{\varepsilon_r \varepsilon_0 A}{d+x} + \frac{\varepsilon_r \varepsilon_0 A}{d-x}} - \frac{1}{2} \right) = V_s \left(\frac{d-x}{d-x+d+x} - \frac{1}{2} \right) = -\frac{V_s}{2d} x$$

Thus the output voltage is linear with the displacement x. The – sign indicates that the output will be 180° out of phase with the input V_s.

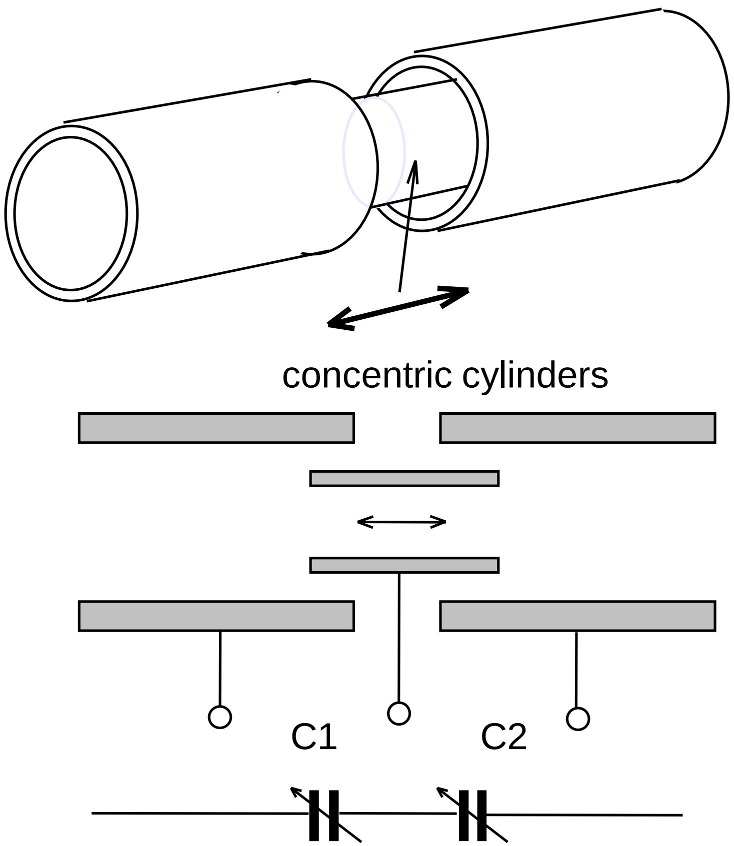
If the displacement was in the $-x$ direction, the output is also linear with x but is in phase with the input V_s.

So the magnitude of the output voltage tells is how far the centre electrode has moved, whilst its phase relative to the input voltage V_s tells us which way it moved.

We need a phase-sensitive detector to fully interpret the output of the bridge.

Concentric Plate Differential Capacitance Transducer

This type of capacitance transducer uses variation of area overlap



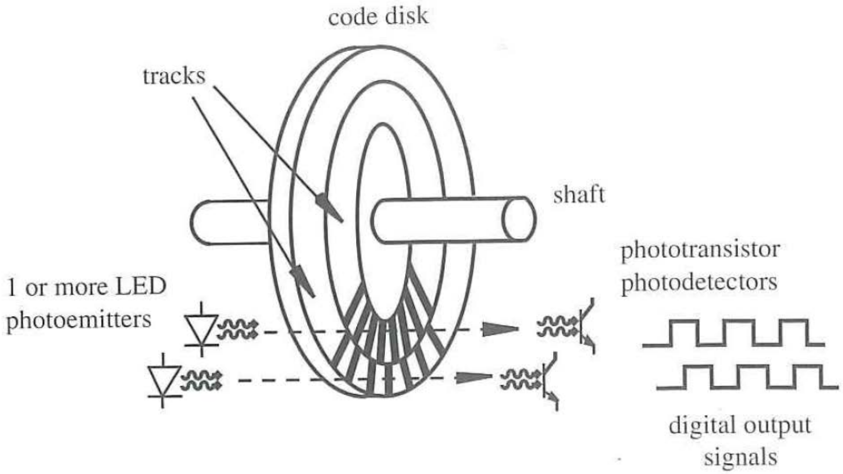
Optical Encoder

An **Optical Encoder** is a device that converts motion into a sequence of digital pulses. By counting a single bit or decoding a set of bits, the pulses can be converted to relative or absolute position measurement.

- Encoders have both linear and rotary configurations, but the most common type is rotary (angular displacement).
- They are of two types: incremental (relative) or absolute.

