Electric and magnetic sensors and actuators

Introduction

- Broadest by far of all other classes
  - In numbers and types of sensors
  - In variety within each type.
- Reasons:
  - Sensor exploits the electrical properties of materials
  - Many electrical effects
  - The requisite output is almost always electrical
- Some electrical/electromagnetic sensors not discussed here:
  - (Thermocouples, optical, ultrasonic sensors etc.)

Introduction

- Most actuators are either electrical or, more commonly, magnetic.
- This is particularly true of actuators that need to provide considerable power.
- We will limit ourselves here to the following types of sensors and actuators:

Introduction

- Sensors and actuators based on electric/electrostatic principles.
  - include MEMS (micro-electro-mechanical sensors), which are most often based on electrostatic forces
  - capacitive sensors (proximity, distance, level, material properties, humidity and other quantities such as force, acceleration and pressure may be sensed) and related field sensors.
- Magnetic sensors and actuators based on static and quasi-static magnetic fields.
  - motors and valves for actuation,
  - magnetic field sensors (hall element sensors, inductive sensors for position, displacement, proximity and others),
  - magnetostrictive sensors and actuators and more.

Definitions

- Electric field: Force per unit charge
  - exists in the presence of charges or charged bodies.
  - electric field may be static when charges do not move or move at constant velocity
  - time dependent if charges accelerate and/or decelerate.
- Moving charges in conducting media or in space cause currents
- Currents produce magnetic fields.
  - Magnetic fields are either static – when currents are constant (dc) or:
  - Time dependent when currents vary in time.

Definitions (cont.)

- If currents vary in time: both an electric and a related magnetic field are established.
- This is called the electromagnetic field.
  - Electromagnetic field implies that both an electric and a magnetic field exists.
  - It is OK to call all electric and magnetic fields by that name since, for example an electrostatic field may be viewed as a time independent electromagnetic field with zero magnetic field.
- All fields described by Maxwell’s equations - will not be discussed here

Sensing strategies

- Anything that influences one of these quantities may be sensed through the electromagnetic field.
- Electromagnetic actuators are based on one of the two basic forces;
  - the electric force (best understood as the attraction between opposite polarity charges or repulsion between like polarity charges)
  - the magnetic force. The latter is the attraction of current carrying conductors with currents in the same directions or repulsion of current carrying conductors with currents in opposite directions.

Electric Field – Capacitive Sensors and Actuators

- Electric field sensors and actuators
  - operate on the physical principles of the electric field and its effects (capacitance, charge, stored energy)
- The primary type: capacitive device.
  - Some sensors such as charge sensors are better explained in terms of the electric field
  - On the whole, discussion of capacitance and its use in sensing and actuation covers most aspects necessary for a thorough understanding of these types of sensors without the need to study the intricacies of the electric field behavior.

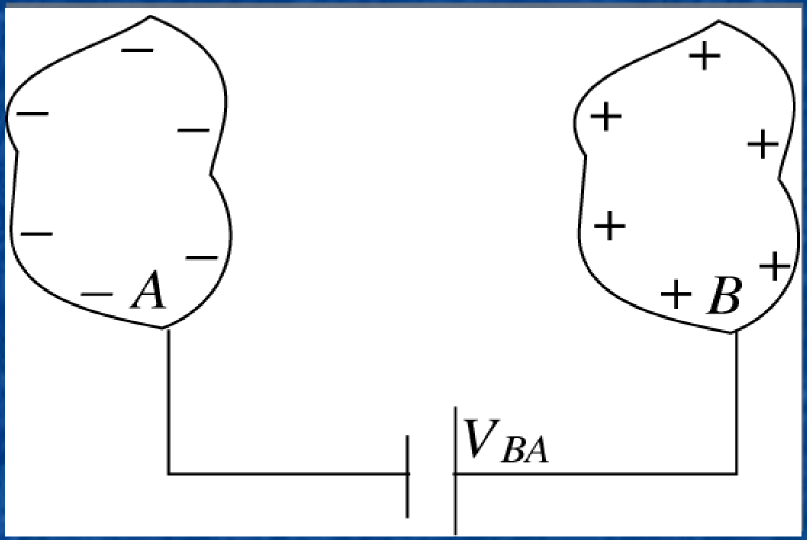
Capacitance

- Capacitance: the ratio between charge and potential of a body
- Measured in coulombs/volt. This unit is called the farad [F].
- Capacitance is only defined for two conducting bodies, across which the potential difference is connected.

$$C = \frac{Q}{V} \quad \left[\frac{\mathrm{C}}{\mathrm{V}}\right]$$

Capacitance (cont.)

- Body B is charged by the battery to a positive charge Q and body A to an equal but negative charge –Q.
- Any two conducting bodies, regardless of size and distance between them have a capacitance.

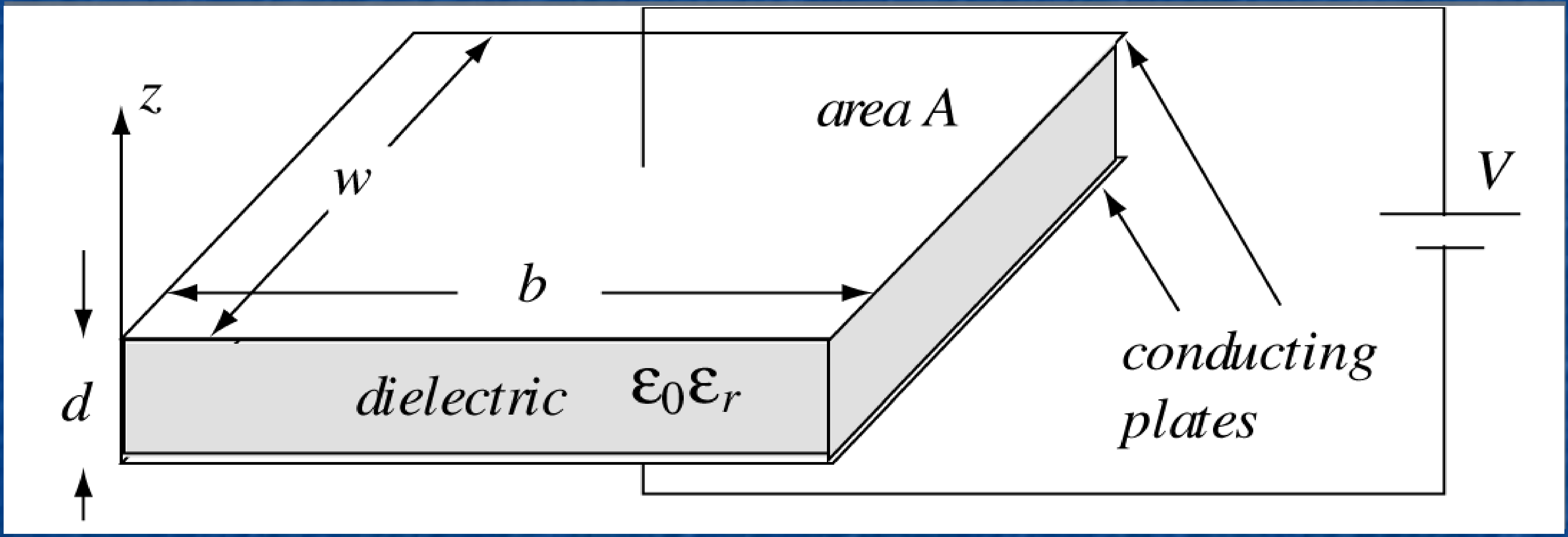


Parallel plate capacitor

- Parallel plate capacitor:
  - Assumes d is small,
  - ε_0 is the permittivity of vacuum,
  - ε_r the relative permittivity (dielectric constant) of the medium between plates,
  - S the area of the plates and
  - *d* the distance between the plates.
  - ε_0 is a constant equal to 8.854×10^{-12} F/m
  - ε_r is the ratio between the permittivity of the medium to that of free space.
  - available as part of the electrical properties of materials.

$$C = \frac{\varepsilon_0 \varepsilon_r S}{d} \quad [\mathrm{F}]$$

Parallel plate capacitor (cont.)



Permittivities of dielectrics

Material	ε_r	Material	ε_r	Material	ε_r
Quartz	3.8-5	Paper	3.0	Silica	3.8
GaAs	13	Bakelite	5.0	Quartz	3.8
Nylon	3.1	Glass	6.0 (4-7)	Snow	3.8
Paraffin	3.2	Mica	6.0	Soil (dry)	2.8
Perspex	2.6	Water (distilled)	81	Wood (dry)	1.5-4
Polystyrene foam	1.05	Polyethylene	2.2	Silicon	11.8
Teflon	2.0	Polyvinyl Chloride	6.1	Ethyl alcohol	25
Ba Sr Titanate	10,000.0	Germanium	16	Amber	2.7
Air	1.0006	Glycerin	50	Plexiglas	3.4
Rubber	3.0	Nylon	3.5	Aluminum oxide	8.8

Capacitors - cont.

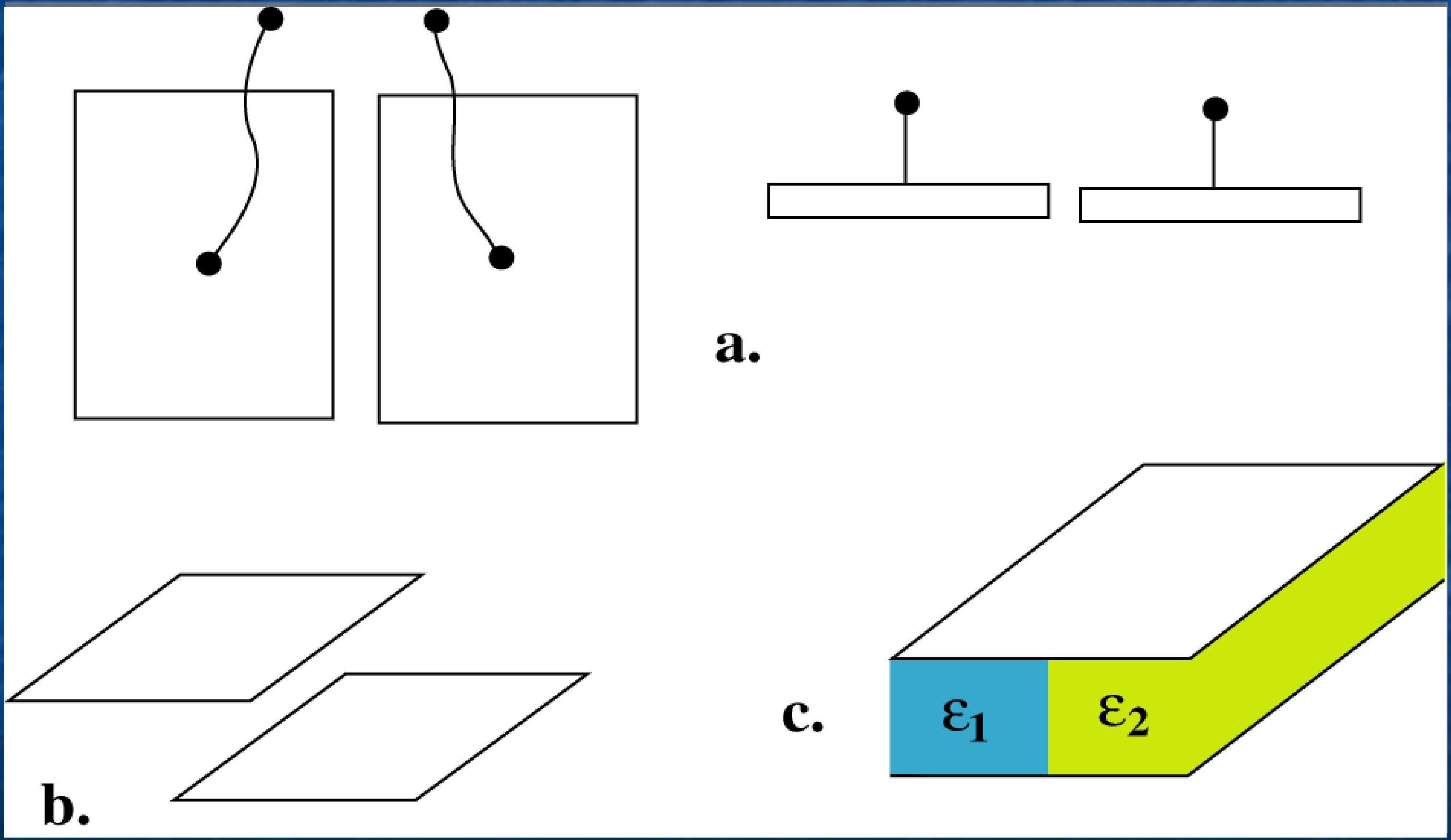
- Any of the quantities in Eq. (2) affect the capacitance
- Changes in these can be sensed.
- A wide range of stimuli including
  - displacement and anything else that can cause displacement (pressure, force), proximity, permittivity (for example in moisture sensors)
  - a myriad of other effects are related to capacitance.

