CHAPTER 2. Sensors and Transducers

2.1 Sensors and transducers

- sensor: An element which produces a signal relating to the quantity being measured

- transducer: An element that when subject to some physical change experience a related change

2.1.1 Smart sensors

- An arrangement which has the sensor and signal conditioning combined with a microprocessor all in the same package.

- Possible function:
  - 1) compensate for random errors
  - 2) adaptation to changes in the environment
  - 3) automatic calculation of measurement accuracy
  - 4) adjust for non-linearity to give a linear output
  - 5) self-calibration and self-diagnosis for faults

2.2 Performance terminology

- 1. Range and span:
  - Range: The limits of input value variation(ex. F/T Sensor: 0kN~50kN)
  - Span=max. – min (ex. 50kN-0kN=50kN → Span)

- 2. Error:
  - The difference between the measurement and the true
    - error = measurement value – true value

- 3. Accuracy:
  - Accuracy is the extent to which indicated by a measurement system might be wrong. It is thus the summation of all the possible errors that are likely to occur, as well as the accuracy to which the transducer has been calibrated.

- 4. Sensitivity:
  - The relationship indicating how much output there is per unit input, i.e. output/input.

2.2 Performance terminology

- 5. Hysteresis error:
  - Transducers can give different outputs from the same value of quantity being measured according to whether that value has been reached by a continuously increasing change or a continuously decreasing change.

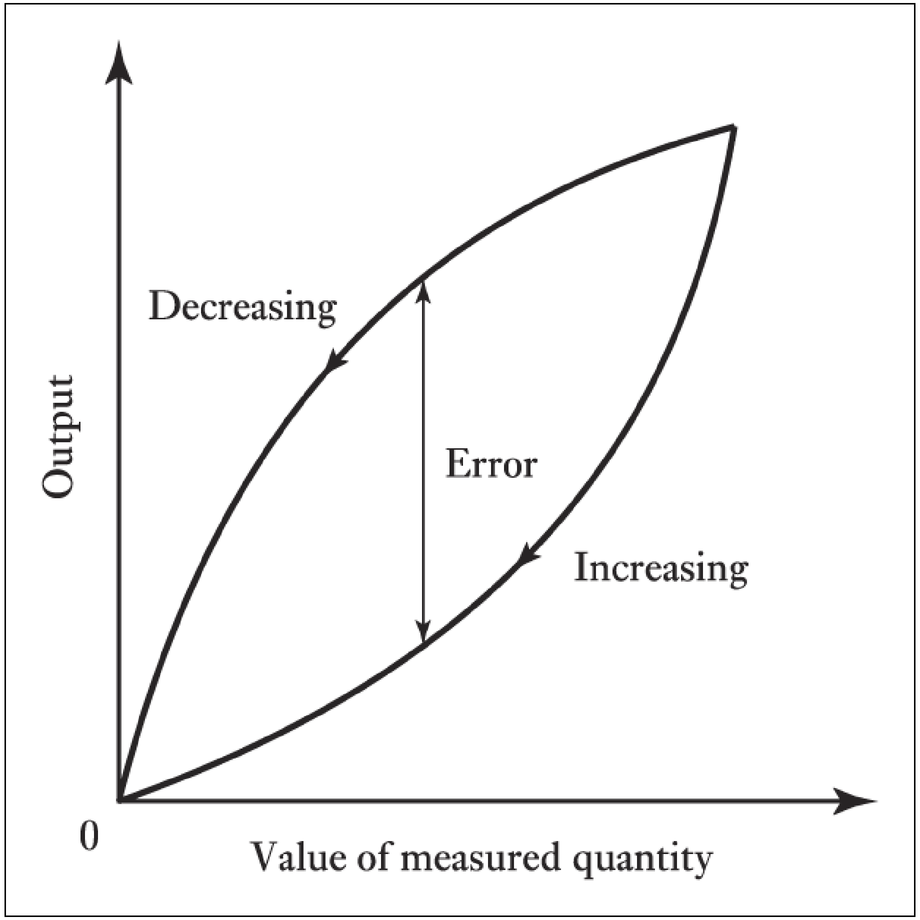


Figure 2.1 Hysteresis

- 6. Non-linearity error:
  - For many transducers a linear relationship between the input and output is assumed. Few transducers, however, have a truly linear relationship and thus errors occur as a result of the assumption of linearity.

  - Solutions:

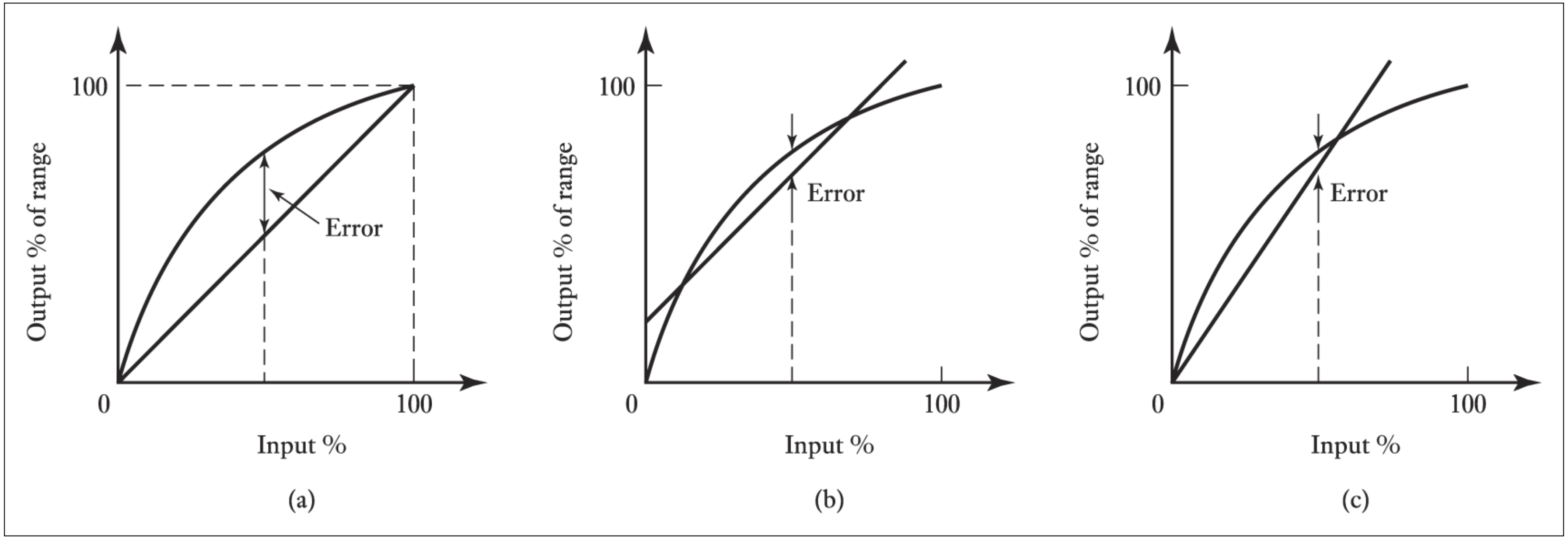


Figure 2.2 Non-linearity error using: (a) end-range values, (b) best straight line for all values, (c) best straight line through zero point

(b) and (c) use LMS(Least mean square) method.

- 7. Repeatability / Reproducibility:
  - The terms repeatability and reproducibility of a transducer are used to describe its ability to give the same output for repeated applications of the same input value.
  - The error resulting from the same output not being given with repeated applications is usally expressed as a percentage of the full range output

$$\text{repeatability} = \frac{\text{max.} - \text{min.values given}}{\text{full range}} \times 100$$

- 8. Stability:
  - The Ability to give the same output when used to measure a constant input over a period of time.
  - The term drift is often used to describe the change in output that occurs over time.

- 9. Dead band/time:
  - The range of input values for which there is not output. (Ex. Friction)

- 10. Resolution:
  - When the input varies continuously over the range, the output signals for some sensors may change in small steps.
  - The smallest change in the input value that will produce an observable change in the output.

- 11. Output impedance:
  - When a sensor giving an electrical output is interfaced with an electronic circuit it is necessary to know the output impedance since this impedance is being connected in either series or parallel with that circuit.
  - The inclusion of the sensor can thus significantly modify the behavior of the system to which it is connected.

2.2.1 Static and dynamic characteristics

- Static characteristics:
  - The values given when steady-state conditions occur, i.e. the value after the transducer settled down
- Dynamic characteristics:
  - The behavior between the time that the input value changes and the time that the value given by the transducer settles down to the steady-state value.