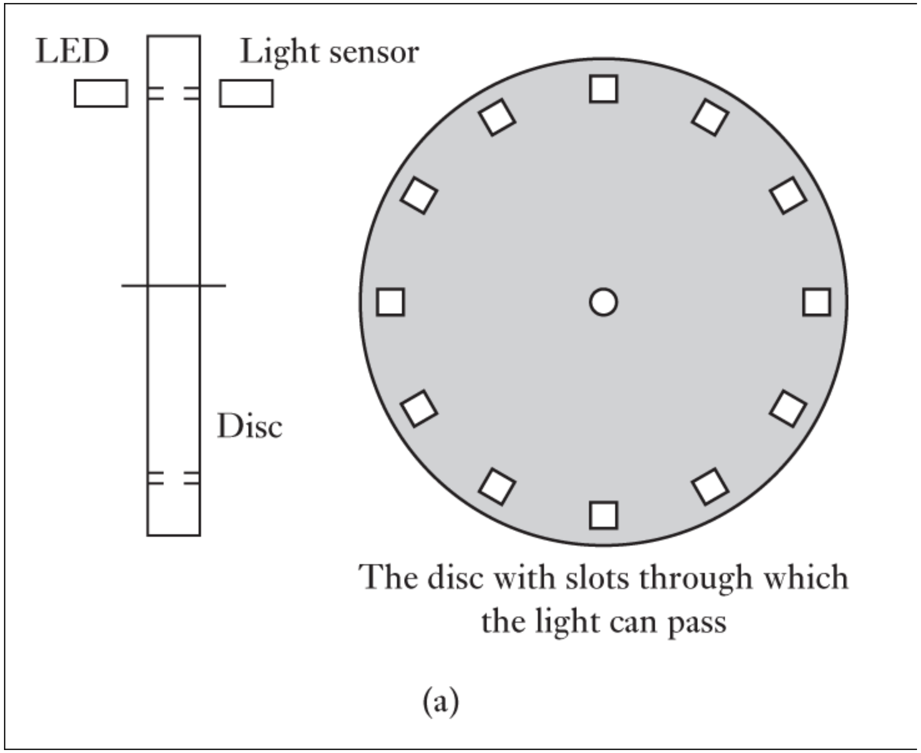
Optical versions obtain their signal output by means of a light source that shines through clear regions in a rotating disk attached to the shaft, allowing light to fall onto a photo-detector.

Incremental Optical Encoder



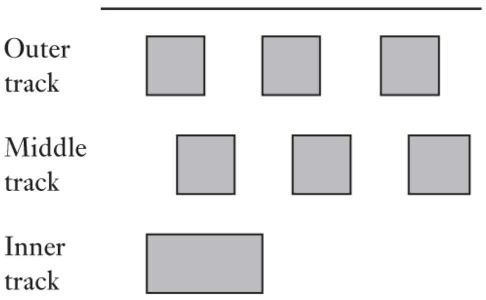
Incremental Encoder

One-track incremental encoder: resolution = 360º / No.of holes



Output:

A beam of light passes through slots in the disc and is detected by a suitable light sensor. When the disc is rotated, a pulsed output is produced by the sensor with number of pulses being proportional to the angle through which the disc rotates.



(b)

In practice, 3 tracks are commonly use.

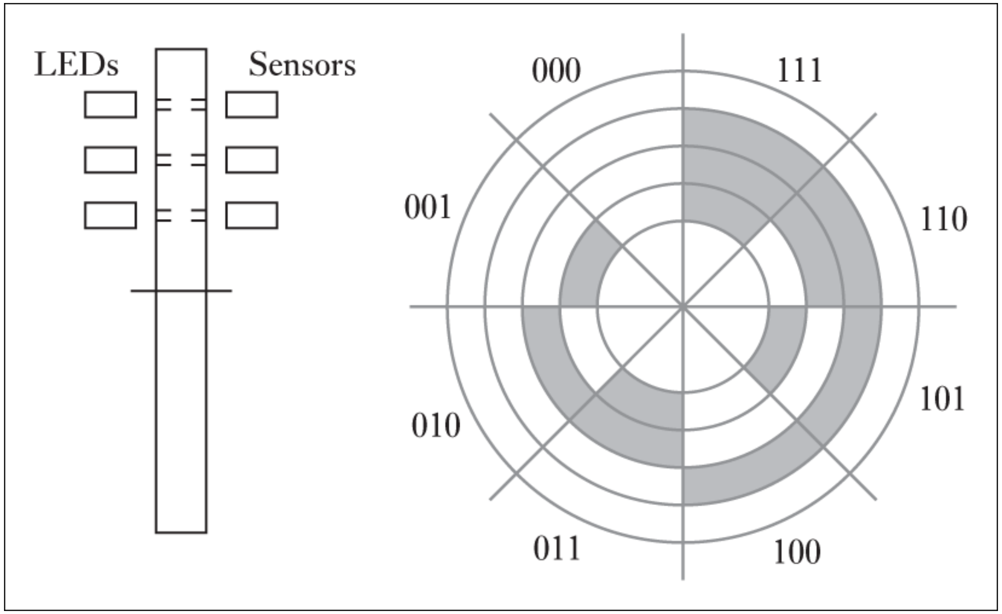
The inner track has just one hole and is used to locate the "home" position of the disc;

The other two tracks have a series of equally spaced holes that go completely round the disc but with the holes in the middle track offset from the holes in the outer track by one-half the width of a hole.