Capacitors - cont.

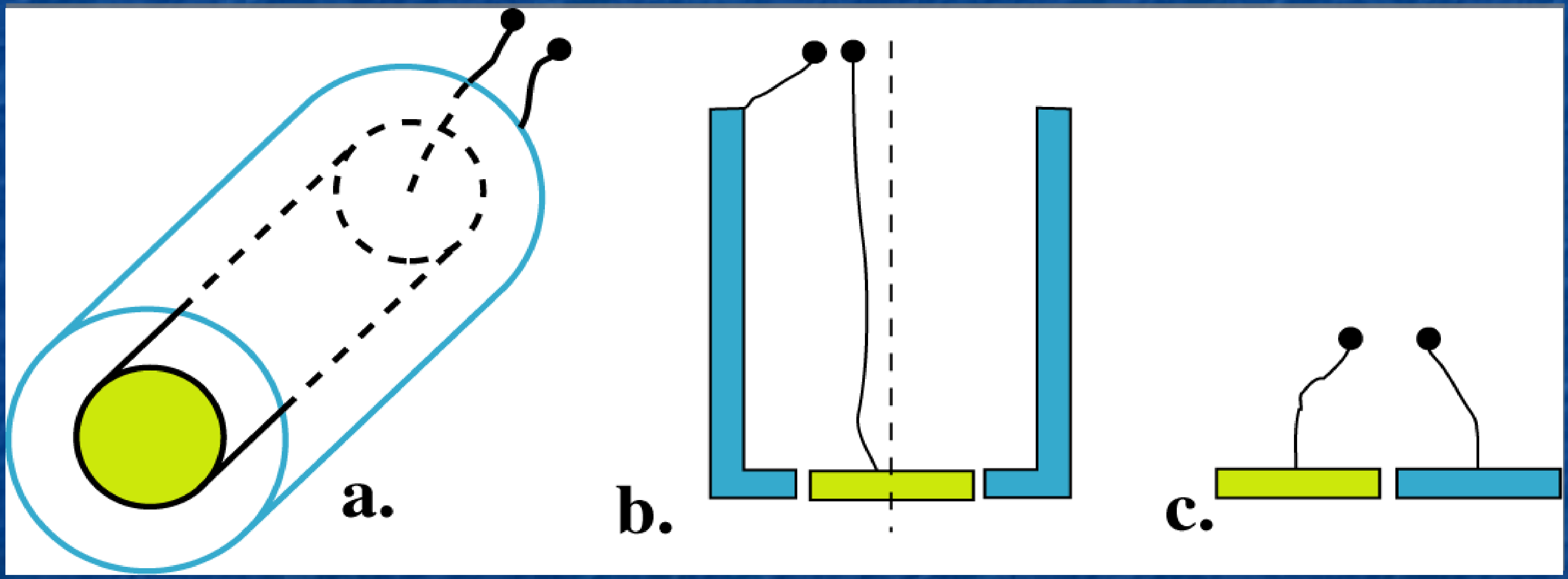
- Eq. (2) describes a very specific device
- Was obtained by assuming that the electric field between the two plates does not leak (fringes) outside the space between the plates.
- In the more general case, when *d* is not small, or:
- Plates are arranged in a different configuration
  - we cannot calculate the capacitance directly
  - but we can still write the following:

$$C = \alpha[\varepsilon_0, \varepsilon_r, S, 1/d]$$

Capacitors - examples



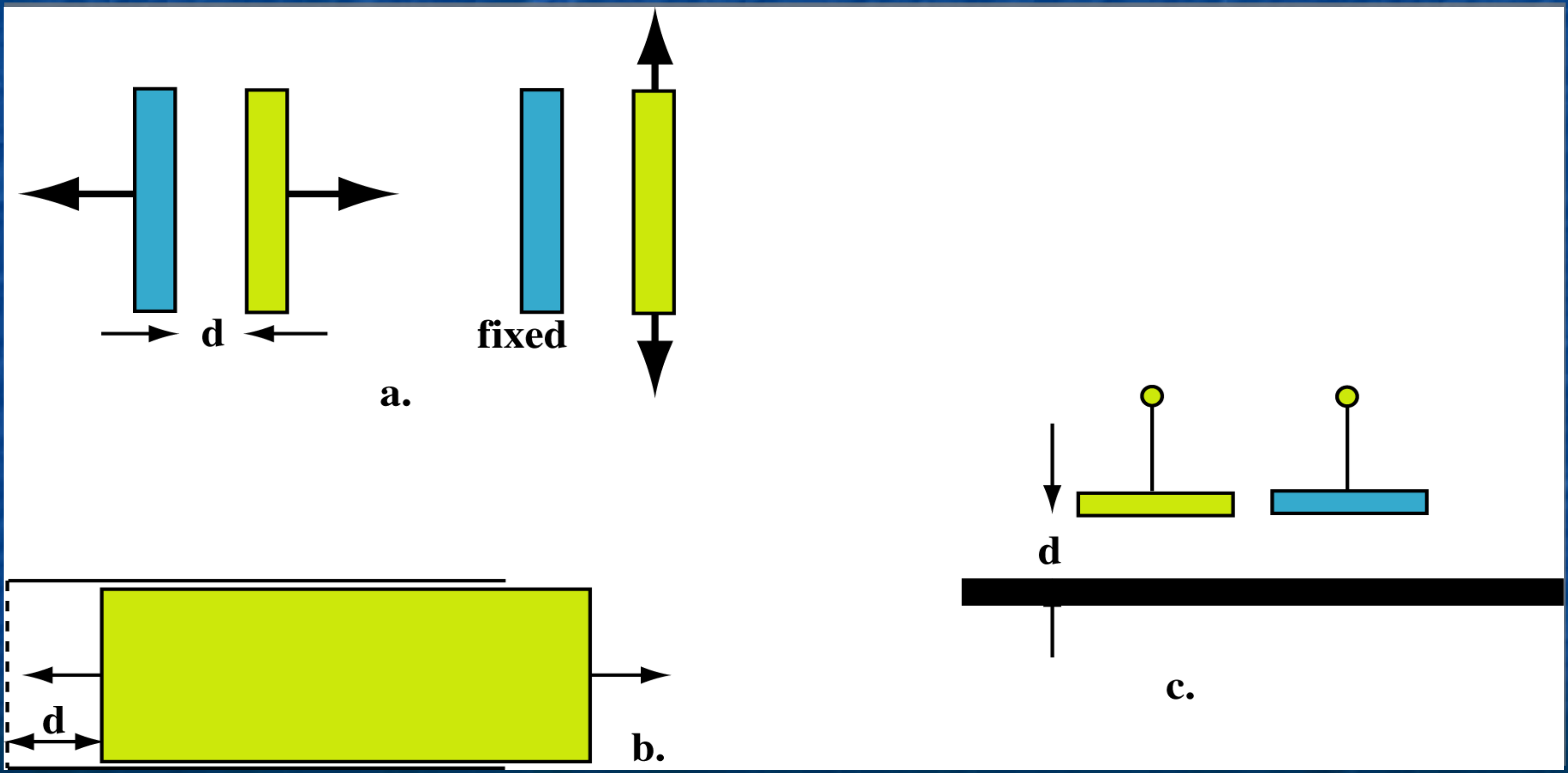
Capacitive position sensors



Capacitive position, proximity and displacement sensors

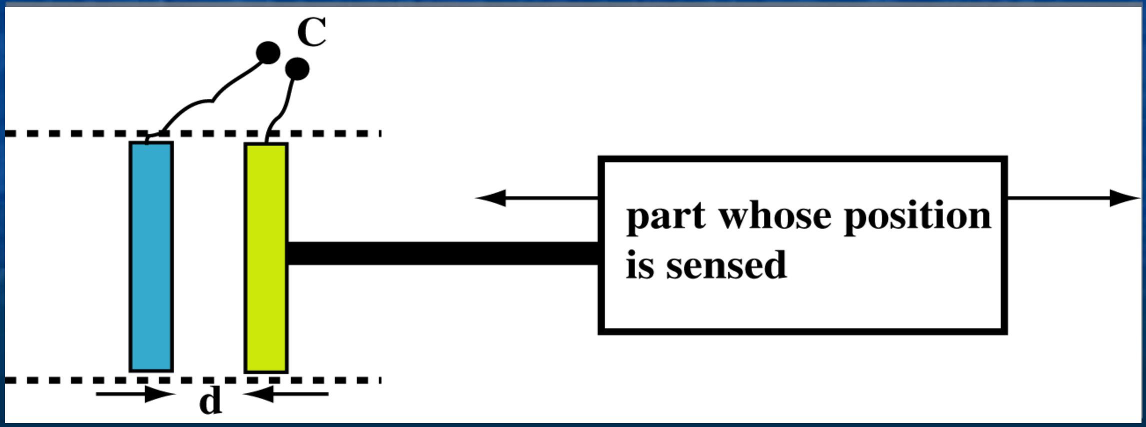
- Position and displacement can be sensed in three fundamental ways:
- (1) By allowing a plate to move relative to the other (figure a).
- A number of configurations are shown next:
  - the sensor is made of a single plate while the second plate is a conductor to which the distance (proximity) is sensed.
  - Requires connection to the sensed object

Position and displacement sensing



Position sensing relative to a fixed conductor

- A schematic position sensor is shown in **below**
- One plate is fixed while the other is pushed by the moving device.
- The position of the moving device causes a change in position of the dielectric and this changes the capacitance. C
- Capacitance is inversely proportional to the motion and
- As long as the distances sensed are small, the output is linear.



Sensing by moving the dielectric

- (2) The plates remain fixed but the dielectric moves in or out as in **Figure b**.
  - Practical for some applications.
  - For example, the dielectric may be connected to a float which then senses the fluid level or
  - It may be pushed by a device to sense end of travel or position.
  - Advantages: linearity, range of motion is rather large and can equal the width of the capacitor.