- 1. Response time

- 2. Time constant:
  - the time when the output reaches 63.2% of steady-state value

- 3. Rise time
  - The time when the output reaches 90% or 95% of steady-state value

2.2.1 Static and dynamic characteristics

- Example

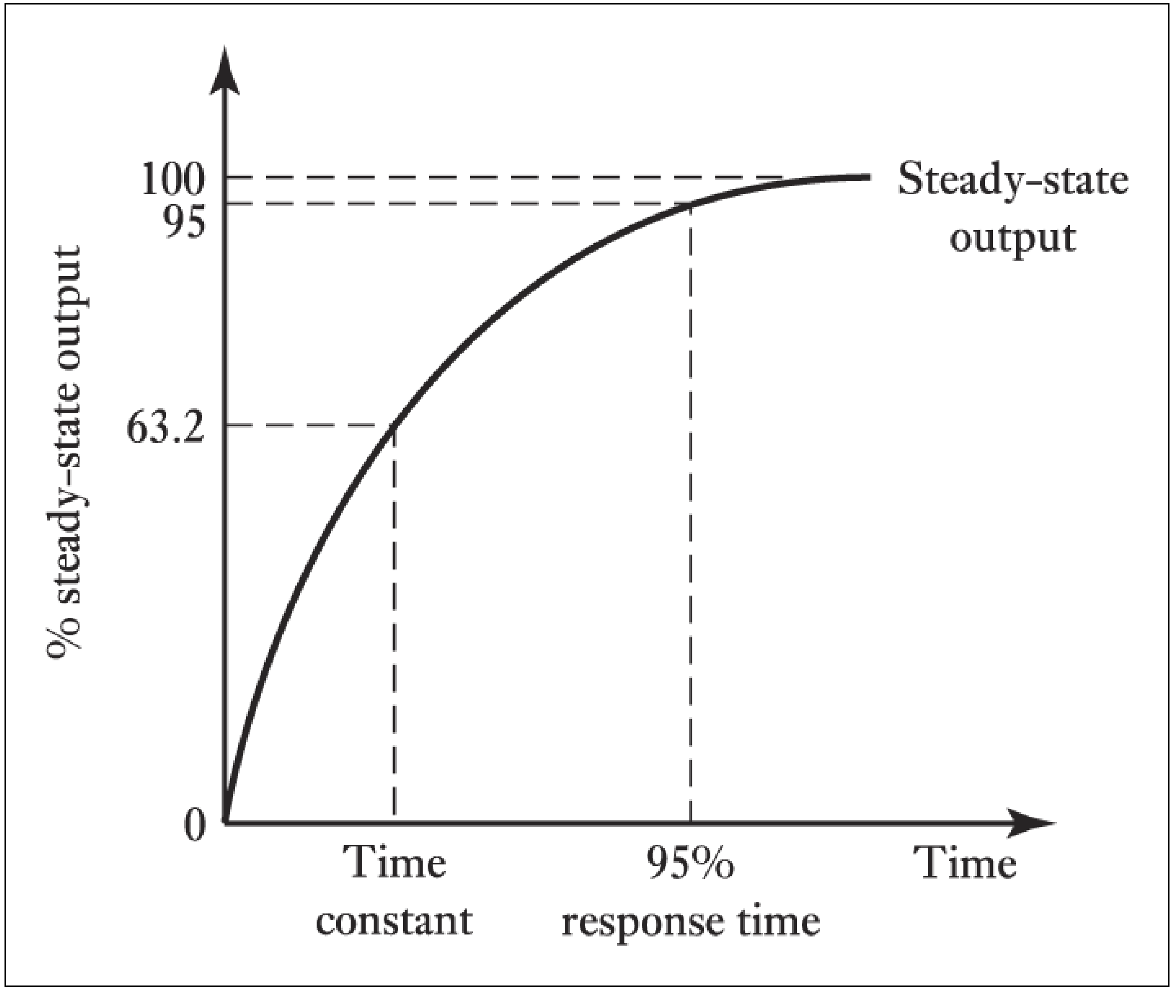


Figure 2.3 Response to a step input

- 4. Settling time:
  - The time taken for the output to settle to within some percentage, e.g. 2%, of the steady-state value.
  - Example:

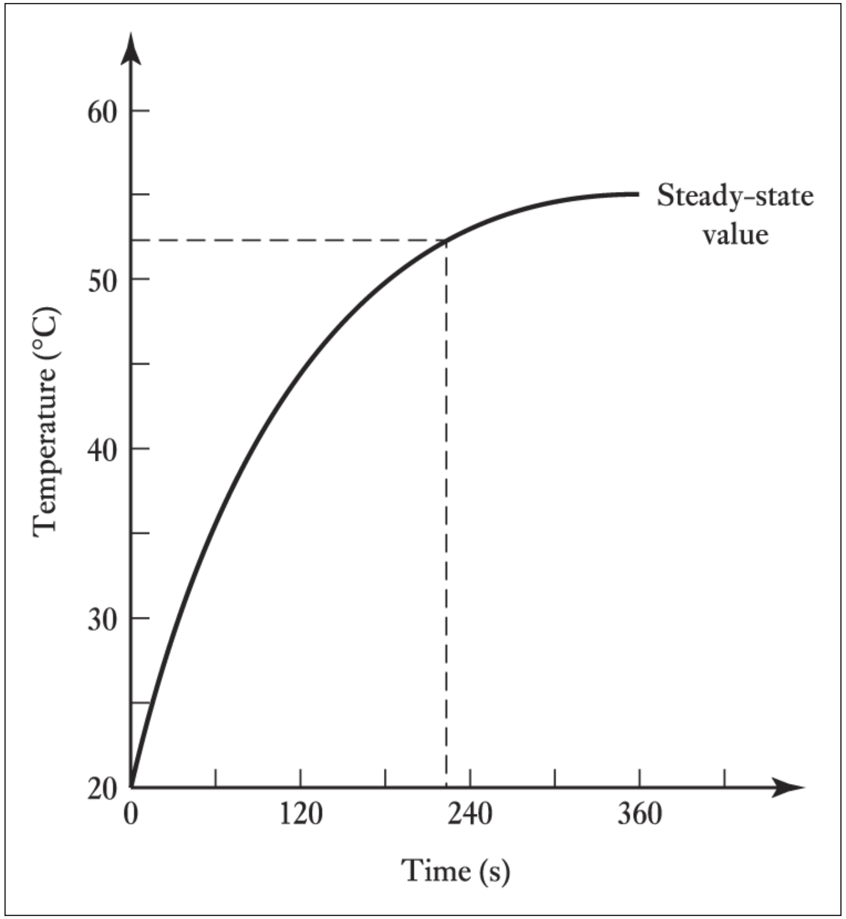


Figure 2.4 Thermometer in liquid

2.3 Displacement, position and proximity

- Displacement:
  - the measurement of the amount by which some object has been moved

- Position:
  - The determination of the position of some object in relation to some reference point

- Proximity:
  - A form of position sensor
  - For determining when an object has moved to within some particular critical distance of the sensor
  - On/Off output

- Contact V.S non-contacting

2.3.1 Potentiometer

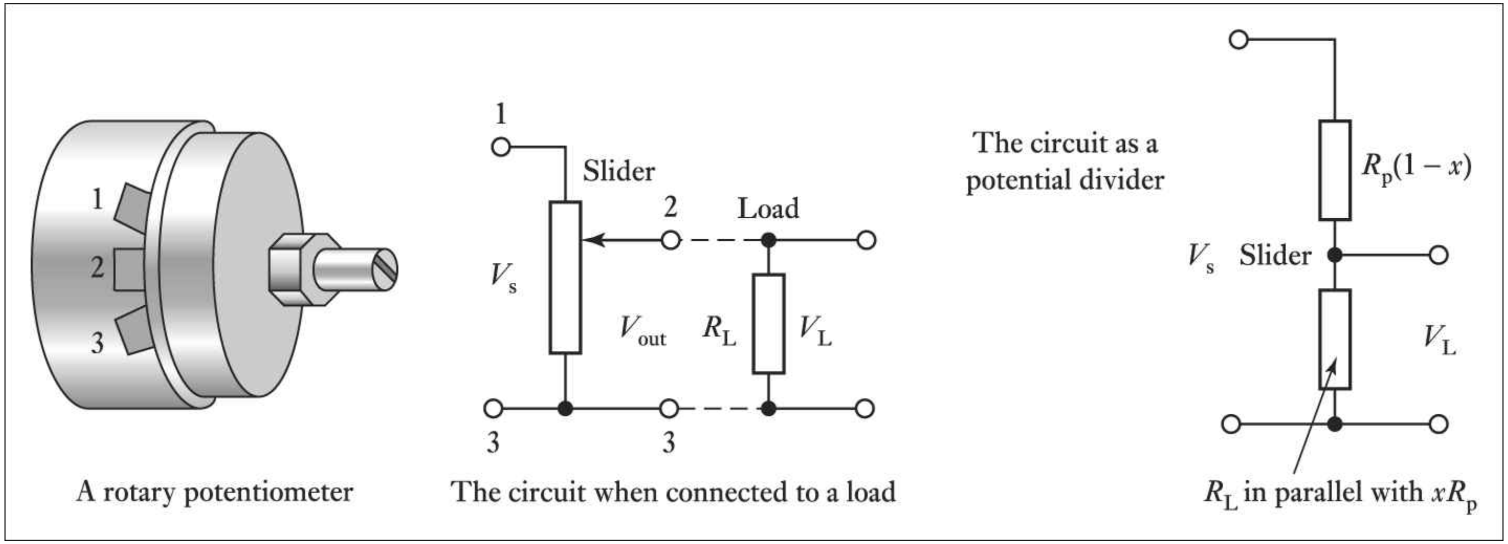


Figure 2.5 Rotary potentiometer

$$combined\ R = R_L x R_P / (R_L + xR_P)$$

$$total\ R = R_P(1-x) + R_L x R_P / (R_L + xR_P)$$

$$\frac{V_L}{V_S} = \frac{R_L x R_P / (R_L + xR_P)}{R_P(1-x) + R_L x R_P / (R_L + xR_P)} = \frac{x}{(R_P / R_L)x(1-x)+1} \rightarrow (R_L = \infty) \rightarrow V_L = xV_S$$

$$error = xV_S - V_L = xV_S - \frac{xV_S}{(R_P / R_L)x(1-x)+1} = V_S \frac{R_P}{R_L}(x^2 - x^3)$$

