Optical Sensors, Lasers, and Cameras:

There are many sensors that use light or laser as the basis of measurement. Also, camera images are widely used for sensing purposes.

***Laser*:**

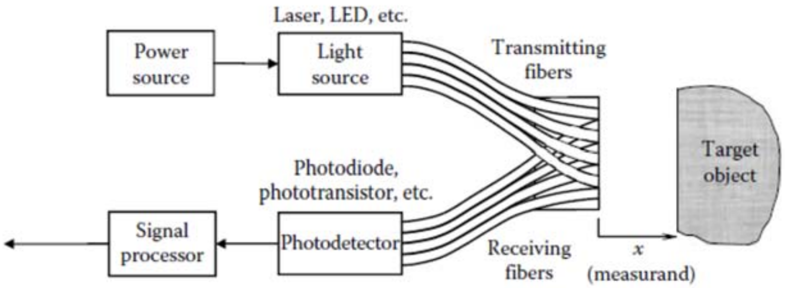
- ***L***ight ***a***mplification by ***s***timulated ***e***mission of ***r***adiation:
- Produces electromagnetic radiation in the ultraviolet, visible, or infrared bands of the spectrum.
- Can provide a single-frequency (*monochromatic*) light source.
- Electromagnetic radiation in a laser is *coherent* in the sense that all waves generated have constant phase angles.
- Uses oscillations of atoms or molecules of various elements.
- Useful in fiber optics, but it can also be used directly in sensing and gauging applications.
- Helium-neon (HeNe) laser and the semiconductor laser are commonly used in optical sensor applications.

***Fiber-optic sensors*:**

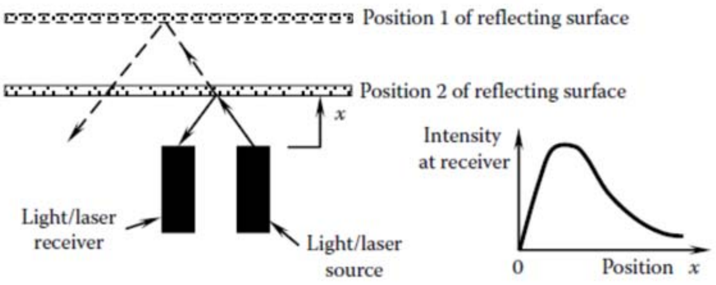
- The characteristic component in a fiber-optic sensor is a bundle of glass fibers (typically a few hundred) that can carry light.
- Each optical fiber may have a diameter on the order of a few μm to about 0.01 mm.
- There are two basic types of fiber-optic sensors:
    - In one type—the *indirect* or the *extrinsic* type—the optical fiber acts only as the medium in which the sensor light is transmitted. In this type, the sensing element itself does not consist of optical fibers.
    - In the second type—the *direct* or the *intrinsic* type—the optical fiber itself acts as the sensing element. When the conditions of the sensed medium change, the light-propagation properties of the optical fibers change as well (e.g., due to micro-bending of a straight fiber as a result of an applied force), providing a measurement of the change in conditions.
    - Examples of the first (extrinsic) type of sensor include fiber-optic position sensors, proximity sensors, and tactile sensors. The second (intrinsic) type of sensor is found, for example, in fiber-optic gyroscopes, fiber- optic hydrophones, and some types of micro-scale displacement or force sensors.

Fiber-Optic Position Sensor:

A schematic representation of a fiber-optic position sensor (or proximity sensor or displacement sensor) is shown and the optical fiber bundle is divided into *two* groups: *transmitting fibers and receiving fibers.*



- Light from the light source is *transmitted along the first bundle* of fibers to the target object whose position is being measured.
- Light reflected (or, diffused) *onto the receiving fibers* by the surface of the target object is carried to a photodetector.
- The intensity of the *light received by the photodetector* will depend on position x of the target object.
- In particular, if x = 0:
  - The *transmitting bundle will be completely blocked off*
  - And *the light intensity at the receiver will be zero*.
- As distance x is increased, the intensity of the received light will increase, because more and more light will be reflected onto the tip of the receiving bundle. This will reach a peak at some value of x.