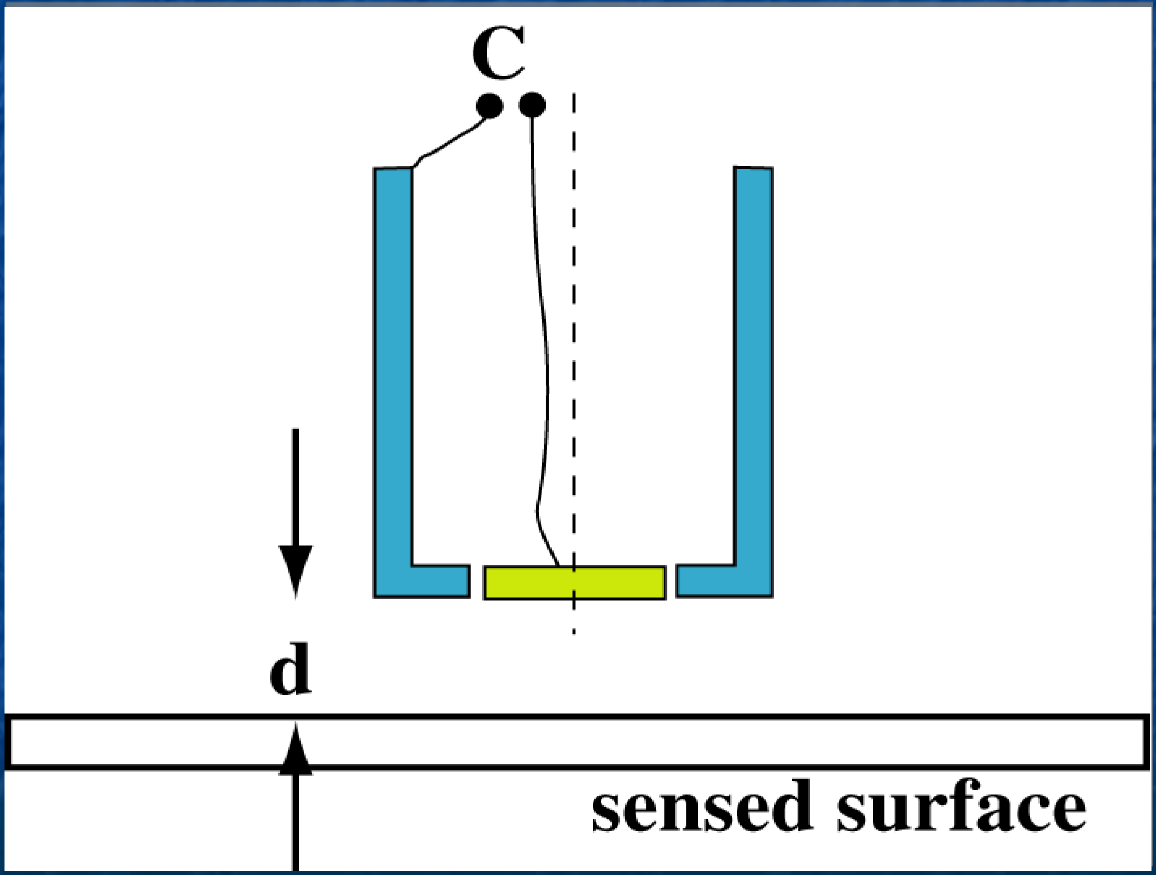
Sensing by moving the whole capacitor

- (3) by keeping the plates fixed as in **Figure c** and sensing the distance to a surface.
- This is a more practical arrangement since the sensor is self contained and requires no mechanical contact to sense distance or position.
- Most capacitive sensors are a variation of this arrangement

Practical proximity sensors

- Typically, a hollow cylindrical conductor forms one plate of the sensor as in **Figure 5.7**.
- The second plate of the sensor is a disk at the lower opening of the cylinder.
- The whole structure may be enclosed with an outer conducting shield or may be encased in a cylindrical plastic enclosure. The capacitance of the device is C_0 based on dimensions, materials and structure.

Structure of a practical proximity sensor



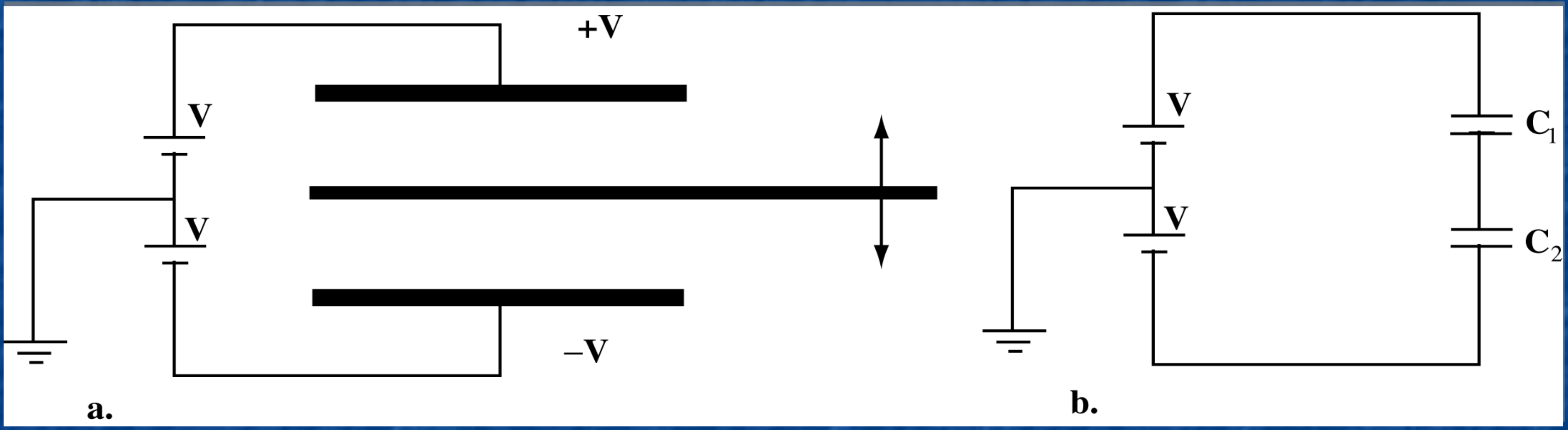
Proximity sensors - cont.

- When any material is present, effective permittivity seen by the sensor and capacitances increases - indicates distance
- Senses distances to conducting or nonconducting bodies of any shape but output is not linear.
  - the smaller the sensed distance d, the larger the sensitivity of the sensor.
  - dimensions of the sensor makes a big difference in span and sensitivity.
  - large diameter sensors will have a larger span while small diameter sensor will have a shorter span.

Proximity sensors - cont.

- Other methods:
- Example: Two fixed plates and one moving plate.
- When the plate is midway, its potential is zero since $C_1 = C_2$.
  - As the plate moves up, its potential becomes positive.
  - When it moves down it is negative.
  - More linear than the previous sensors
  - Motion must be small or the capacitances will be very small and difficult to measure.

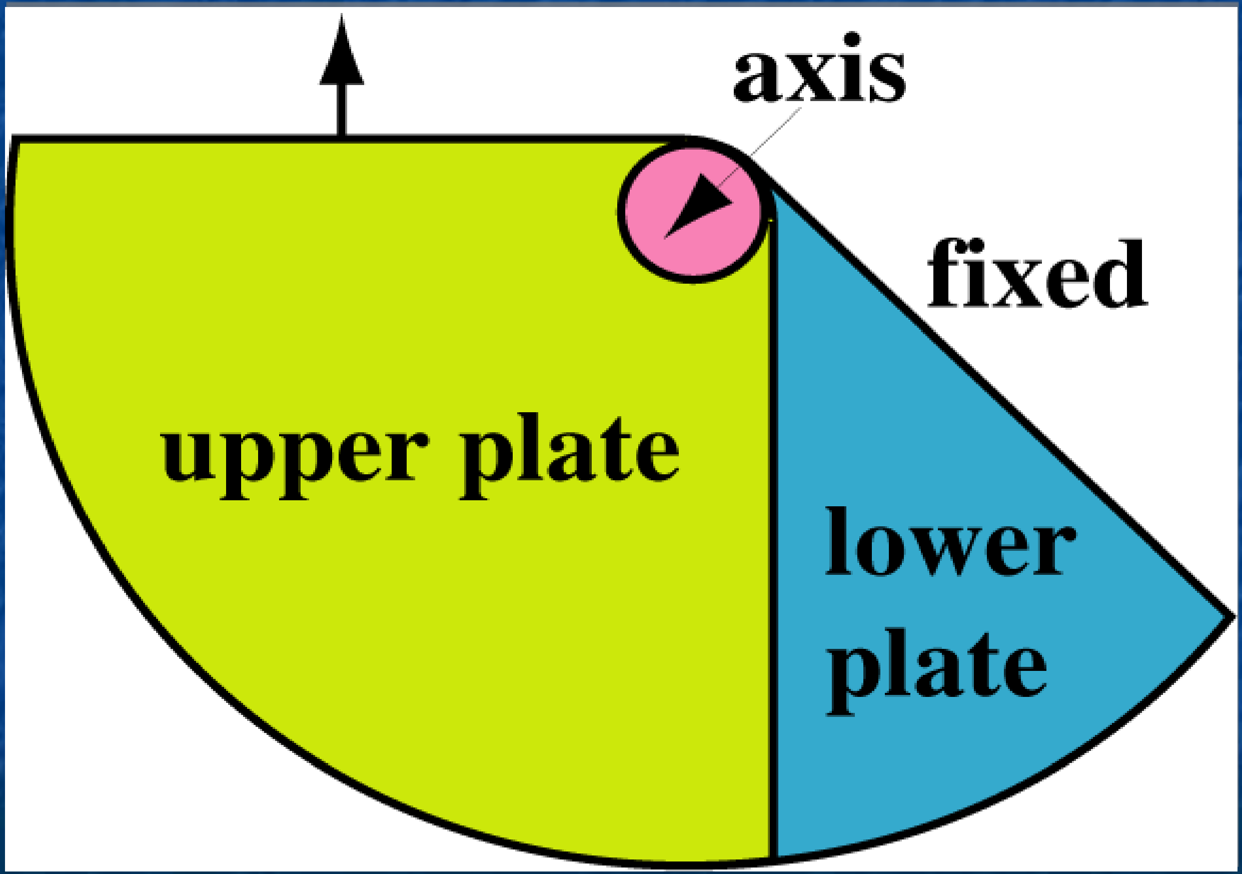
Position sensor



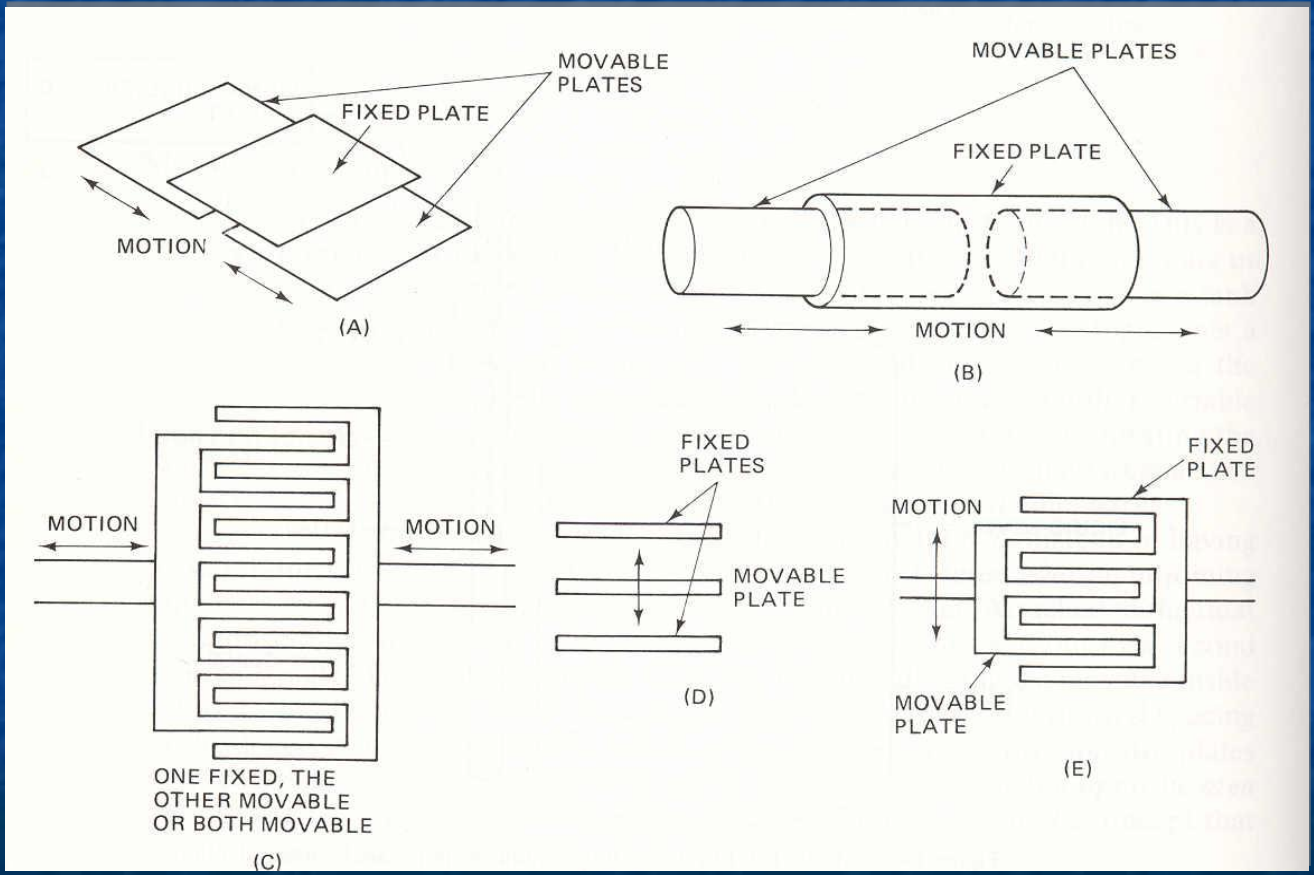
Other position, displacement, proximity sensors:

- Rotary (angular) position sensors
- Linear displacement sensors:
  - Integrated comb-like sensors
  - Sideways sliding plates
  - Plunger type sensors
- Others

Rotary position sensor



Other configurations for linear displacement sensors

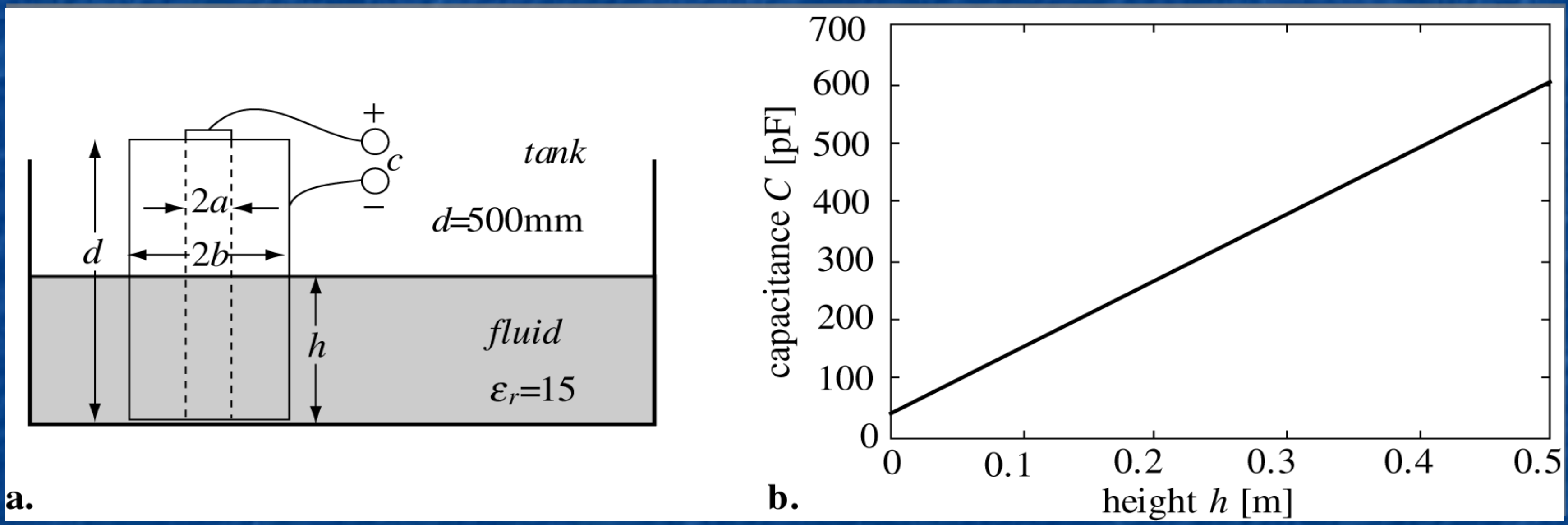


Commercial capacitive sensors

Capacitive fluid level sensors

- Fluid level:
  - may be sensed by any of the position or proximity sensors discussed in the previous paragraph
  - by sensing the position of the fluid surface directly
  - or through a float which then can change the capacitance of a linear capacitor or a rotary capacitor.
- There is however another method which is linear but can have a very large range. The method is shown next:

Co-axial fluid level sensor



Co-axial fluid level sensor

- A coaxial capacitor is made of two concentric cylinders establishing a capacitance C_0.
- Capacitance of a coaxial capacitor of length L, inner radius a and outer radius b is:

$$C_0 = \frac{2\pi\varepsilon_0 L}{ln(b/a)} \quad [F]$$

- If the fluid fills the capacitor to a height h, capacitance is:

$$C_0 = \frac{2\pi\varepsilon_0}{ln(b/a)}(h\varepsilon_r + L - h) \quad [F]$$

Co-axial fluid level sensor

- Capacitance is linear with respect to h from h=0 to h=L
- Capacitive fuel gages are of this type but the idea can be used for any fluid that is nonconductive such as oils.

Capacitive sensors - comments

- Simple and rugged sensors
- Useful in many other applications (pressure, acoustic sensors, etc.)
- Capacitances are small and changes in capacitance even smaller.
  - Require special methods of transduction.
  - Often part of LC oscillator (measure freq.)
  - Others use an ac source (measure imped.)

Capacitive actuators

Capacitive actuation is simple:

- Potential is connected across the two plates of a capacitor
- Plates acquire opposite charges.
- These charges attract each other based on Coulomb’s law
- Force tends to pull the plates together.

Capacitive actuators

- Mechanical motion of the plates is possible - constitutes actuation
- In a parallel plate capacitor the force is:

$$F = \frac{CV^2}{d} = \frac{\varepsilon_0 \varepsilon_r S V^2}{d^2}$$

- For other configurations: no exact relation but:
- Same general behavior

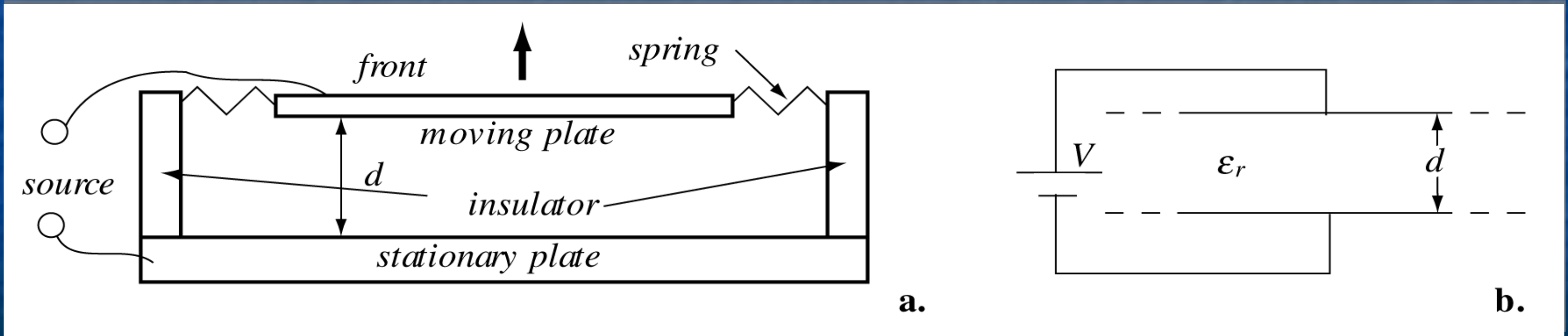
Capacitive actuators

- Force developed is proportional to:
- Capacitance:
- Distance between plates:
- Potential across plates
- Forces are typically small (ε is very small)

$$F = \frac{CV^2}{d} = \frac{\varepsilon_0 \varepsilon_r S V^2}{d^2}$$

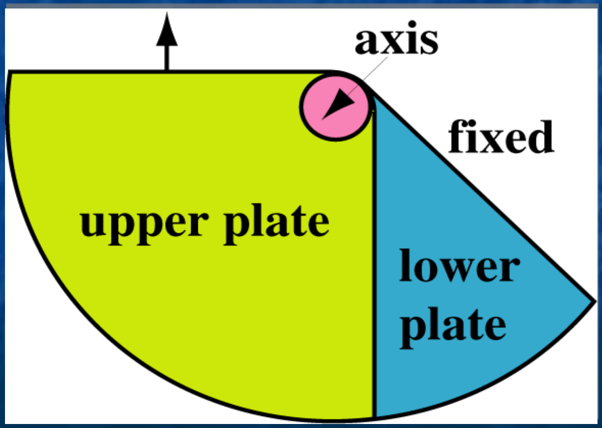
Basic capacitive actuator

- An electrostatic actuator (electrostatic speaker)
- Upper plate is attracted or repelled by lower, fixed plate
- Motion may be used for positioning or for voice reproduction



Angular capacitive actuator

- Upper plate moves relative to lower plate
- Force proportional to position (capacitance changes)
- Useful for small, low force motion.



Electrostatic actuators - comments

- Motion is usually small (except loudspeakers)
- Voltages are high
- Force is low
- Usually accurate and linear
- Very common in MEMs

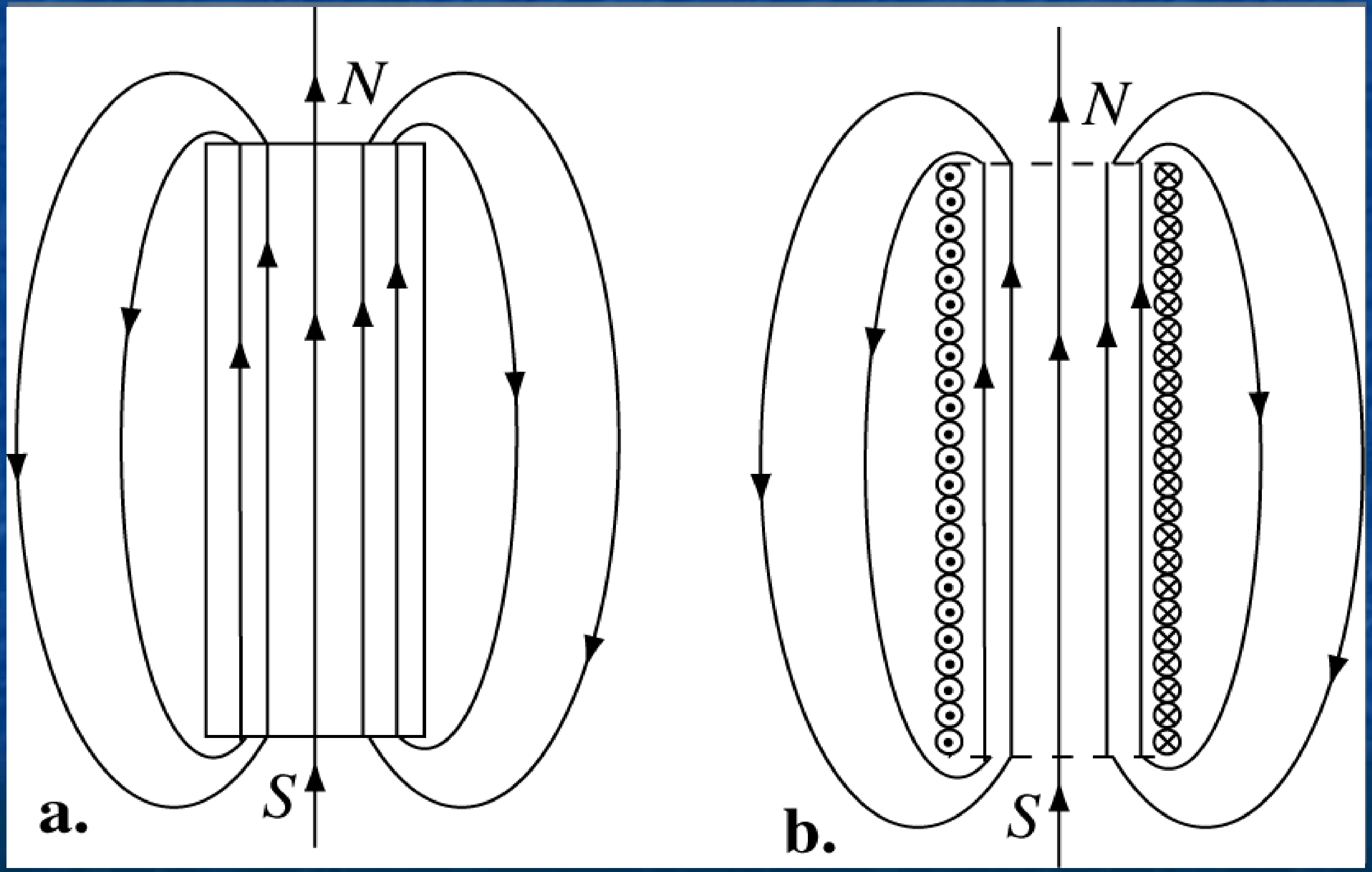
Magnetic sensors and actuators

- Magnetic sensors and actuators are governed by the magnetic field and its effects.
- The magnetic flux density is also called magnetic induction. Therefore, these sensors tend to be named inductive sensors.
- We will rely on inductance, magnetic circuits and magnetic forces which can be explained, at least qualitatively, without resorting to Maxwell's equations.