2.3.2 Strain gauge

- Strain(ε):
  - (change in length)/(original length)

- Gauge factor(G):
  - constant of proportionality

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

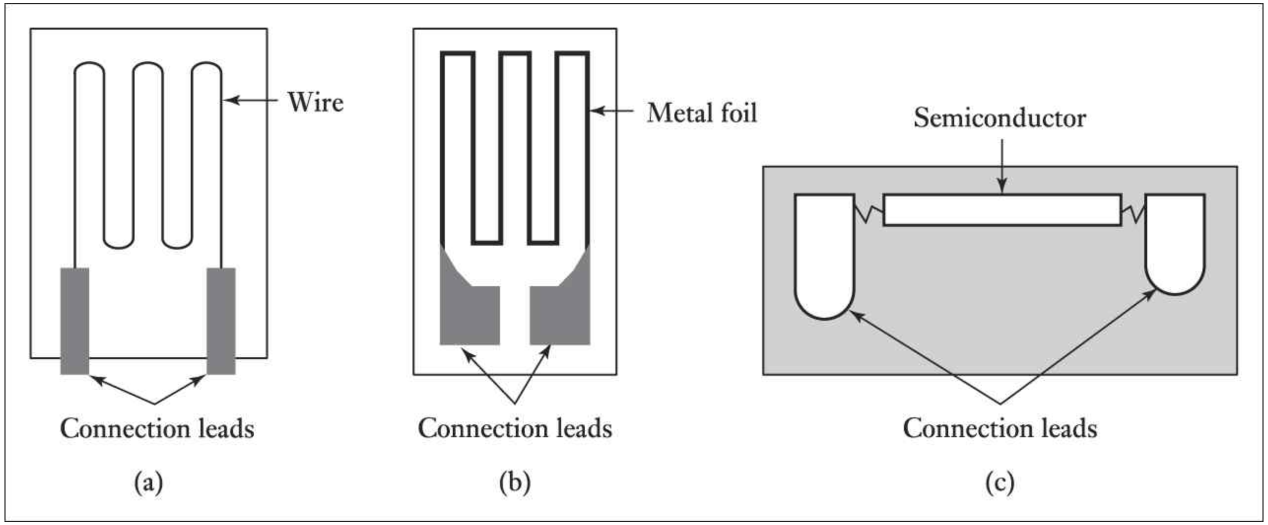


Figure 2.6 Strain gauges: (a) metal wire, (b) metal foil, (c) semiconductor

2.3.2 Strain gauge

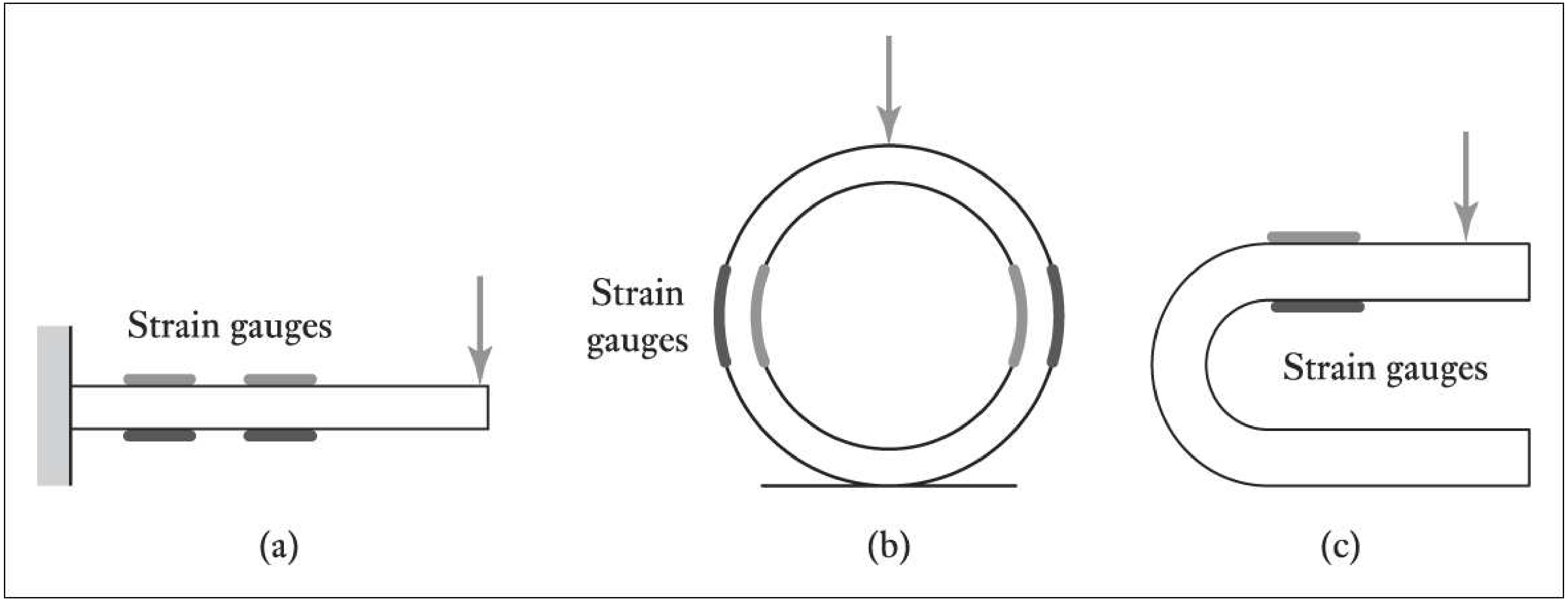


Figure 2.7 Strain-gauged element

2.3.3 Capacitive element

- Capacitance

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

- ε_r : Permittivity between the plates
- ε_0 : Permittivity of free space
- A : The area of overlap
- d : Plate separation

- Linear displacement

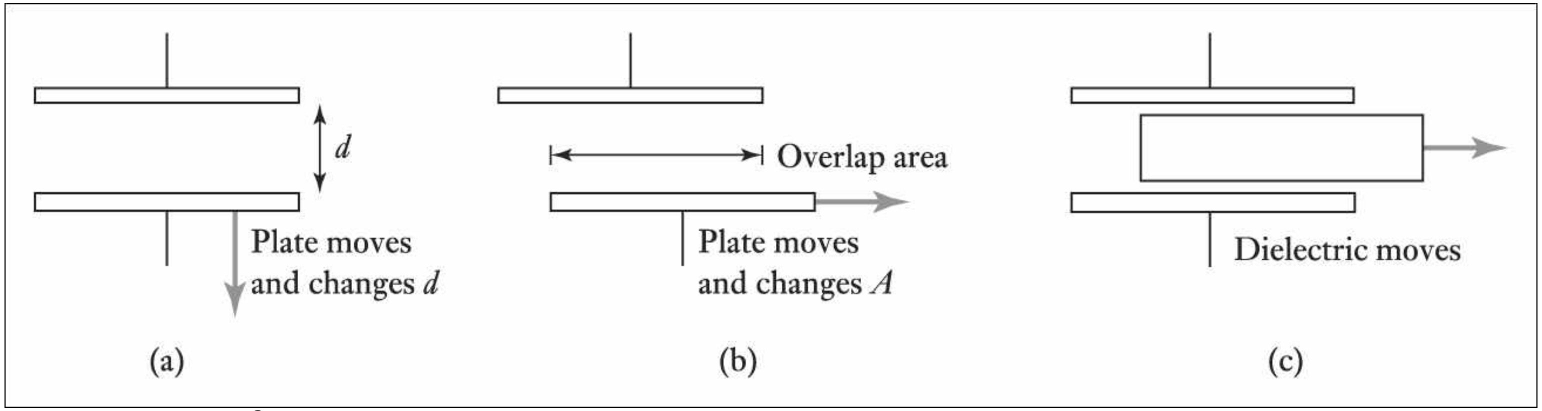
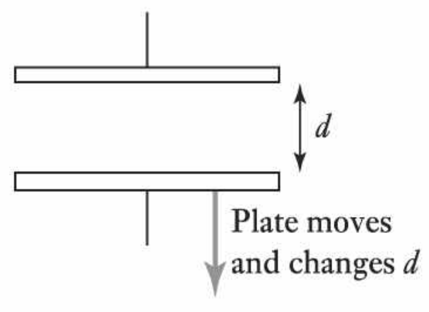


Figure 2.8 Forms of capacitive sensing element

2.3.3 Capacitive element

- For case (a)



(a)

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

- Capacitance: $C - \Delta C = \dfrac{\varepsilon_0 \varepsilon_r A}{d + x}$

- Capacitance change ratio:

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

- Non-linear

2.3.3 Capacitive element

- Small non-linearity configuration

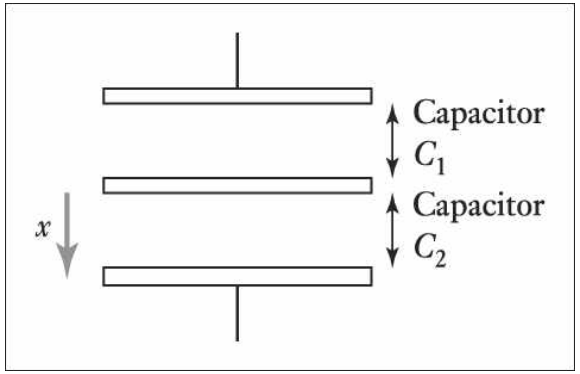
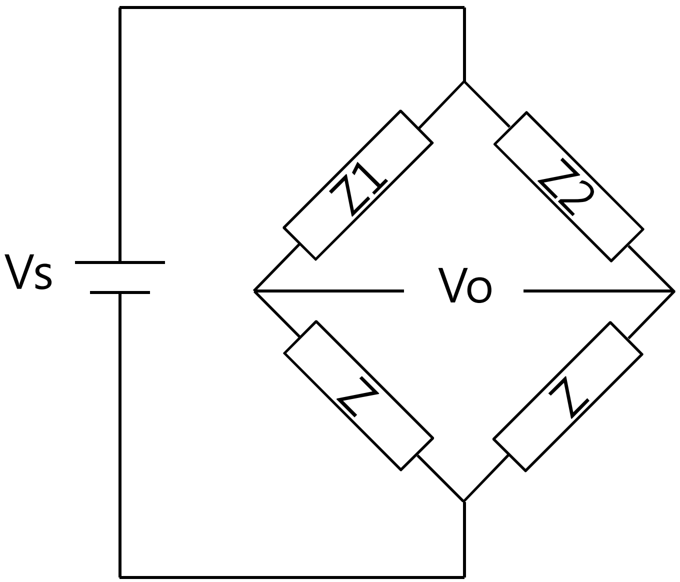


Figure 2.9 Push–pull sensor

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

Impedance

$$Z_1 = \frac{1}{C_1 s} = \frac{d + x}{\varepsilon_r \varepsilon_0 A s} \qquad Z_2 = \frac{1}{C_2 s} = \frac{d - x}{\varepsilon_r \varepsilon_0 A s}$$



If Z1 increases and Z2 decreases,

Vo?

2.3.3 Capacitive element

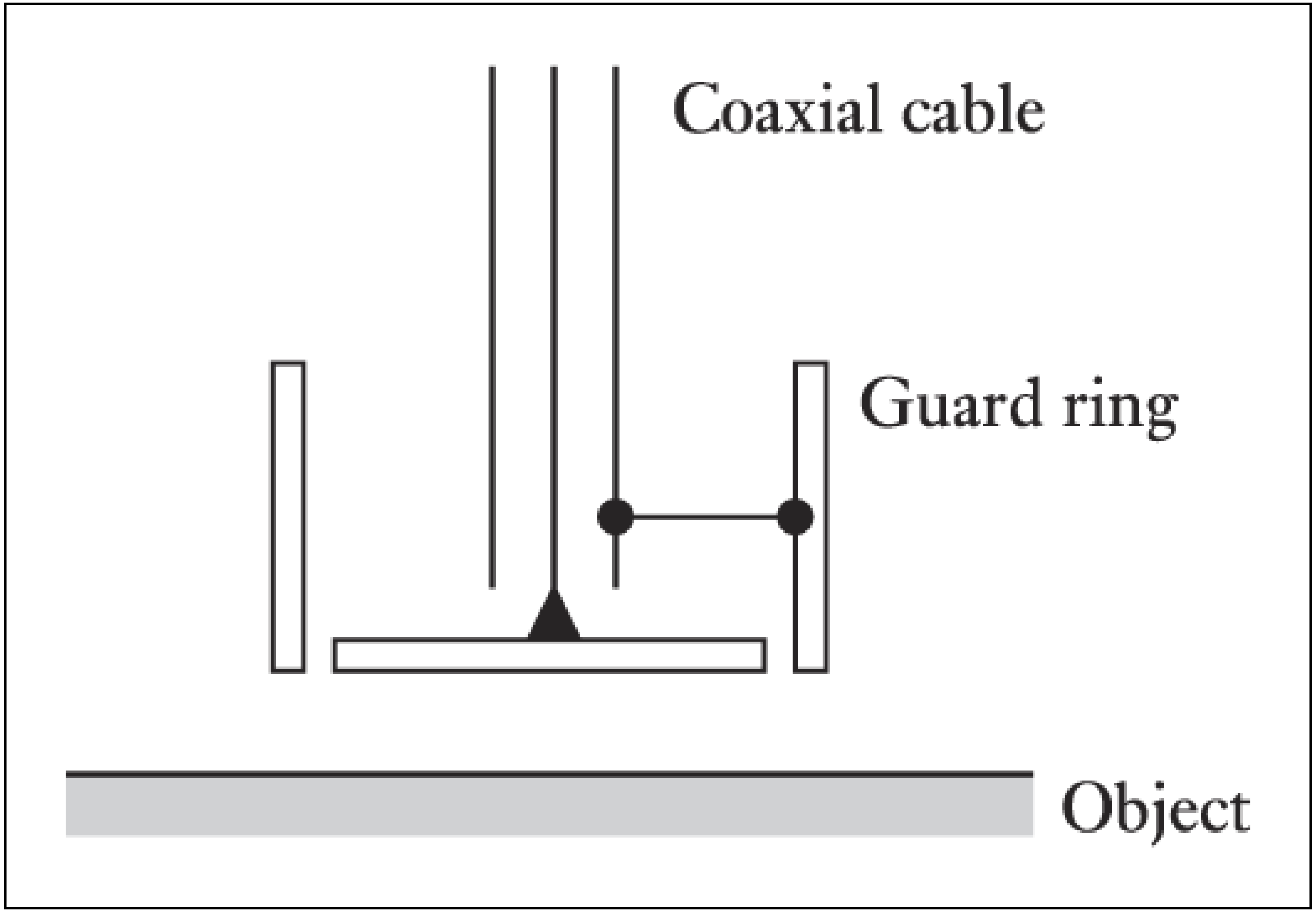


Figure 2.10 Capacitive proximity sensor

2.3.4 Differential transformers

- Linear Variable Differential Transformer (LVDT)

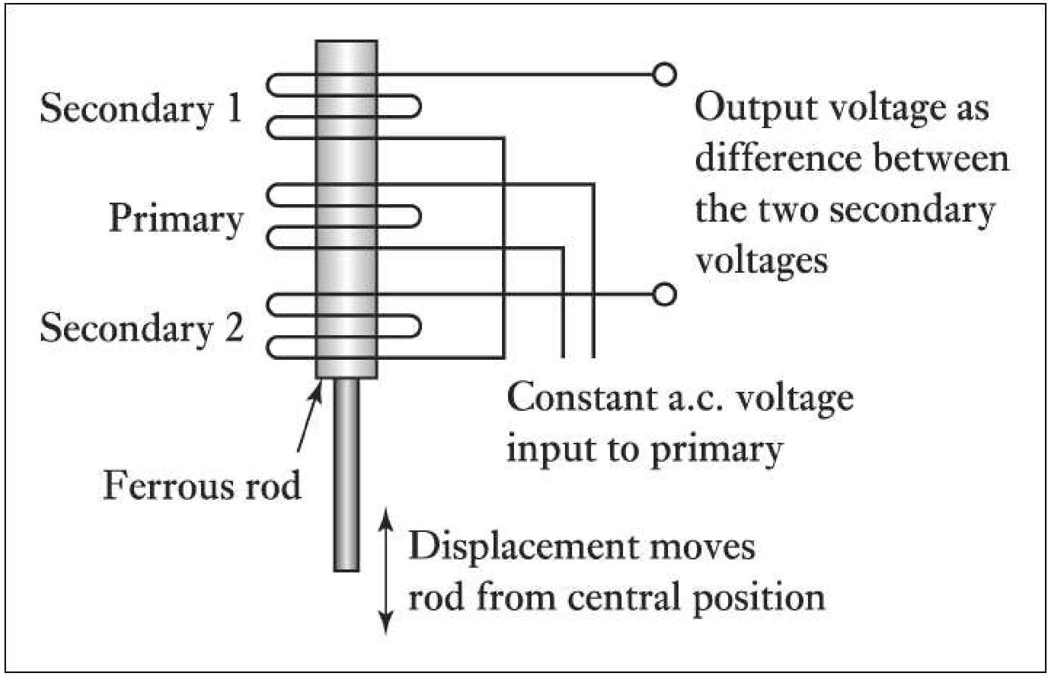


Figure 2.11 LVDT

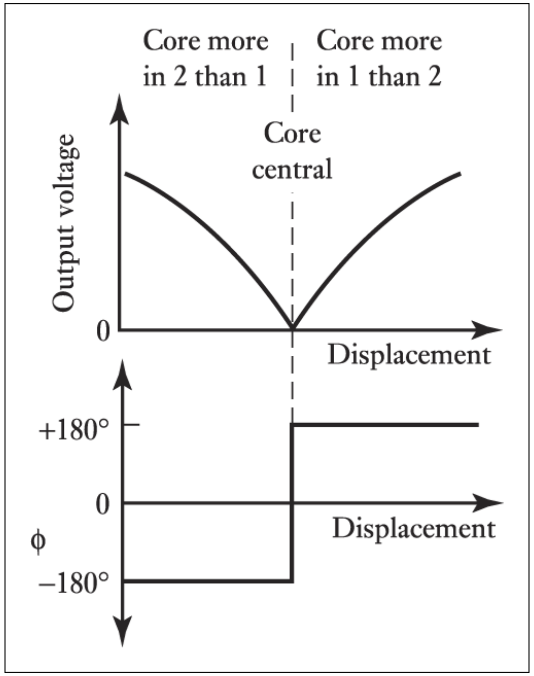
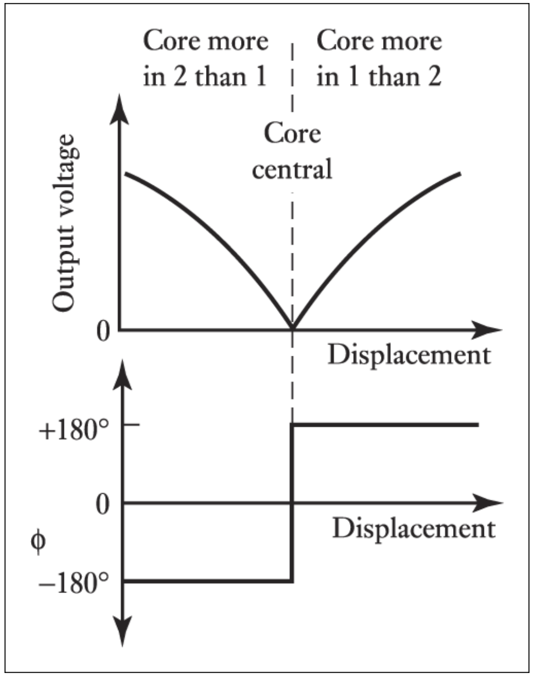