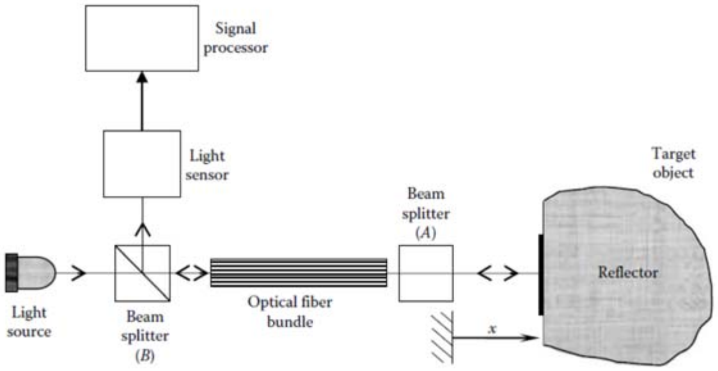


- When x is increased beyond that value:
  - more and more light will be reflected outside the receiving bundle;
  - Hence, the intensity of the received light will drop.

- The proximity–intensity curve for an optical proximity sensor will be nonlinear and will have the shape shown in diagram.
- Using this (calibration) curve, we can determine the position (x) once the intensity of the light received at the photosensor is known.
- This type of fiber-optic sensors can be used, with a suitable front-end device (such as bellows, springs, etc.) to measure pressure, force, etc. as well.

Laser Interferometer:

- Useful in the accurate measurement of small displacements.
- This is an *extrinsic application of fiber optics* where optical *fiber is used for light transmission* rather than light sensing.



- In this fiber-optic position sensor, the *same bundle of fibers is used for sending and receiving* a monochromatic beam of light (typically, laser).
- *Alternatively, monomode fibers, which transmit only monochromatic light (of a specific wavelength) may be used for this purpose*.

- In either case, as shown above, a beam splitter (A) is used so that:
  - Part of the light is directly reflected back to the bundle tip and
  - The other part reaches the target object (as in Figure last page) and reflected back from it (*using a reflector mounted on the object*) on to the bundle tip.
  - In this manner, part of the light returning through the bundle had not traveled beyond the beam splitter while the other part had traveled between the beam splitter (A) and the object (through an extra distance equal to twice the separation between the beam splitter and the object).
  - As a result, the two components of light will have a phase difference ϕ, which is given by: $\phi = \frac{2x}{\lambda} 2\pi$
    - *x is the distance of the target object from the beam splitter*
    - *λ is the wavelength of monochromatic light*
  - The returning light is directed to a light sensor using a beam splitter B.
  - The sensed signal is processed using principles of interferometry to determine ϕ, and from Equation above, the distance x.
  - Very fine resolutions better than a fraction of a micrometer (µm) can be obtained using this type of fiber-optic position sensors.

Advantages:

The advantages of fiber optics include:

- Insensitivity to electrical and magnetic noise (due to optical coupling);
- Safe operation in explosive, High- temperature, corrosive, and hazardous environments; and high sensitivity.
- Mechanical loading and wear problems do not exist because fiber-optic position sensors are *noncontact* devices with no moving parts.

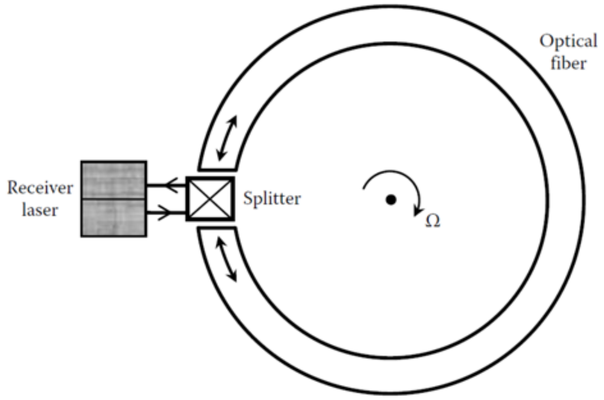
Disadvantages:

The disadvantages of fiber optics include:

- Direct sensitivity to variations in the intensity of the light source and
- Dependence on ambient conditions (temperature, dirt, moisture, smoke, etc.). Compensation can be made, however, with respect to temperature.

Intrinsic application - Fiber-optic Gyroscope

This is an angular speed sensor that uses fiber optics. Contrary to its name, however, it is not a gyroscope in the conventional sense.