Magnetics - some theory

- Lets start with a permanent magnet.
- It exerts a force on another magnet through space.
- We can say that a “field” exists around the magnet through which it interacts.
- This force field is in fact the magnetic field.
- The same can be observed by driving a current through a coil
- Since the two fields are identical, their sources are identical - currents generate magnetic fields

Equivalence between permanent magnet and coil



Magnetics - some theory

- A magnet attracts or repels another magnet – this gives us the first observable interaction in the magnetic field –it also attracts a piece of iron.
- It will not attract a piece of copper.
- Conclusion: there are different types of material in terms of their magnetic properties.
- Magnetic properties are governed by the permeability of the material, μ [henry/meter]

Magnetics - some theory

- The strength of the magnetic field is usually given by the magnetic flux density **B** [tesla]
- The magnetic flux density is also called magnetic induction
- The magnetic field intensity **H** [ampere/meter].
- The relation between the two is simple:

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$$

Magnetics - some theory

- $\mu_0 = 4\pi x 10^{-7}$ [H/m] is the permeability of vacuum
- μ_r is the relative permeability of the medium in which the relation holds,
- μ_r is given as the ratio between the permeability of the medium and that of vacuum
- A dimensionless quantity associated with each material in nature.
- Permeabilities of some useful materials are given next.

Magnetics - some theory

- Magnetic materials:
- Diamagnetic, $\mu_r < 1$
- Paramagnetic $\mu_r > 1$
- **Ferromagnetic** $\mu_r >> 1$ (iron-like)
- The latter are often the most useful materials when working with magnetic fields.
- There are other types of magnetic materials (ferrites, magnetic powders, magnetic fluids, magnetic glasses, etc.)

Permeabilities of diamagentic and paramagnetic materials

Material	Relative Permeability
Silver	0.999974
Water	0.9999991
Copper	0.999991
Mercury	0.999968
Lead	0.999983
Gold	0.999998
Graphite (Carbon)	0.999956
Hydrogen	0.999999998

Material	Relative Permeability
Air	1.00000036
Aluminum	1.000021
Palladium	1.0008
Platinum	1.00029
Tungsten	1.000068
Magnesium	1.00000693
Manganese	1.000125
Oxygen	1.0000019

Permeabilities of ferromagnetic materials

Material	μ_r	Material	μ_r
Cobalt	250	Permalloy (78.5% Ni)	100,000
Nickel	600	Fe_3O_4 (Magnetite)	100
Iron	6,000	Ferrites	5,000
Supermalloy (5% Mo, 79% Ni)	10^7	Mumetal (75% Ni, 5% Cu, 2% Cr)	100,000
Steel (0.9%C)	100	Permendur	5,000
Silicon Iron (4% Si)	7,000		

Magnetics - some definitions

- Soft magnetic materials are those for which magnetization is reversible
- Hard magnetic materials are materials which retain magnetization and are therefore used for production of permanent magnets
- Hysteresis - a property of ferromagnetic materials best explained through the magnetization curve
- Nonlinear magnetization: permeability is field dependent.

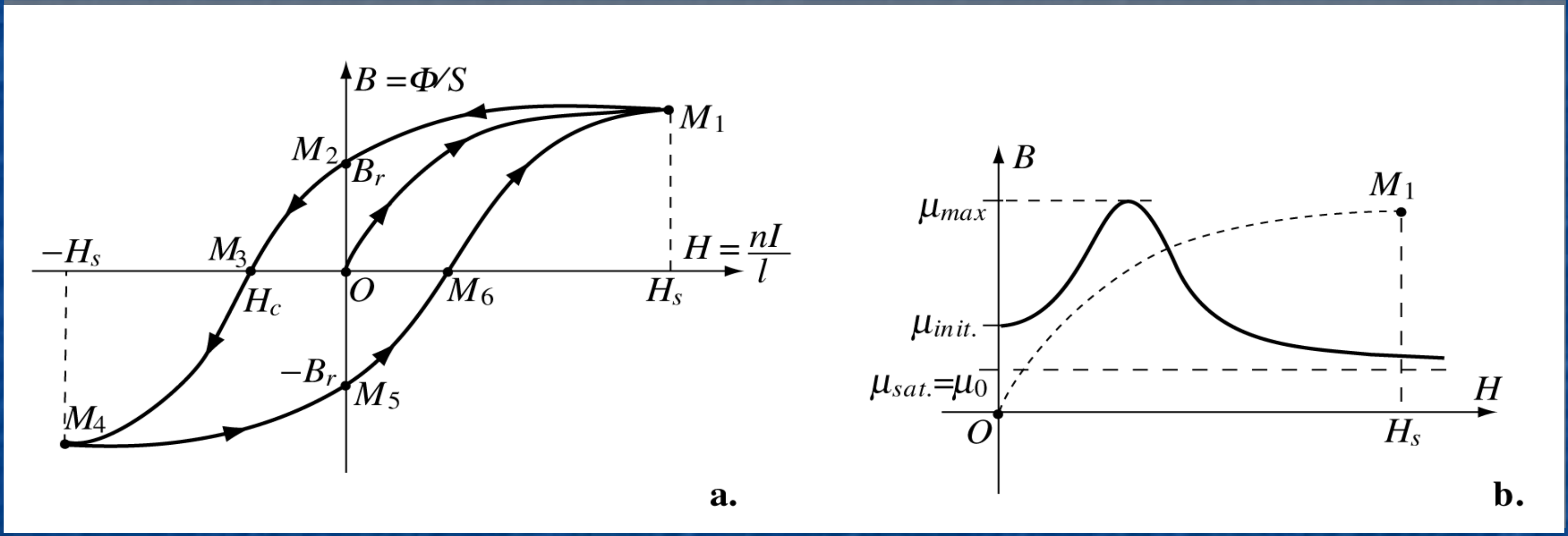
Soft magnetic materials - used as magnetic cores

Material	Relativepermeability(Max.) μ_r
Iron(0.2% impure)	9,000
Pure iron (0.05% impure)	2×10^5
Silicon iron (3%Si)	55,000
Permalloy	10^6
Superm-alloy (5% Mo,79% Ni)	10^7
Permendur	5,000
Nickel*	600

Hard magnetic materials - used in permanent magnets

Material	μ_r
Alnico (Aluminum-Nickel-Cobalt)	3-5
Ferrite (Barium-Iron)	1.1
Sm-Co (Sammarium-Cobalt)	1.05
Ne-Fe-B (Neodymium-Iron-Boron)	1.05

Magnetization curve and permeability of ferromagnetic materials

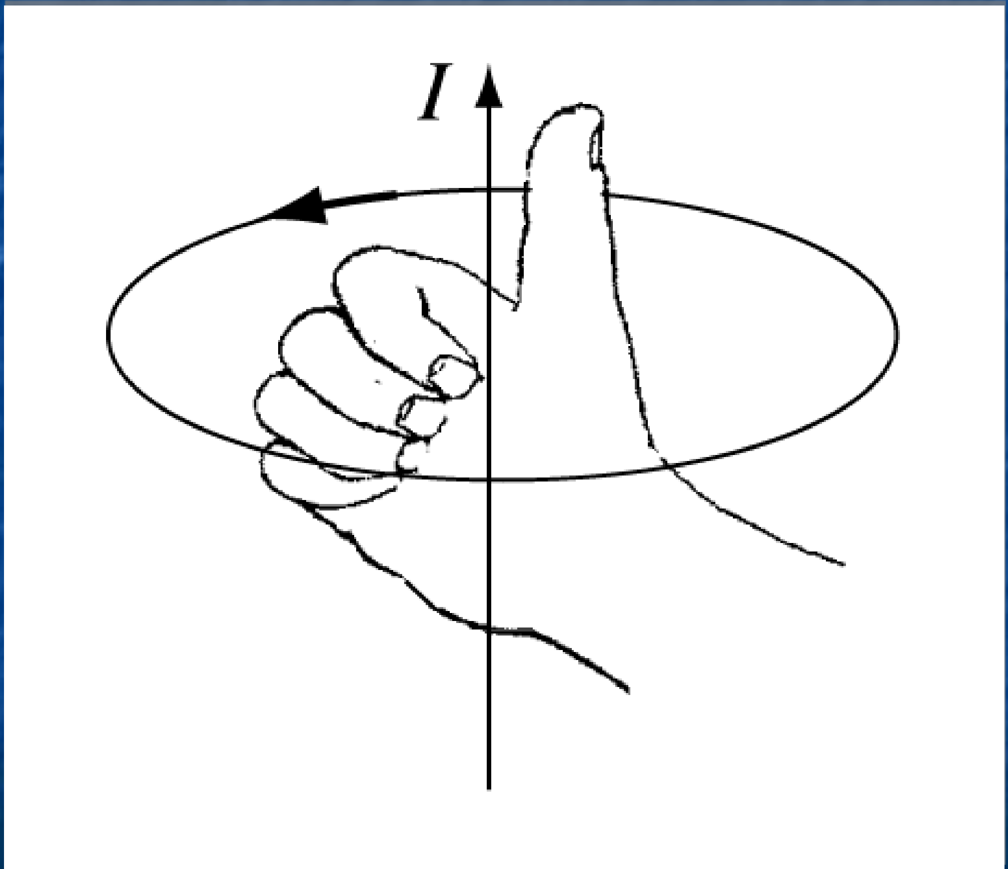


Currents, fields and flux

- Relation between current and magnetic flux density.
- For a long straight wire carrying a current I and placed in a medium of permeability $\mu=\mu_0\mu_r$. The magnitude of the magnetic flux density is:
  - *r* is the distance from the wire to the location where the field is calculated
  - the magnetic field is a vector and has a direction (next) - field is perpendicular to I

$$B = \mu_0\mu_r\frac{I}{2\pi r}$$

Relation between current and magnetic field



General idea:

- In more practical configurations, the wire may not be very long or it may be wound in a coil but, nevertheless, the basic relations hold: The larger the current and/or the permeability, or the shorter the distance between current and the location where the magnetic field is needed, the larger the magnetic field

Magnetic flux

- Flux is the integral of flux density over an area S:
- If **B** is constant over an area *S* and at an angle θ to the surface, flux is $\Phi = BS\cos\theta$.
- Unit of flux is the weber [Wb]
- 1 [Wb] = 1 [Tm^2]
- Flux relates to power and energy in the magnetic field