Figure 2.12 LVDT output

- The induced voltage at secondary coil

$$e = M\frac{\mathrm{d}i}{\mathrm{d}t}$$

  - i: current in the primary coil
  - M: mutual inductance



- Input current:

$$i = I\sin\omega t$$

- Output voltage:

$$v_1 = k_1\sin(\omega t - \phi)$$

$$v_2 = k_2\sin(\omega t - \phi)$$

$$k_1 > k_2, \quad v_o = (k_1 - k_2)\sin(\omega t - \phi)$$

$$k_1 < k_2, \quad v_o = -(k_1 - k_2)\sin(\omega t - \phi) = (k_2 - k_1)\sin(\omega t + (\pi - \phi))$$

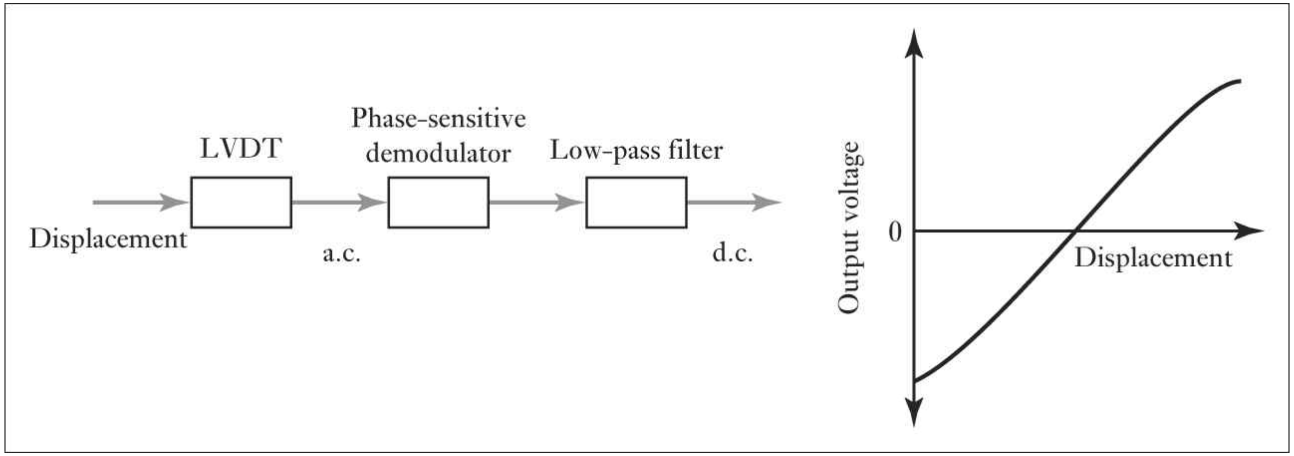


Figure 2.13 LVDT d.c. output

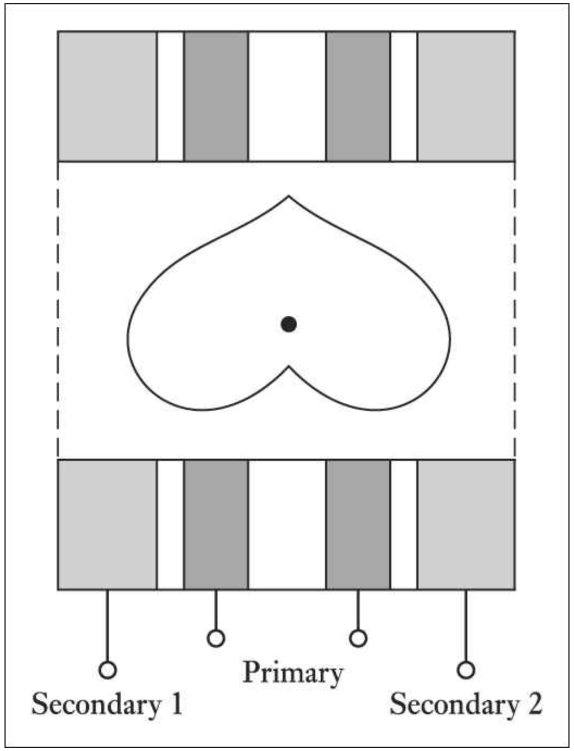


Figure 2.14 RVDT

2.3.5 Eddy current proximity sensor

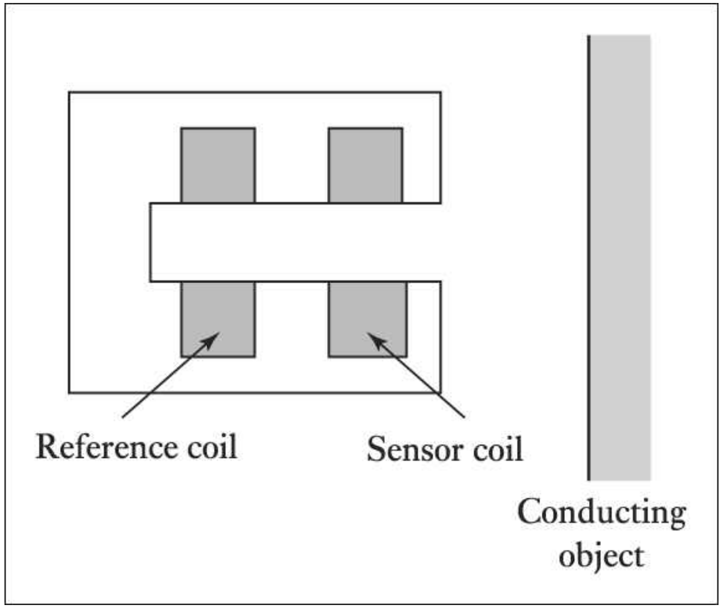


Figure 2.15 Eddy current sensor

Alternating current on coil
→ Alternating magnetic field
→ Eddy currents induction
→ Magnetic field
→ Distortion of magnetic field
→ Change of impedance

2.3.6 Inductive proximity switch

- Only be used for the detection of metal objects: ferrous metals

2.3.7 Optical encoders

- Encoder:
  - Linear or angular desplacement
  - Incremental or Absolute encoder
- Incremental encoder

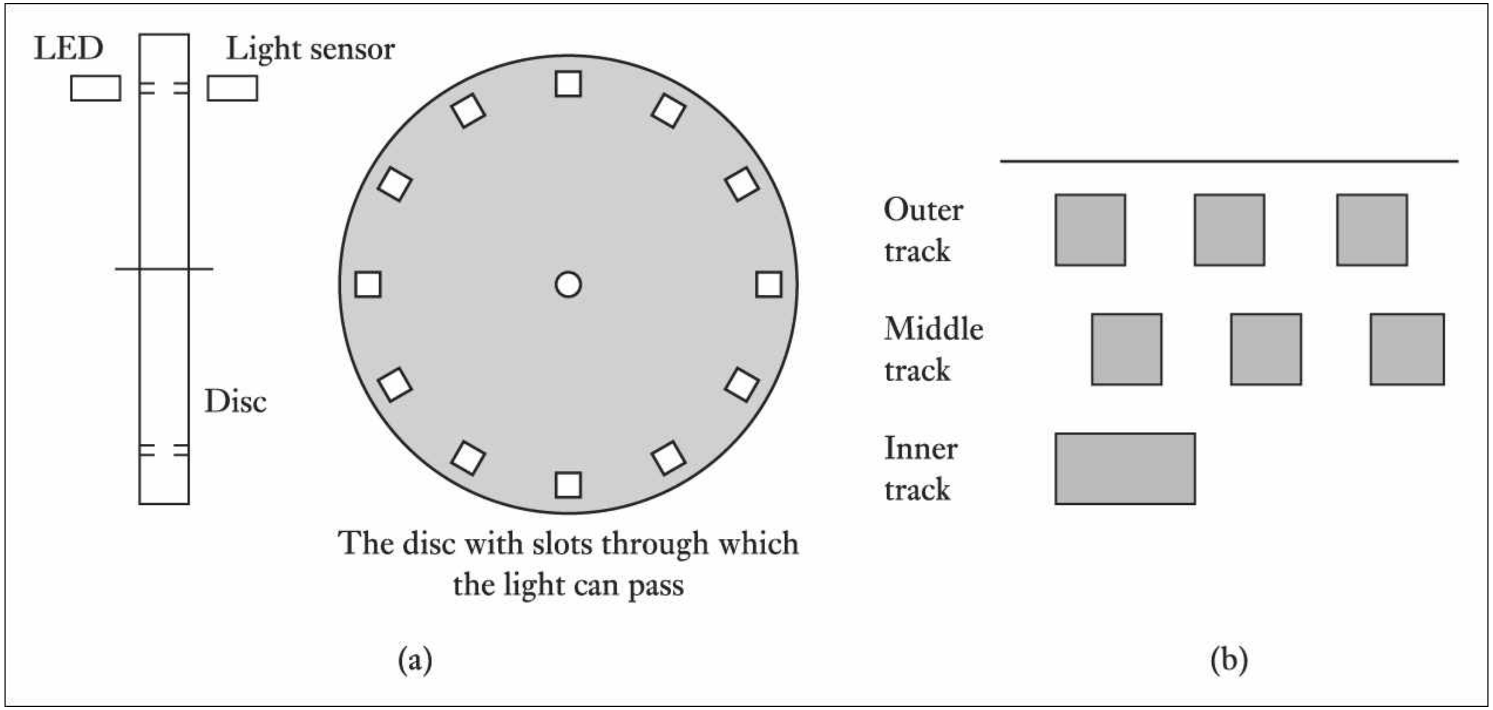


Figure 2.16 An incremental encoder: (a) the basic principle, (b) concentric tracks