This offset enables the direction of rotation to be determine.

- In a clockwise direction, the pulses in the outer track lead those in the inner;
- In the anti-clockwise direction, they lag.

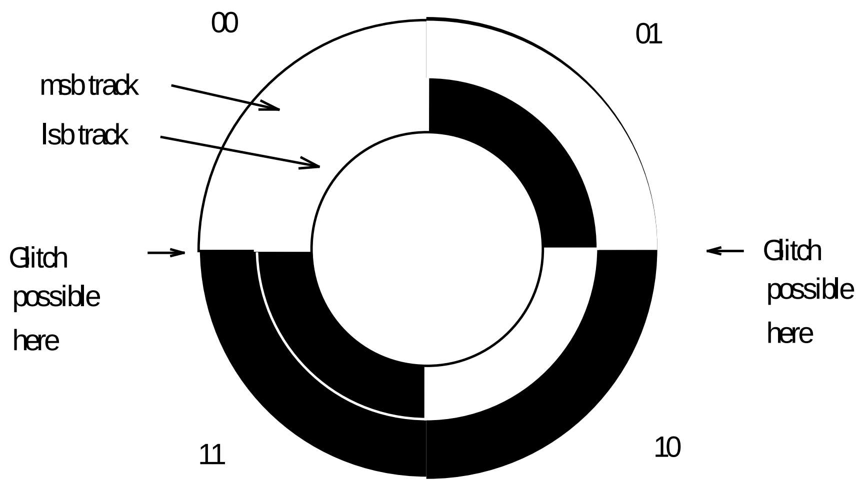
Absolute Encoder



resolution = 360° / (2^No.of tracks)

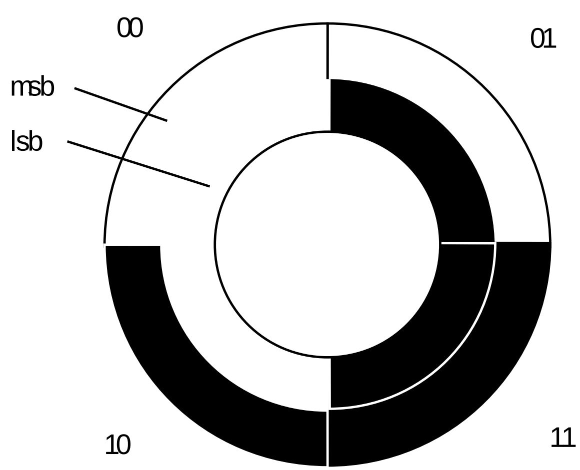
- Another class of optical rotary displacement transducer detects the rotation in absolute terms, i.e. in terms of angular position.
- This requires an appropriately coded disk. The slots are arranged in such a way that the sequential output from the sensor is a number in binary code.
- Typical encoders tend to have up to 10 or 12 tracks. The number of bits in the binary number will be equal to the number of tracks. i.e., with 10 tracks, there will be 10 bits, therefore the resolution is $360^{o}/10^{24}=0.35^{o}$.

Gray Code



The normal form of binary code is generally not used because changing from one binary number to the next can result in more than one bit changing (for example, from 01 to 10).

In practice, the outputs may not change at precisely the same instant, giving a false reading ("glitch").



By using the "**Gray code**" scheme, no two tracks are required to change simultaneously.

Gary Code Construction

Note that a Gray code sequence can be generated by:

1) place the sequence 0, 1 one above the other

2) draw a mirror line below

3) repeat the 0, 1 sequence as a *mirror image* in the mirror line and add a 0 prefix to the codes above the line and a 1 prefix to those below the line.

4) repeat 2 & 3 until the required number of bits is reached to obtain the solution needed

	Normal binary	Gray code
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111
6	0110	0101
7	0111	0100
8	1000	1100
9	1001	1101
10	1010	1111

step 1	step 2	step 3	step 4
0	0 0	0 0 0	0 0 0 0
1	0 1	0 0 1	0 0 0 1
	-------		
	1 1	0 1 1	0 0 1 1
	1 0	0 1 0	0 0 1 0
		---------	
		1 1 0	0 1 1 0
		1 1 1	0 1 1 1
		1 0 1	0 1 0 1
		1 0 0	0 1 0 0
			--------
			1 1 0 0
			etc.

Quiz 4.1

What is the non-linearity error as %FSD produced when a $1k\Omega$ potentiometer has a load of $10k\Omega$ and is at one-third of its maximum displacement?

Thank You !