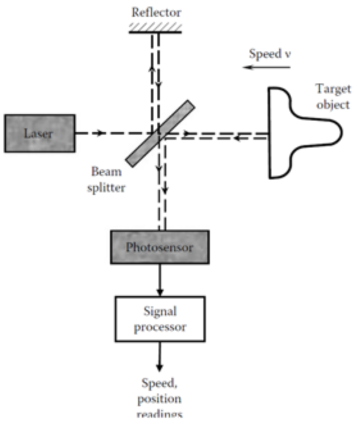
- *Two loops of optical fiber wrapped around a cylinder are used in this sensor, and they rotate with the cylinder, at the same angular speed that needs to be sensed.*
- *One loop carries a monochromatic light (or laser) beam in the clockwise direction, and the other loop carries a beam from the same light (laser) source in the counterclockwise direction.*
- *Since the laser beam traveling in the direction of rotation of the cylinder attains a higher frequency than that of the other beam. The difference in speed or frequencies (known as the Sagnac effect) of the two laser beams received at a common location will measure the angular speed of the cylinder.*
- *This may be accomplished through interferometry, because the combined signal is a sine beat. As a result, light and dark patterns (fringes) will be present in the detected light, and they will measure the frequency difference and hence the rotating speed of the optical fibers.*
- *Note that in a laser (ring) gyroscope, it is not necessary to have a circular path for the laser. Triangular and square paths are used as well. In general the beat frequency* **Δω** *of the combined light from two laser beams traveling in opposite directions is given by:*

$$\Delta\omega = \frac{4A}{p\lambda}\Omega$$

A is the area enclosed by the travel path (πr^2 for a cylinder of radius r)
p is the length (perimeter) of the traveled path ($2\pi r$ for a cylinder)
λ is the wavelength of the laser
Ω is the angular speed of the object (or, optical fiber)

Laser Doppler Interferometer:

- Used for accurate measurement of speed.
- Based on two phenomena: Doppler Effect (DE) and light wave interference: *Constructive and Destructive*
- DE -- Consider a wave source (e.g., a light source or sound source) that is moving w.r.t. a receiver (observer).
  - If source moves toward the receiver, the Frequency of received wave appears ↑ or $f_2 = f + \Delta f$
  - If the source moves away from the receiver, the frequency of received wave ↓ or $f_2 = f - \Delta f$
  - $\Delta f \propto$ Velocity of the source relative to the receiver. This phenomenon is known as the *Doppler Effect*. $\Delta f = \frac{2f}{c}v = k\,v$

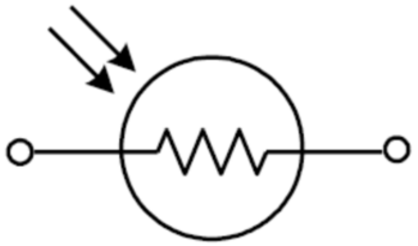


Light Sensors

Semiconductor-based light sensors as well as light sources are needed in optoelectronics. A light sensor is also known as a *photodetector* or *photosensor*.

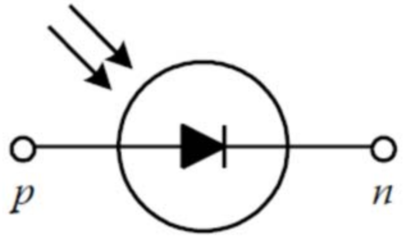
Photoresistor (or *photoconductor*):

- R ↓ (or ↑ σ) as the intensity of light falling on it ↑
- Typically, the resistance of a photoresistor could change from very high values (megohms) in the dark to reasonably low values (less than 100 Ω) in bright light. As a result, *very high sensitivity to light is possible*.
- e.g: *cadmium sulfide* (CdS) or *cadmium selenide* (CdSe) between two electrodes. *Lead sulfide* (PbS) or *lead selenide* (PbSe) may be used in infrared photoresistor.



Photodiode:

- *pn* junction of semiconductor material that produces electron–hole pairs in response to light. Two types of photodiodes are available.
- A *photovoltaic* diode generates a sufficient potential at its junction in response to light (photons) falling on it. Hence an external bias source is not necessary for a photovoltaic diode.
- A *photoconductive* diode undergoes a resistance change at its junction in response to photons.