2.3.7 Optical encoders

- Absolute encoder

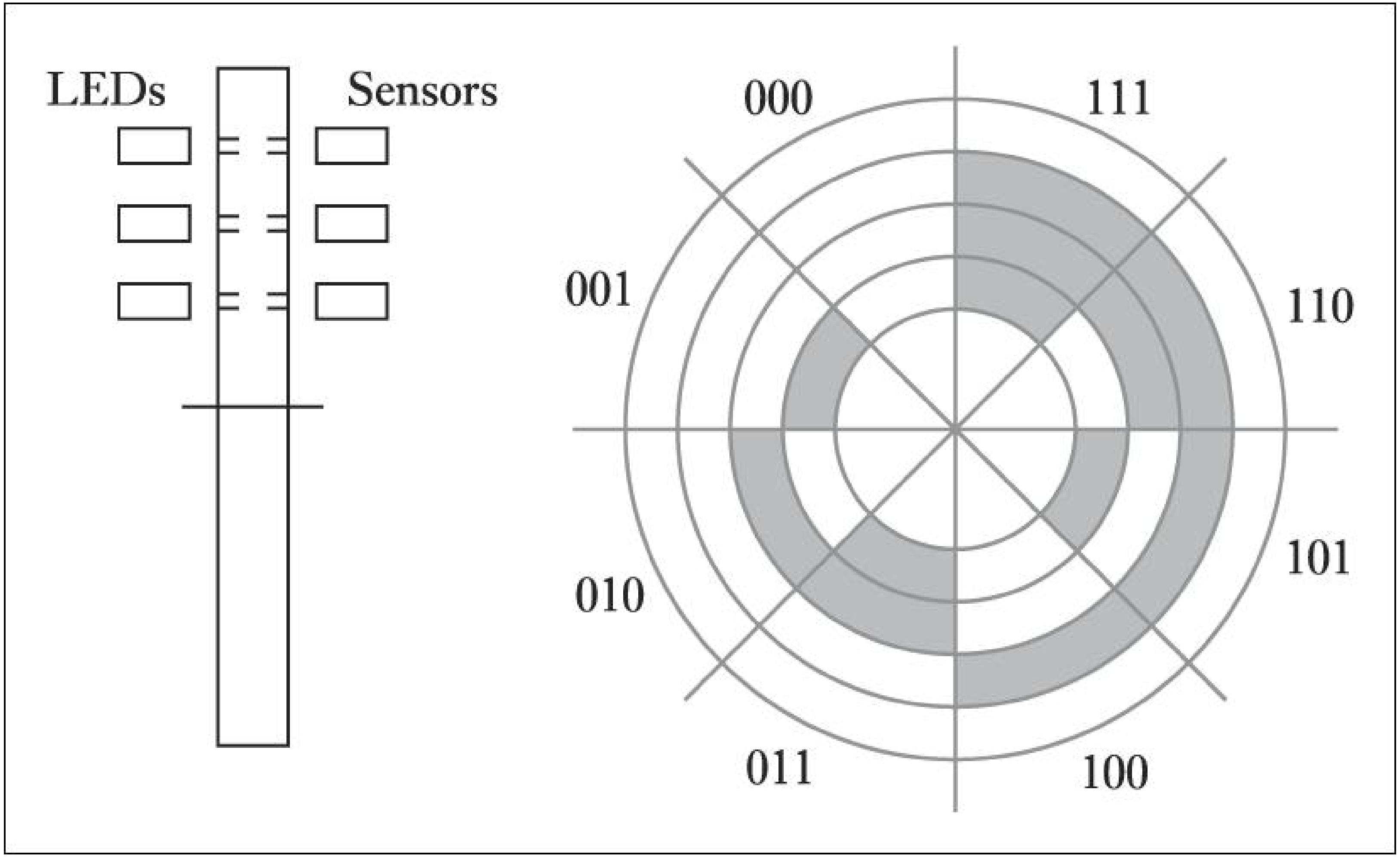


Figure 2.17 A 3-bit absolute encoder

2.3.7 Optical encoders

- Gray code: 1bit change

	Normal binary code	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

Figure 2.18 Binary and Gray codes

2.3.8 Pneumatic sensors

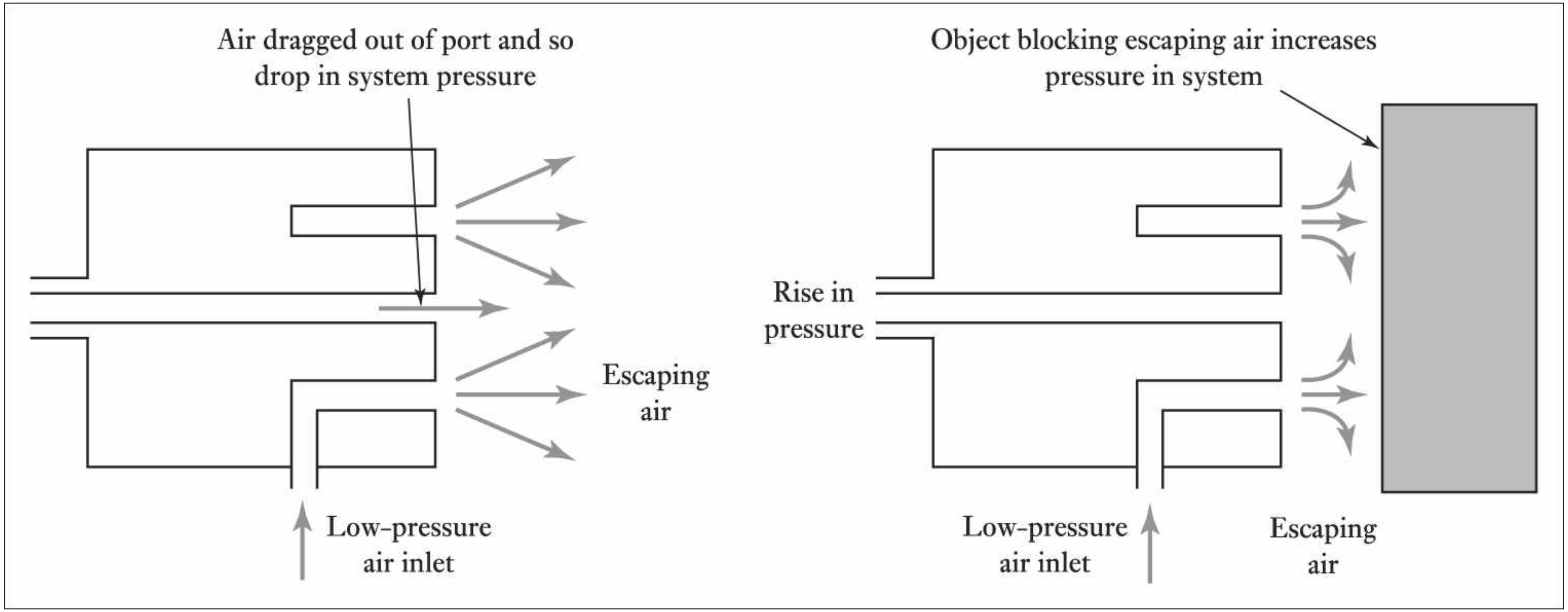


Figure 2.19 Pneumatic proximity sensor

2.3.9 Proximity switches