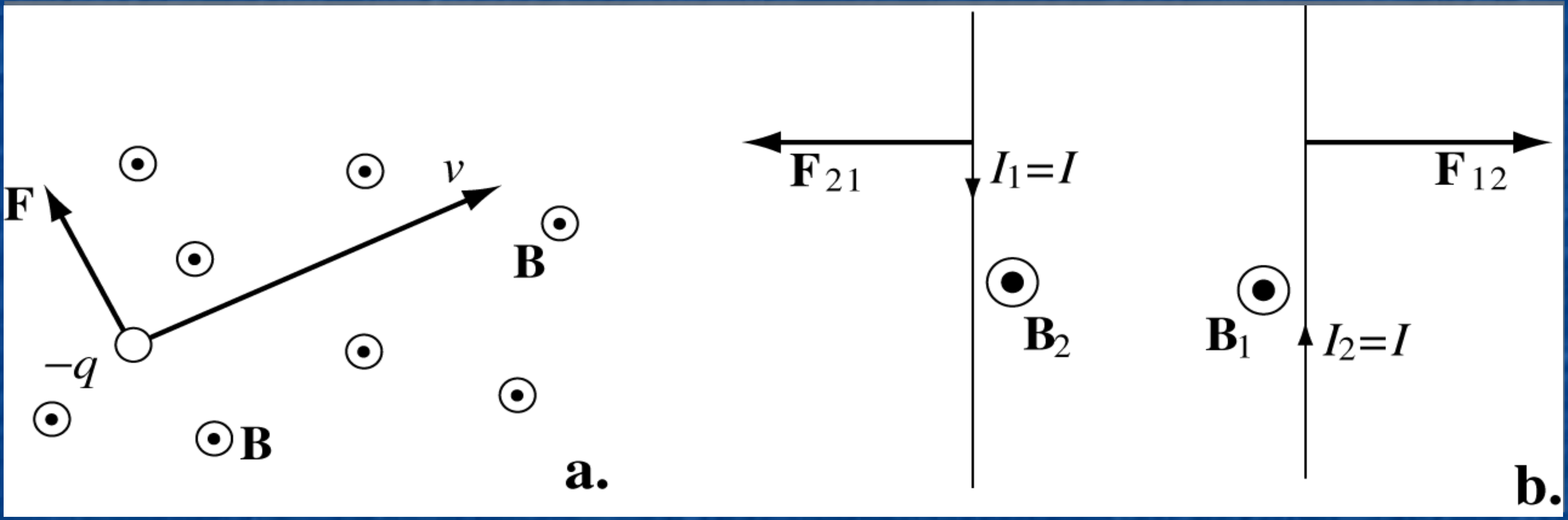
$$\Phi = \int_S \mathbf{B}.d\mathbf{s} \qquad [\mathrm{Wb}]$$

Force in the magnetic field

- Force in a magnetic field is based on the fact that a charge moving at a velocity **v** in a magnetic field **B** experience a force (called the Lorentz force) given as:
  - θ_{vB} is the angle between the direction of motion and the direction of **B**
  - **F** is perpendicular to both **v** and **B** as shown (next).

$$F = qvB\sin\theta_{vb} \qquad [\mathrm{N}]$$

Relation between charge, current and force in a magnetic field



Forces on currents

- Charges (electrons) move in conductors (current)
- Two wires carrying currents in opposite directions exert forces on each other
- The forces the wires exert on each other are in opposite direction and tend to separate the wires.
- If the currents were in the same direction (or the magnetic field reversed) the wires would attract.

Forces on currents

- For long parallel wires, the force for a length *L* of the wire is: F = BIL
- For other configuration the relation is much more complicated but force is proportional to *B*, *I* and *L*.
- A single wire carrying a current will be attracted or repelled by a permanent magnet
- These principles are the basis for magnetic actuation
- Forces can be very large since *B*, *I* and *L* can be controlled and can be quite large.

Inductive sensors

Rely on two basic phenomena:

- Inductance of a coil and changes of inductance due to a variety of effects (distance, materials, dimensions, etc.)
- Induced currents in conducting materials.

- Inductance is a property of a magnetic device just as capacitance is the property of an electric device
- Usually associated with coils and conductors
- Inductance can be made to respond (change) to almost any physical property either directly or indirectly

Inductance

- Defined as the ratio of flux and the current that produced is:

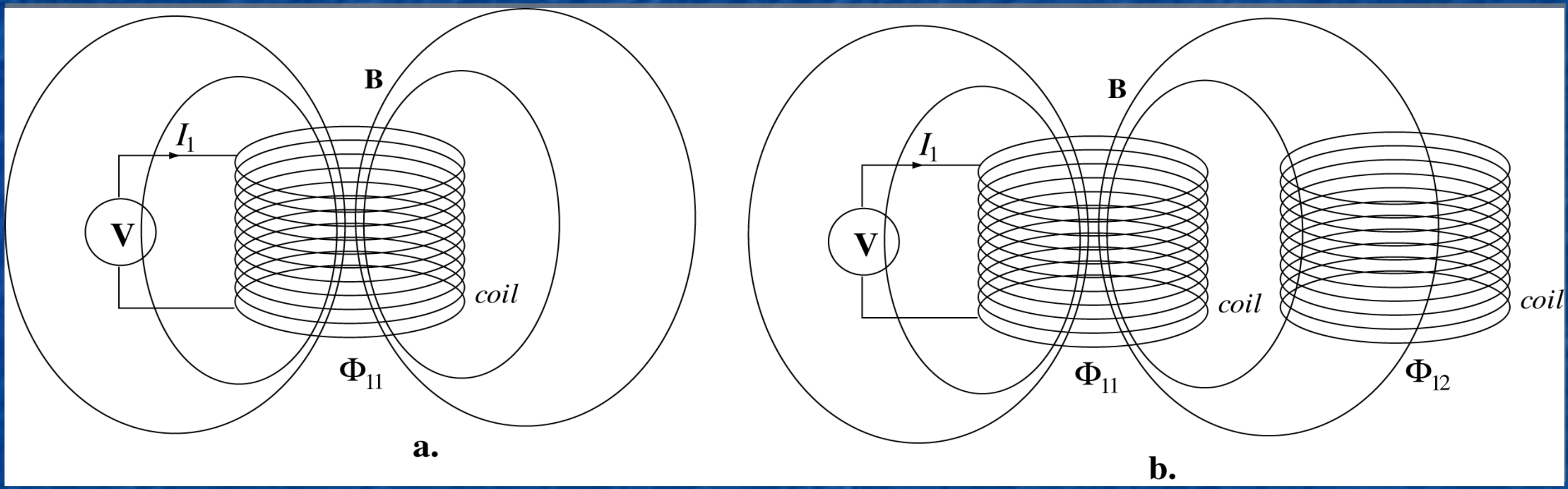
$$L = \frac{\Phi}{I} \quad \left[\frac{webber}{ampere}\right] \ or \ [henry]$$

- Inductance is independent of current since Φ is current dependent
- All magnetic devices have an inductance but inductance is most often associated with coils

Inductance

- Two types of inductance:
- 1. Self inductance: the ratio of the flux produced by a circuit (a conductor or a coil) in itself and the current that produces it. Usually denoted as L_{ij}.
- 2. Mutual inductance: the ratio of the flux produced by circuit *i* in circuit *j* and the current in circuit *i* that produced it. Denoted as M_{ij}.
- A mutual inductance exists between any two circuits as long as there a magnetic field (flux) that couples the two.
- This coupling can be large (tightly coupled circuits) or small (loosely coupled circuits).

Self and mutual inductance

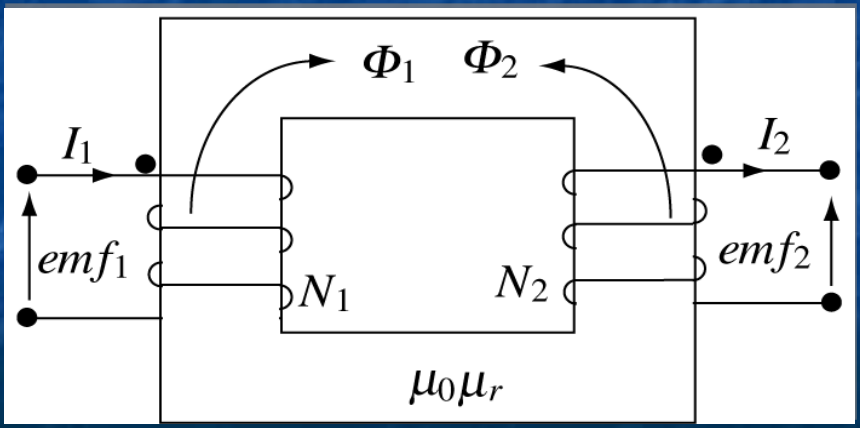


Inductors and transformers

- A coil is also called an inductor (having inductance)
- Transformers are made of two or more coils, coupled through mutual inductances
- Many sensors are in fact transformers of one type or another
- Transformer are ac devices

The transformer

- A primary and a secondary circuit
- A magnetic path for the flux (closed or open)
- Transformer ratio is N_1/N_2



The transformer

- An ac voltage applied to one circuit (or coil) produces a voltage in any other circuit that couples to the driving coil as shown in **Figure 5.17**.
- Coils, of N_1 and N_2 turns respectively. All flux produced by coil 1 couples to coil 2 through the magnetic circuit made of a ferromagnetic material (iron for example). The voltages and currents relate as follows ($a = N_1/N_2$)

$$V_2 = \frac{N_2}{N_1} V_1 = \frac{1}{a} V_1, \qquad I_2 = \frac{N_1}{N_2} I_1 = a I_1$$

The transformer

- The transformer so defined is a tightly coupled transformer (all flux links both coils)
- Loosely coupled transformers:
  - Only part of the flux produced by one coil links the second coil
  - The magnetic path is said to be open
  - These are more often used in sensors than tightly coupled transformers

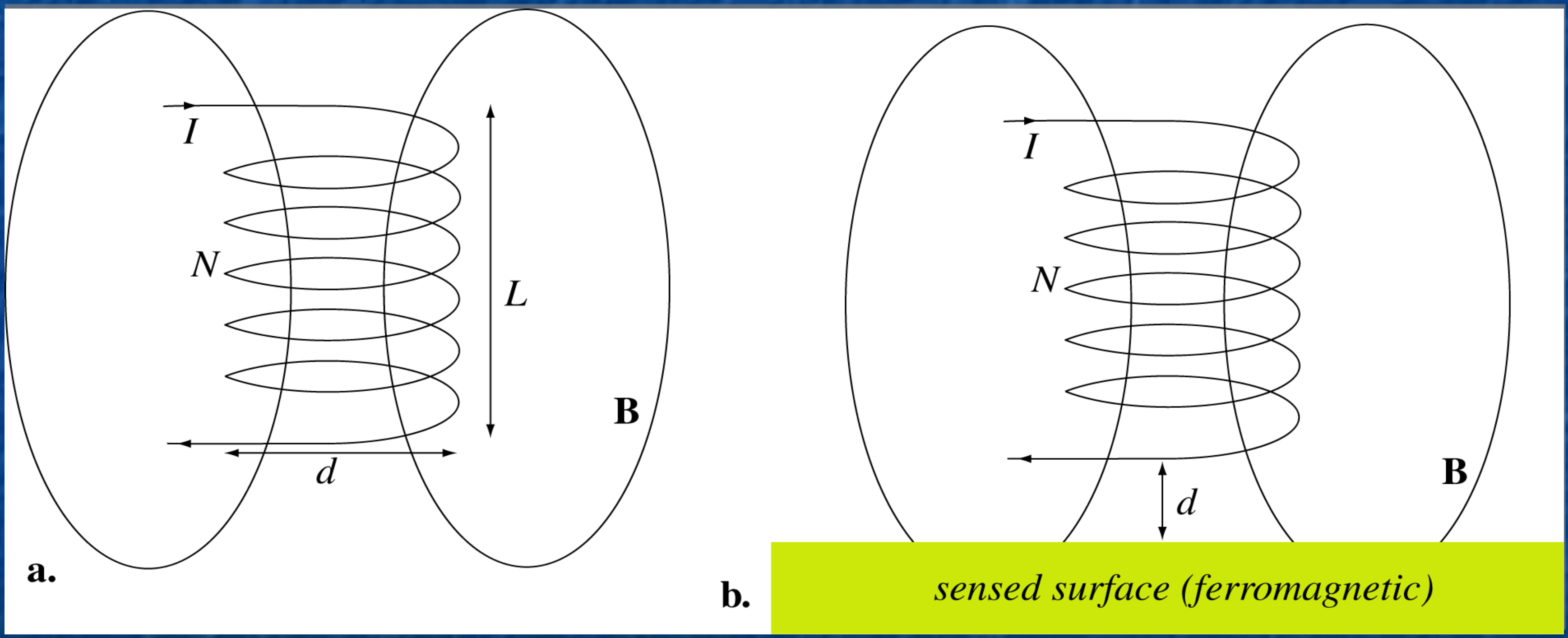
Inductive sensors - general

- Most inductive sensors relay on self inductance, mutual inductance or transformer concepts
- Inductors require currents to sense (passive devices)
- A magnetic field is produced - the sensor can be said to respond to changes in this magnetic field.
- The most common type of stimuli sensed by inductive sensors are position (proximity), displacement and material composition.
- Inductance and induction is often used to sense other quantities indirectly.