Phototransistor:

- Semiconductor photosensor with amplification circuitry built into the same package (chip) is popularly called a phototransistor. Hence a photodiode with an amplifier circuit in a single unit might be called a phototransistor and this is an *npn* transistor.
- *i_c is nearly proportional to the intensity of the light falling, hence, i_c can be used as a measure of the light intensity. Germanium or silicon is the semiconductor material that is commonly used in phototransistors.*

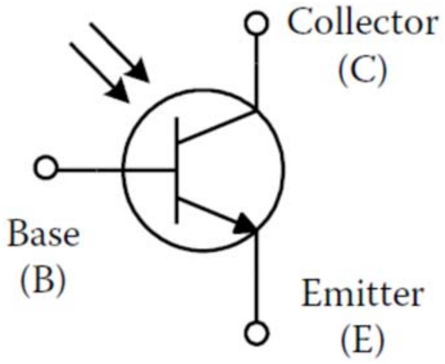
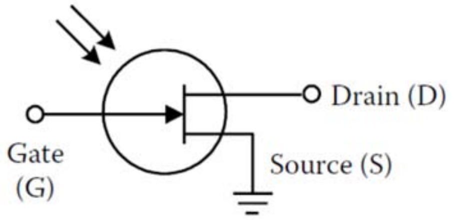


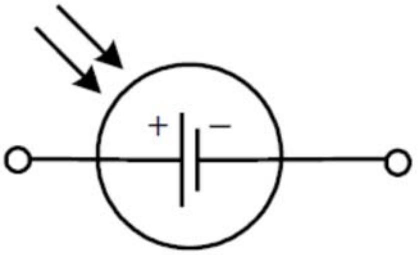
Photo-FET:

- A photo-field effect transistor is similar to a conventional FET. The symbol shown is for an n-channel photo-FET.
- This consists of an n-type semiconductor element (e.g., silicon doped with boron), called channel.
- When *light is projected at the gate, the drain current i_d will increase*.
- Hence, drain current (current at the D lead) can be used as a measure of light intensity.



Photocell:

- Photocells are similar to photosensors except that a photocell is used as an electricity source rather than a sensor of radiation.
- Solar cells, which are more effective in sunlight, are commonly available.
- A *typical photocell is a semiconductor junction element made of a material such as single-crystal silicon, polycrystalline silicon, and cadmium sulfide*.
- Cell arrays are used in moderate-power applications and typical power output is 10 mW/cm2 of surface area, with a potential of about 1.0 V.



Charge-Coupled Device

- A charge-coupled device (CCD) is an integrated circuit element (a *monolithic device*) of semiconductor material.
- A silicon wafer (*p* type or *n* type) is oxidized to generate a layer of SiO2 on its surface.
- A *matrix of metal electrodes is deposited on the oxide layer and is linked to the CCD output leads*.
- When light falls onto the CCD element (from an object), a *charge packets* are generated within the substrate *silicon wafer*. Now if an external potential is applied to a particular electrode of the CCD, a *potential well* is formed under the electrode and a charge packet is deposited here. This charge packet can be moved across the CCD to an output circuit