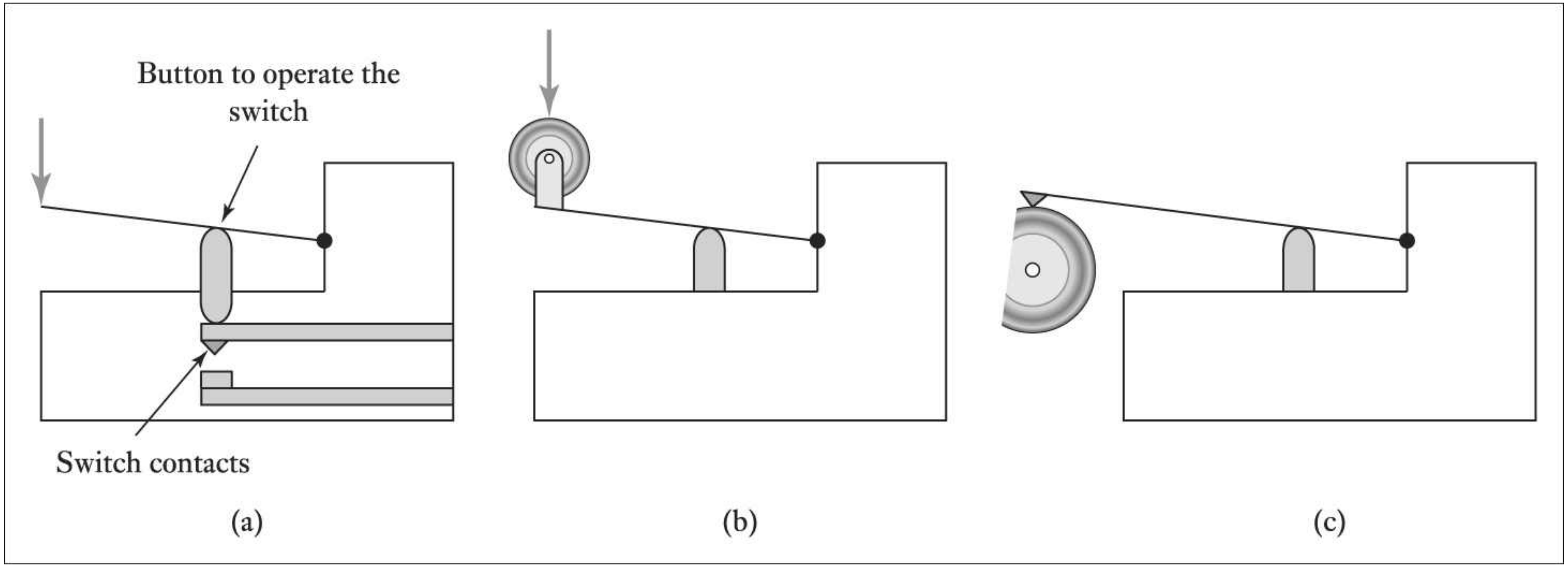


Figure 2.20 (a) Lever-operated, (b) roller-operated, (c) cam-operated switches

2.3.9 Proximity switches

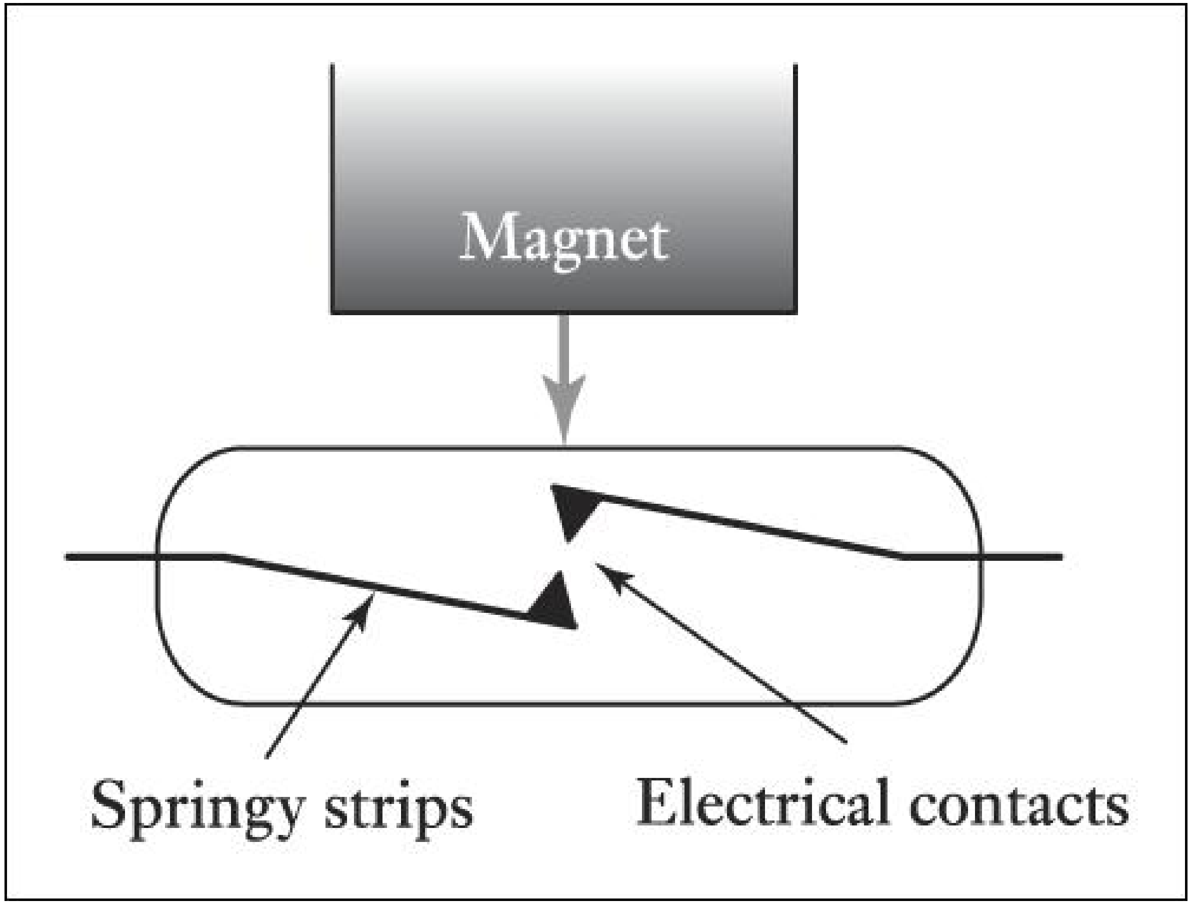


Figure 2.21 Reed switch

2.3.9 Proximity switches

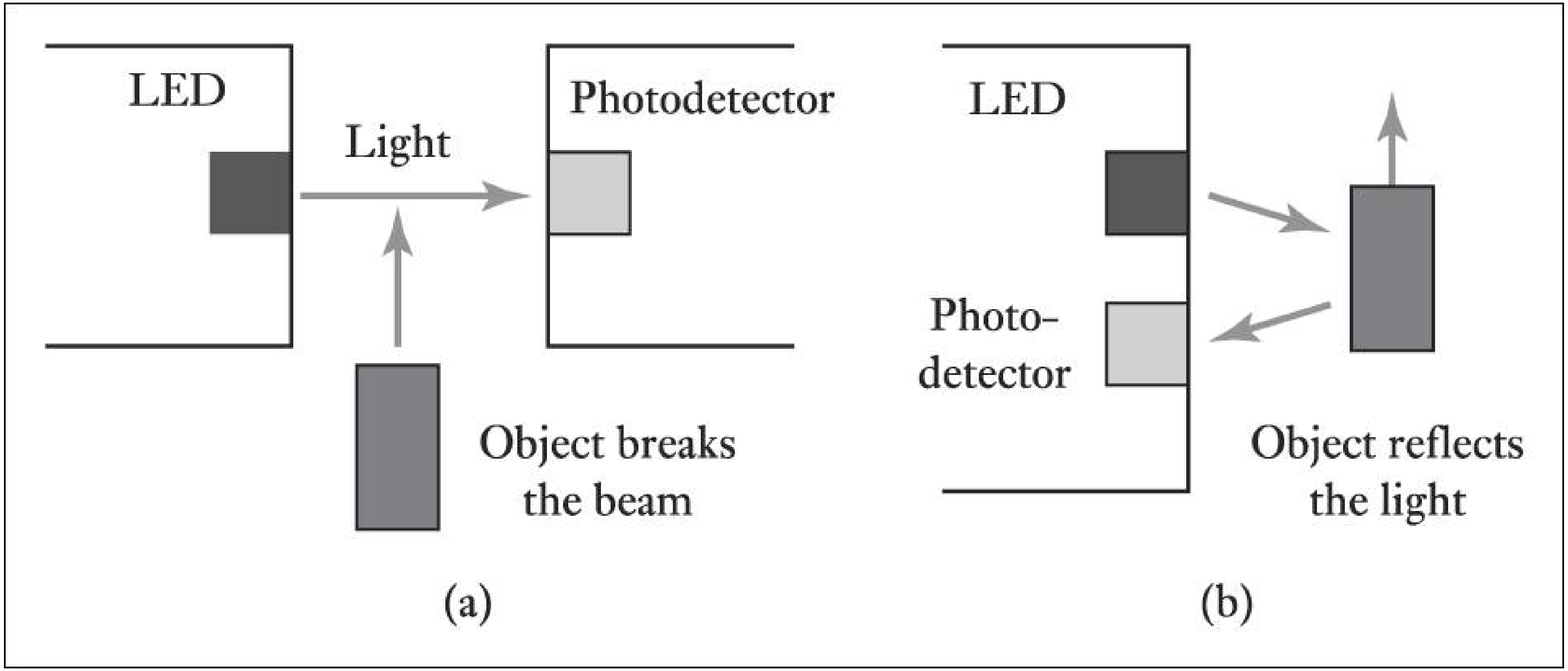


Figure 2.22 Using photoelectric sensors to detect objects by (a) the object breakin g the beam, (b) the object reflecting light