Inductive proximity sensors

- Inductive proximity sensor contain:
  - At the very least a coil (inductor)
  - Generates a magnetic field
  - The coil's inductance depends on dimensions of the coil, number of turns and materials around it.
  - The current and the diameter of the coil define the extent to which the field projects away from the coil and therefore the span of the sensor.
  - Operation:
  - As the sensor gets closer to the sensed surface the inductance of the coil increases if the sense surface is ferromagnetic
  - It is then sufficient to use a means of measuring this inductance to infer proximity and position

Sensing position and proximity



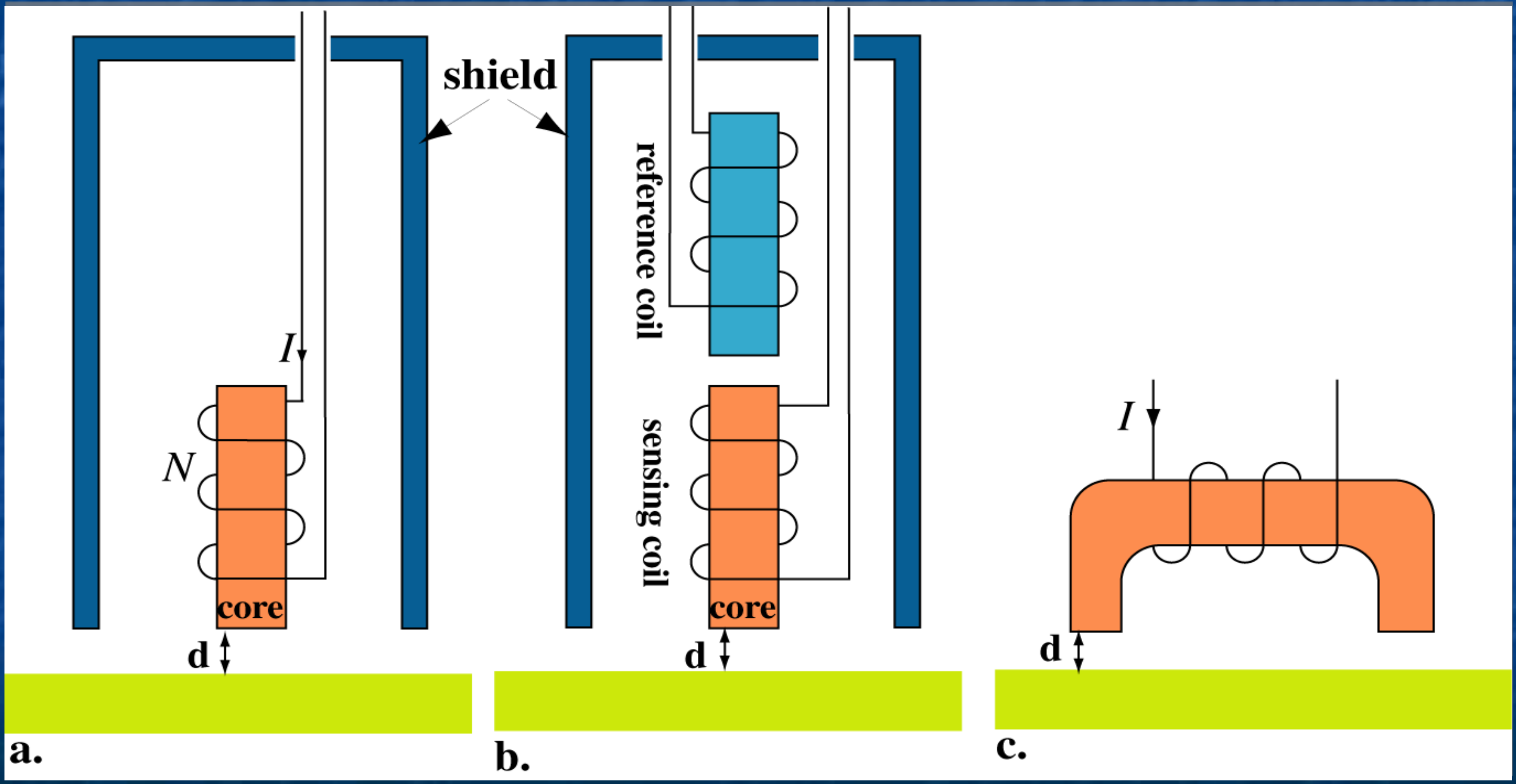
Inductance - additional details

- Inductance is measured with an ac current source and a voltmeter or an ac bridge.
- By measuring the voltage across the inductor the impedance can be evaluated and since $Z=R+j\omega L$ (R is the ohmic resistance and $\omega=2\pi f$ the angular frequency) the inductance L is immediately available as a measure of position of the coil or proximity to the surface.
- We assumed here that R is constant but even if it is not, the impedance in air (nothing being sensed) is known and this can be used for calibration.

Inductance sensor - practical

- A ferromagnetic core is added to increase the inductance of the sensor.
- Most often iron or a ferrite (a powdered magnetic material such as Fe_2O_3, CoO_2 in a binding material and sintered into the shape needed)
- A shield may be placed around the sensor to prevent sensitivity to objects on the side of the sensor or at its back
- The net effect of the shield is to project the field in front of the sensor and hence increase both the field (inductance) and the span of the

Practical construction of inductive sensors



Proximity sensor with reference coil

- In other sensors, there are two coils, one serving as reference, the other as a sensor (**Figure 5.19b**).
- The reference coil's inductance remains constant and the two are balanced.
- When a surface is sensed, the sensing coil has a larger inductance and the imbalance between the coils serves as a measure of distance.

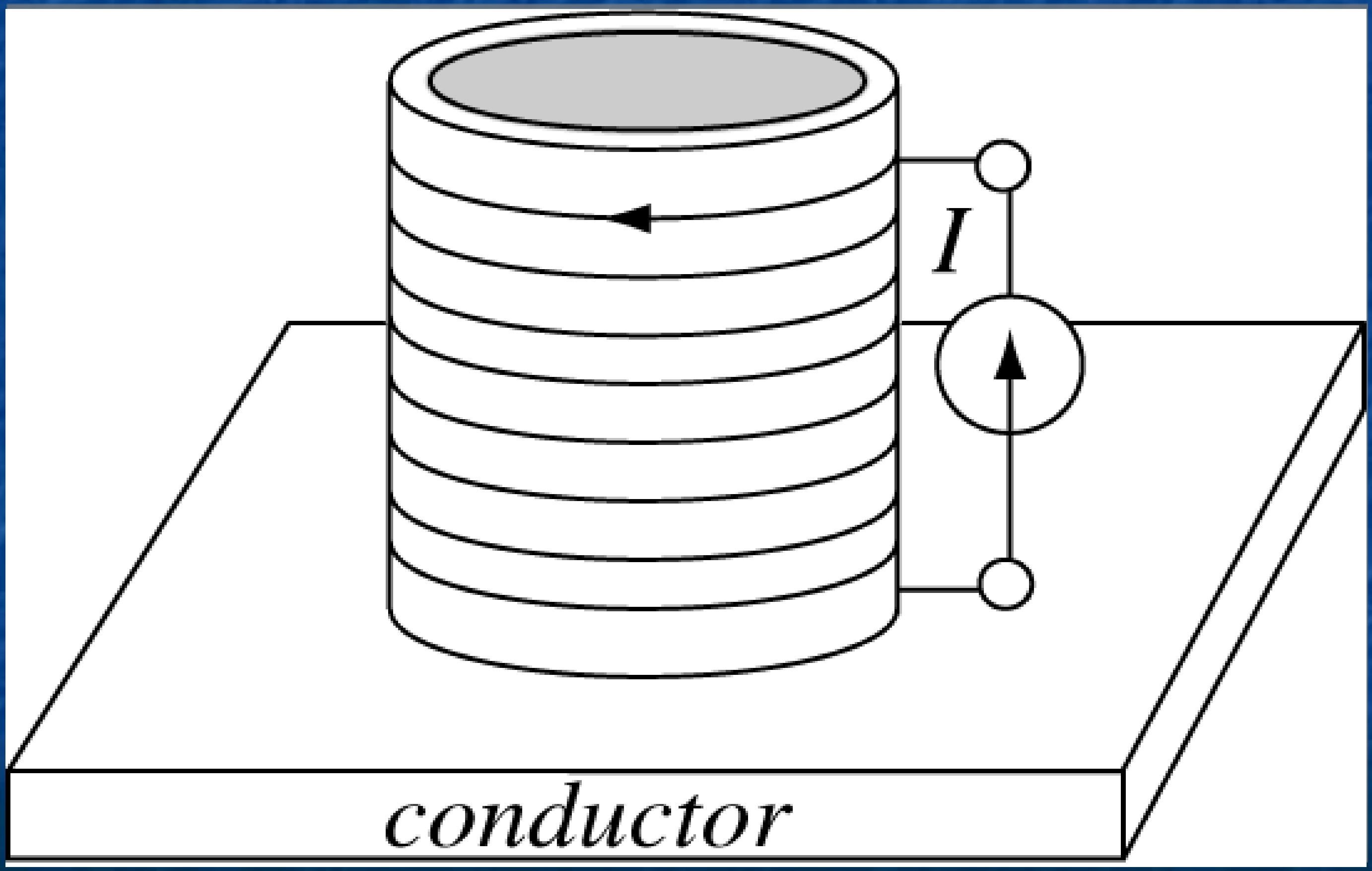
Closed magnetic circuit proximity sensor

- Other sensors, like the one is **Figure 5.19c** may employ a closed magnetic circuit which tends to concentrate the magnetic field in the gaps and usually do not require shielding since within the sensor, the magnetic field is constrained within the ferromagnetic material

Eddy current sensors

- Inductive proximity sensors are sensitive to the presence (proximity) of non-conducting ferromagnetic materials or to any conducting media.
- Nonconductors in general do not affect proximity sensors.
- Many inductive proximity sensors are of the eddy current type.

Eddy current sensor



Eddy current sensors

- The name eddy current comes from the fundamental property of ac magnetic fields to induce currents in conducting media
- There are two related phenomena at work.
  - The currents produced in the conductor, called eddy currents because they flow in closed loops, cause a field which opposes the original field that produces them (Lenz's law). This field reduces the net flux through the sensor coil.
  - Second, the currents flowing in the conductor being sensed, dissipate power.

Eddy current sensors

- The sensing coil is now forced to supply more power than it would otherwise supply and hence, given a constant current, its effective resistance increases.
- This change in impedance from $Z=R+j\omega L$ to $Z'=R'+j\omega L'$ is easily sensed either in absolute terms or as a change in the phase of the measured voltage (given a constant current).
- A second effect is the skin effect in conducting media.

Eddy current sensors

A magnetic field penetrating into a conducting medium is attenuated exponentially from the surface inwards (and so are the eddy currents and other quantities):

$$B = B_0 e^{-d/\delta}, \qquad or: \qquad I = I_0 e^{-d/\delta}$$

B_0 and I_0 are the flux density and the current density at the surface,
d is depth in the medium
δ is the skin depth. Skin depth is defined as the depth at which the field (or current) is attenuated to 1/e of its value at the surface.

Skin depth

- For planar surfaces, skin depth is given as:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad [m]$$

f is the frequency of the field.
Penetration depends on frequency, conductivity and permeability.
The main implication here is that the sensed conductor must be thick enough compared to skin depth.
Alternatively, operation at higher frequencies may be needed.

Proximity sensors - comments

- Proximity sensors (either capacitive or inductive) can be used to sense distance.
- Their transfer function is much too nonlinear and their span too small to be effective except for short spans
- Proximity sensors are usually used as switches to provide a clear indication when a certain, preset distance is reached.
- Inductive sensors can produce an electric output such as voltage based on the change in their impedance
- Often the inductor is part of an oscillator (LC oscillator is the most common) and the frequency of the sensor is then used as the output.