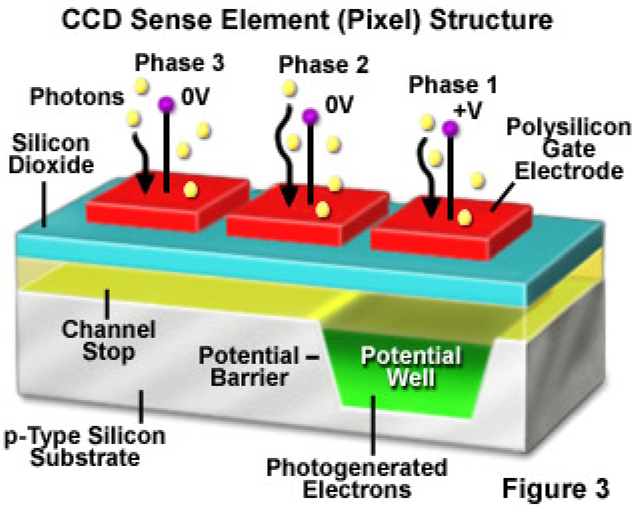


Figure 3

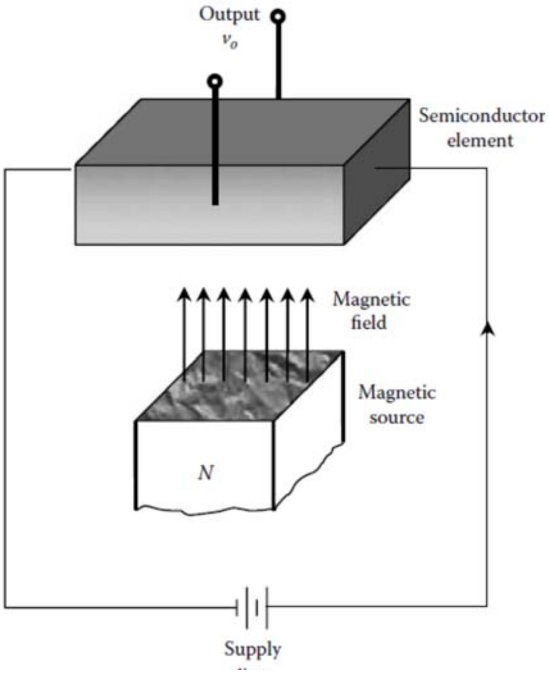
Image Sensors:

- Imaging device is a sensor, and an image is the sensed data.
- Depending on the imaging device, an image can be of many varieties such as optical, thermal or infrared, x-ray, ultraviolet, acoustic, ultrasound, and so on.

Image Processing and Computer Vision:

- An image may be processed (analyzed) to obtain a more refined image from which useful information such as edges, contours, areas, and other geometrical information can be determined.
- Computer Vision involves higher level operations than image processing and is akin to what humans infer based on what they see.
    1. ***Filtering:*** *(to remove noise and enhance the image) including directional filtering (to enhance edges, for edge detection)*
    2. ***Thresholding:*** *(to generate a two-level black-and-white image where the gray levels above a set threshold are assigned white and those below the threshold are assigned black)*
    3. ***Segmentation:*** *(to subdivide an enhanced image, identify geometric shapes/objects, and capture properties such as area and dimensions of the identified geometric entities)*
    4. ***Morphological processing:*** *(sequential shrinking, filtering, stretching, etc. to prune out unwanted image components and extract those that are important)*
    5. ***Subtraction:*** *(e.g., subtract the background form the image)*
    6. ***Template matching:*** *(to match a processed image to a template—useful in object detection)*
    7. ***Compression:*** *(to reduce the quantity of data that is needed to represent the useful information of an image)*

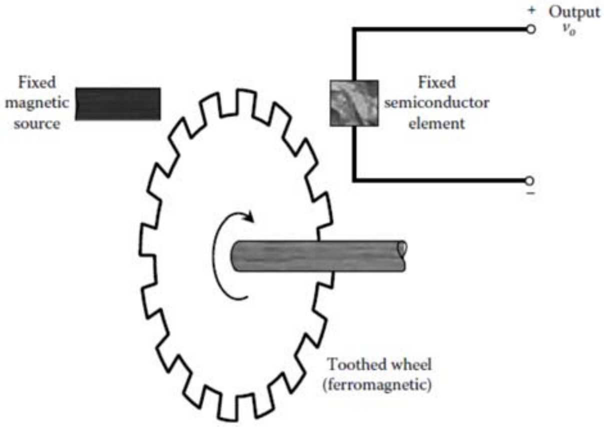
Hall-Effect Sensor:



- Consider a semiconductor element subject to a dc voltage v_{ref}.

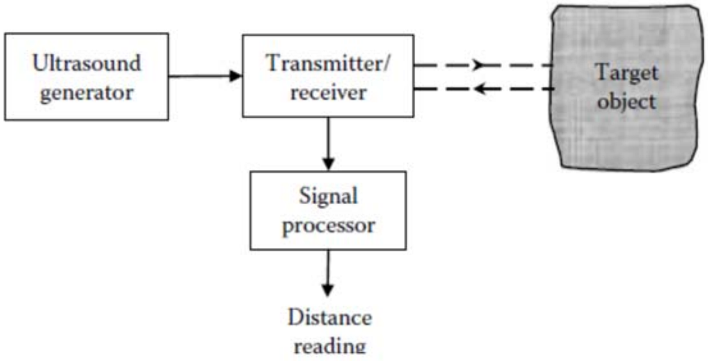
- If a magnetic field is applied perpendicular to the direction of this voltage, a voltage v_o will be generated in the third orthogonal direction within the semiconductor element. This is known as the Hall Effect (observed by E.H. Hall in 1879).