Inductive sensors

Eddy current sensors for NDT

Eddy current sensors for NDT

Position and displacement sensing

- Position and displacement are usually understood as measuring the exact distance from a point or the travel of a point relative to another.
- Requires accurate measurements and possibly linear transfer functions of the sensors involved.
- One approach to this task is through the use of variable inductance sensors, sometimes called variable reluctance sensors.

Magnetic reluctance

- Magnetic reluctance is the equivalent magnetic term to resistance and is defined as

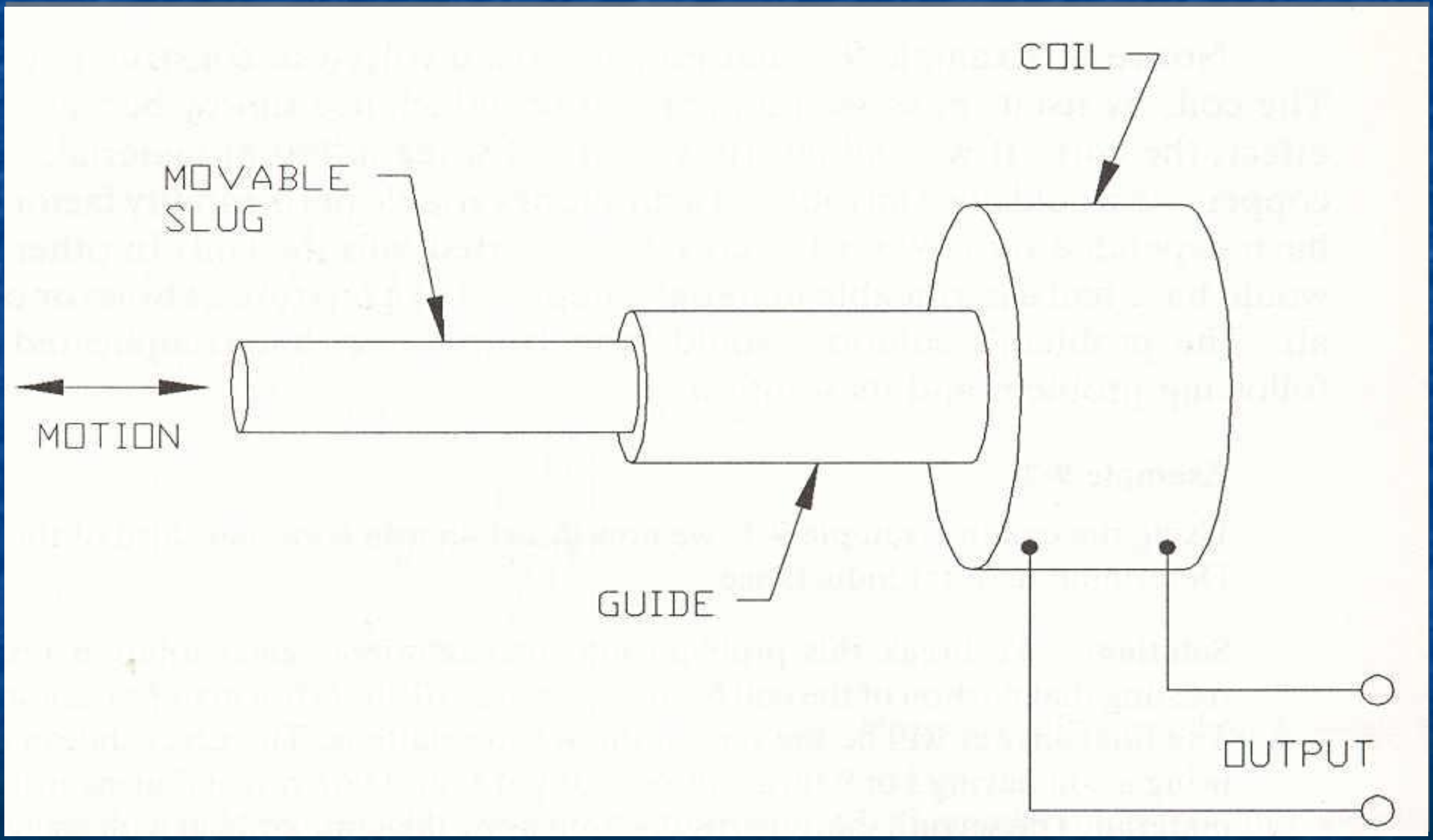
$$R = \frac{L}{\mu S} \quad \left[\frac{1}{\mathrm{H}}\right]$$

Reluctance is smaller the shorter the magnetic path, the larger its cross sectional area and the larger its permeability.
Reluctance is then related to inductance through permeability and reducing reluctance also increases inductance and vice versa.
Typically, the reluctance of a coil can be changed by adding a gap in the magnetic path and changing the effective length of this gap.

Movable core sensors

- Thus, a simple method of changing inductance of a coil is to provide it with a movable core:
- The further the movable core moves in, the smaller the reluctance of the magnetic path and the larger the change in inductance.
- This type of sensor is called a linear variable inductance sensor. (Linear here means that the motion is linear).
- Inductance is a measure of the position of the core
- The same of course may be used to measure force, pressure, or anything else that can produce linear displacement.

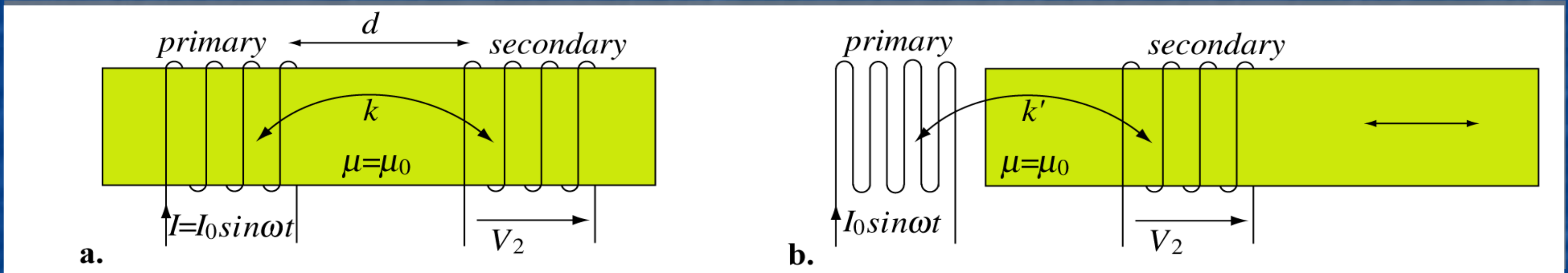
Variable reluctance (inductance) sensor - the LVDT



LVDT

- A better displacement sensor is a sensor based on the idea of the transformer.
- Based on one of two related principles;
  - the distance between two coils of a transformer is varied (the coupling between the coils changes) or
  - the coupling coefficient between the two coils is varied by physically moving the core while the two coils are fixed.
- Both principles are shown next.

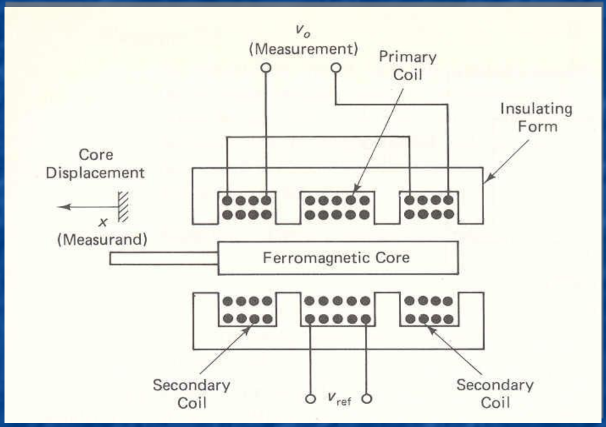
Principle of the LVDT

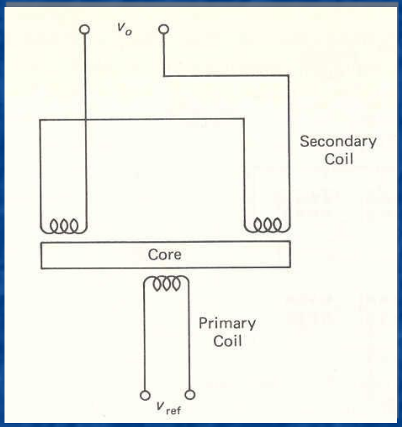


LVDT

- LVDT - Linear Variable Differential Transformer
- Based on the 2nd principle
- One primary coil, two secondary coils connected in opposition
- Output is zero if coupling is balanced
- Motion to either side changes the output

Structure and equivalent circuit of an LVDT





- The output is zero for core centered
- Motion to the right or left changes the output in different directions (polarity)
- This is a variable reluctance transformer
- Detects both distance and direction of change

LVDT - properties

- LVDTs are very sensitive and useful
- In a relatively small range of motion, the output is linear.
- The primary coil is driven with a stable sinusoidal source at a constant frequency and the core is ferromagnetic.
- The whole sensor is enclosed and shielded so that no field extends outside it and hence cannot be influenced by outside fields.

LVDT - properties

- The core slides in and out and that motion is often used for accurate measurements of displacement for applications in industrial control and machine tools.
- LVDT sensors are extremely rugged and come in various dimensions to suit many needs (some as small as 10mm long).
- In most practical applications, the voltage output is measured (amplification is usually not needed) while the phase is detected with a zero-crossing phase detector (a comparator).

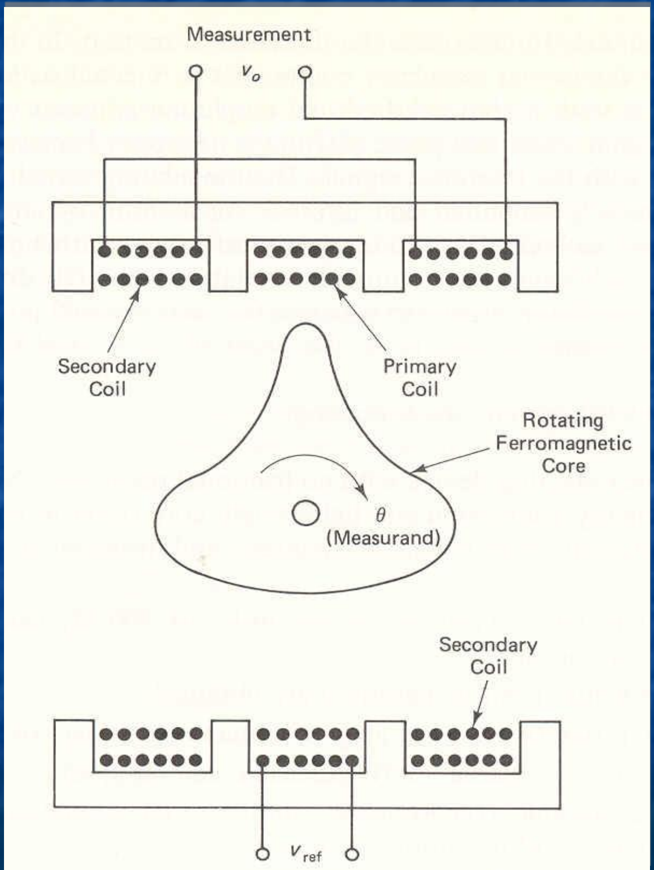
LVDT - properties

- Frequency of the source must be high with respect to the frequency of motion of the core (a figure of 10 times higher is common) to avoid errors in the output voltage due to slow response of the LVDT.
- The operation of LVDTs can be from ac sources or dc sources (with internal oscillator providing the sinusoidal voltage).
- Typical voltages are up to about 25V while output is usually below 5V.
- Resolution can be very high while the linear span is about 10-20% of the length of the coil assembly

RVDT - Rotary Variable Differential Transformer

- A variation of the LVDT
- Intended for angular displacement and rotary position sensing.
- In all respects it is identical in operation to the LVDT device but the rotary motion imposes certain restrictions on its construction.
- The span is given in angles and can be up to ±30° to ±40°. Beyond that the output is nonlinear.

RVDT


Measurement
v_o
Secondary
Coil
Primary
Coil
Rotating
Ferromagnetic
Core
θ
(Measurand)
Secondary
Coil
v_{ref}

Response of an RVDT