Hall-Effect Motion Sensors:



- A Hall-effect sensor may be used for motion sensing in many ways; for example, as an analog proximity sensor, a limit switch (digital), or a shaft encoder.
- Output voltage v_o increases as the distance from the magnetic source to the semiconductor element decreases, the *output signal v_o can be used as a measure of proximity*.
- Digitally speaking, certain threshold level of the output voltage v_o can be used to generate a binary output, which represents the presence/absence of an object.
- The use of a toothed ferromagnetic wheel (as for a digital tachometer) to alter the magnetic flux will result in a shaft encoder.

Ultrasonic Sensors:

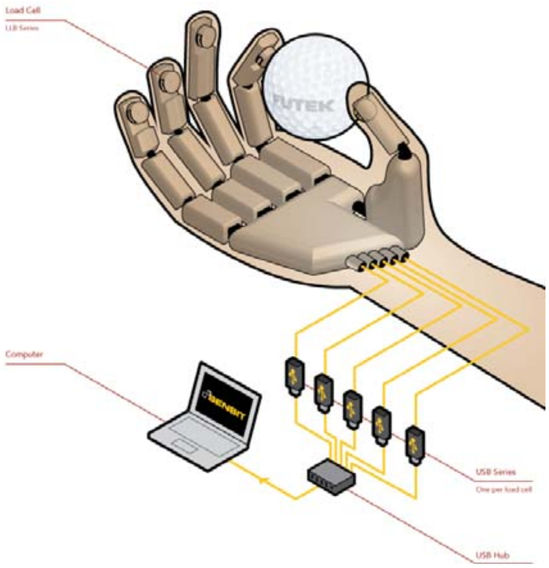


- Ultrasound waves are pressure waves, just like sound waves, but their frequencies are higher (ultra) than the audible frequencies (range of 20 Hz to 20 kHz).
- Ultrasonic sensors are used in many applications, including medical imaging, ranging systems for cameras with autofocusing capability, level sensing, and speed sensing.
- Velocity - Using Doppler Effect.

$$x = \frac{ct}{2};$$

- t is the time of flight of the ultrasound pulse (from generator to receiver)
- x is the distance between the ultrasound generator/receiver and the target object
- c is the speed of sound in the medium (typically, air)

Tactile Sensing:



- Tactile sensing is usually interpreted as touch sensing, but tactile sensing is different from a simple clamping where very few discrete force measurements are made.
- In tactile sensing, a force distribution is measured, using a closely spaced array of force sensors and usually exploiting the skin-like properties of the sensor array.
- Tactile sensing is particularly important in two types of operations:
    - Grasping and fine manipulation, and
    - Object identification.
- In *grasping and fine manipulation*, the object has to be held in a stable manner without being allowed to slip and without being damaged.
- *Object identification* includes recognizing or determining the shape, location, and orientation of an object as well as detecting or identifying surface properties (e.g., density, hardness, texture, flexibility), and defects.

Ideally, these tasks would require two types of sensing:

- Continuous spatial sensing of time-variable contact force
- Sensing of surface deformation profiles (time-variable)

- Note that learning also can be an important part of tactile sensing.
- Typical specifications for an industrial tactile sensor are as follows:
    - Spatial resolution of about 1 mm (about 100 sensor elements)
    - Force resolution of about 2 g
    - Dynamic range of 60 dB
    - Force capacity (maximum touch force) of about 1 kg
    - Response time of 5 ms or less (a bandwidth of over 200 Hz)
    - Low hysteresis (low energy dissipation)
    - Durability under harsh working conditions
    - Robustness and insensitivity to change in environmental conditions (temperature, dust, humidity, vibration, etc.)
    - Capability to detect and even predict slip

Dexterity:

Dexterity is an important consideration in sophisticated manipulators and robotic hands that employ tactile sensing:

$$Motion\ Dexterity = \frac{\text{Number of degrees of freedom in the device}}{\text{Motion resolution of the device}}$$

$$Force\ Dexterity = \frac{\text{Number of degrees of freedom}}{\text{Force resolution}}$$

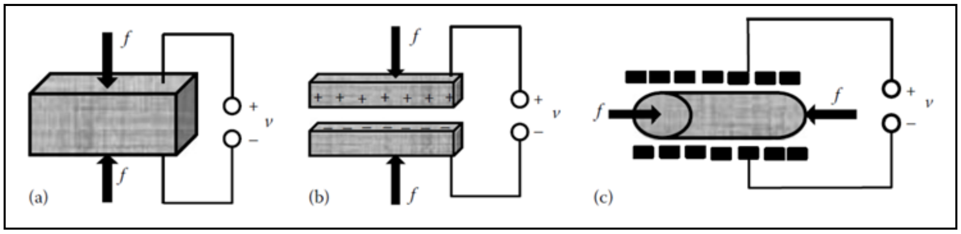
Read Example 6.10 and Strain Gauge example 6.11

MEMS Sensors:

- **M**icro**e**lectro**m**echanical **s**ystems (MEMS) are microminiature devices consisting of microminiature components such as sensors, actuators, and signal processing integrated and embedded into a single chip while exploiting both electrical/electronic and mechanical features of them.
- The device size can be in the sub-millimeter scale (0.01–1.0 mm) and
- The component size can be as small as a micrometer (micron), in the range 0.001–0.1 mm. Since MEMS exploits the integrated-circuit (IC) technologies in their fabrication, many components can be integrated into a single device (e.g., a few to a million).

The advantages of MEMS are primarily the advantages of IC devices which include:

- Microminiature size and weight
- Large surface area to volume ratio (when compared in the same measurement units)
- Large-scale integration (LSI) of components/circuits
- High performance
- High speed (20 ns switching speeds)
- Low power consumption
- Easy mass-production
- Low cost (in mass production)
- In particular, the microminiature size also means negligible mechanical loading, fast response, and negligible power consumption (and related electrical loading).



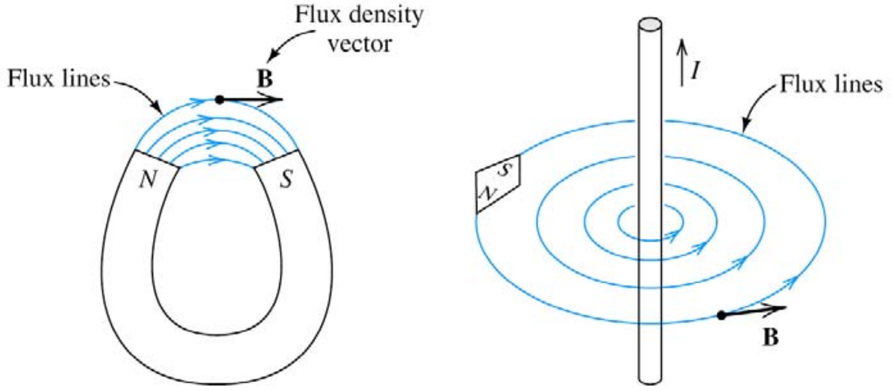
Energy Conversion Mechanism:

Piezoelectric: Mechanical strain in a piezoelectric material causes a charge separation across the material producing a voltage. Strain energy produced by the mechanical work that is needed to deform the material, is converted into electrostatic energy. This is a passive device.

Electrostatic: A voltage causes + and − charges to separate into the capacitor plates. The attraction force between the plates is supported by an external mechanical force. If *plates move apart, mechanical work is done, capacitance is reduced, and the voltage is increased*. Hence, mechanical energy is converted into electrical energy. This is a passive device.

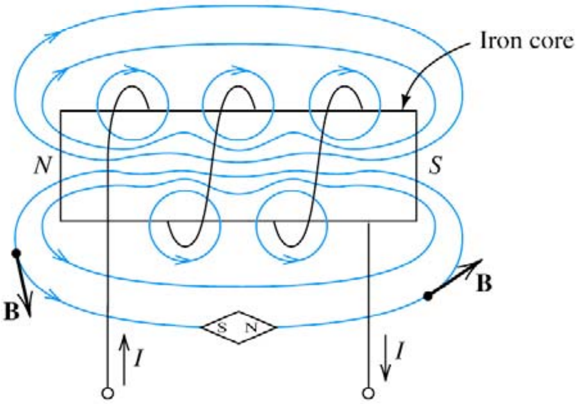
Electromagnetic: As a coil moves in a magnetic field, a current is induced in the coil. In this process, *mechanical energy is converted into electrical energy*. This is a passive device.

Magnetic Circuits:



(a) Permanent magnet

(b) Field around a straight wire carrying current *I*



(c) Field for a coil of wire

Figure 15.1 Magnetic fields can be visualized as lines of flux that form closed paths. Using a compass, we can determine the direction of the flux lines at any point. Note that the flux density vector **B** is tangent to the lines of flux.