2.3.10 Hall effect sensors

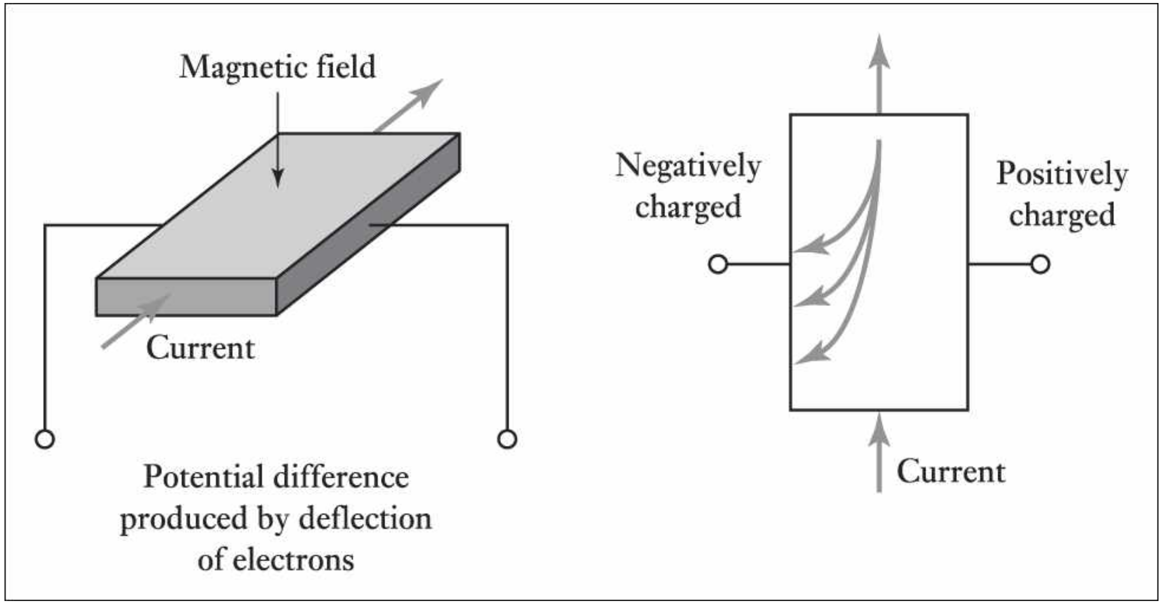


Figure 2.23 Hall effect

- B: magnetic flux density
- I: current
- t: Thickness
- K_H: Hall coefficient

$$V = K_H \frac{BI}{t}$$

2.3.10 Hall effect sensors

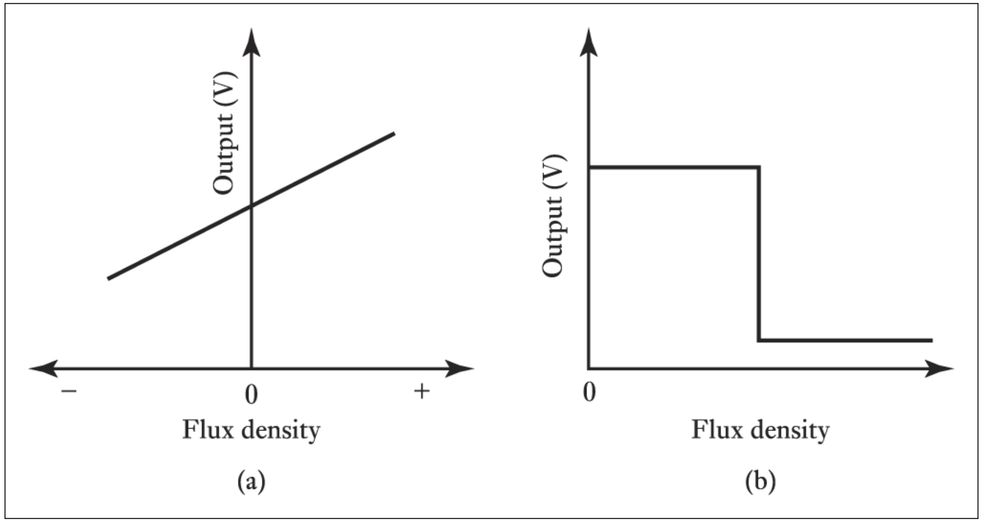


Figure 2.24 Hall effect sensors:

(a) linear, (b) threshold

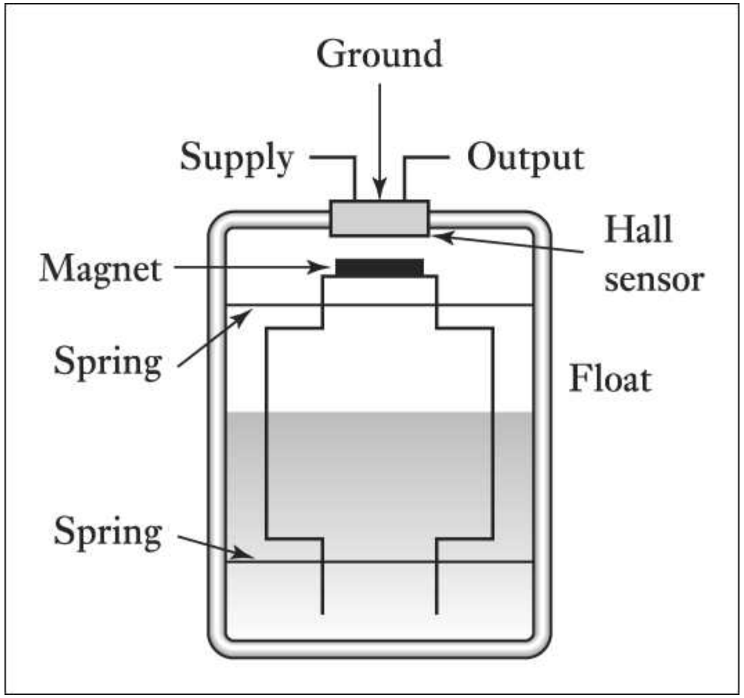


Figure 2.25 Fluid-level detector

2.4 Velocity and motion

2.4.1 Incremental encoder

2.4.2 Tachogenerator

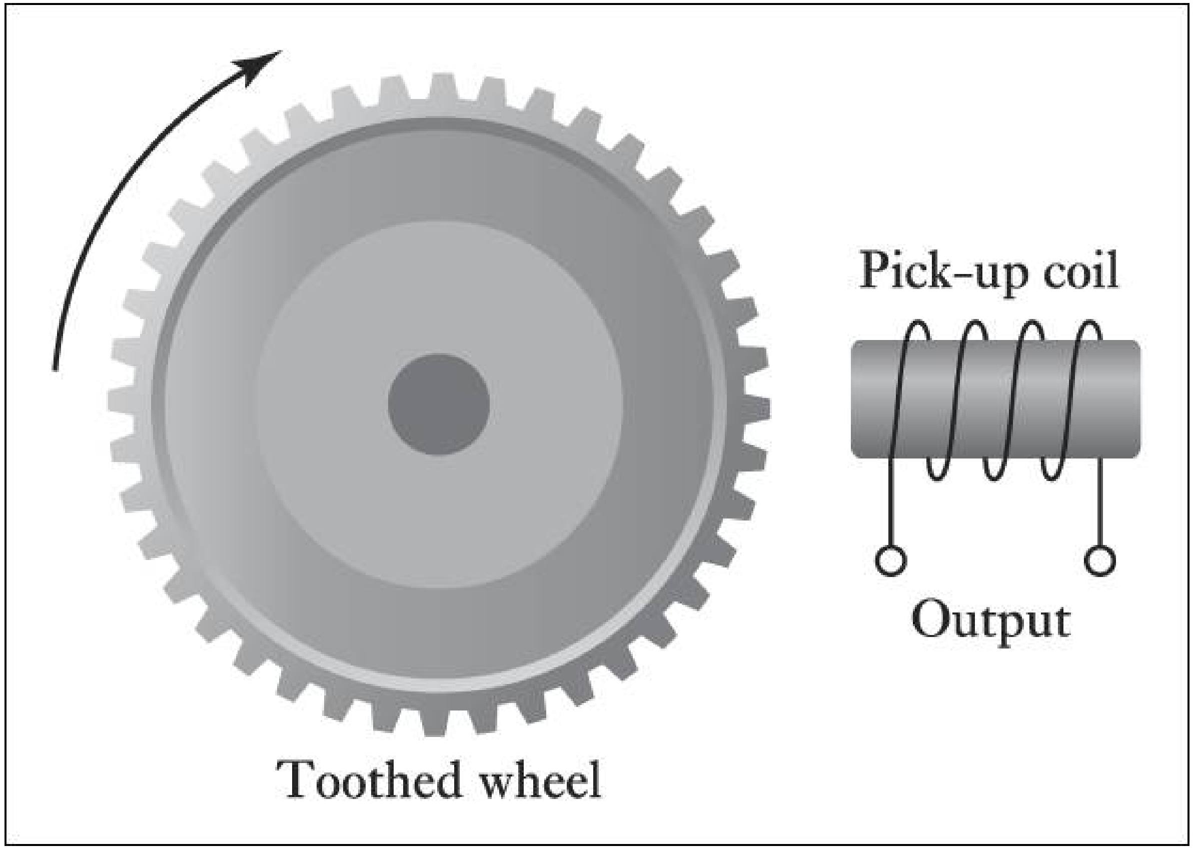


Figure 2.26 Variable reluctance tachogenerator

$$\Phi = \Phi_0 + \Phi_a \cos\ n\omega t$$

$$e = N\Phi_a n\omega \sin \omega t$$

$$e = -N\frac{d\Phi}{dt}$$

$$e = E_{\max} \sin n\omega t$$

$$E_{\max} = N\Phi_a n\omega$$

2.4 Velocity and motion

2.4.2 Tachogenerator

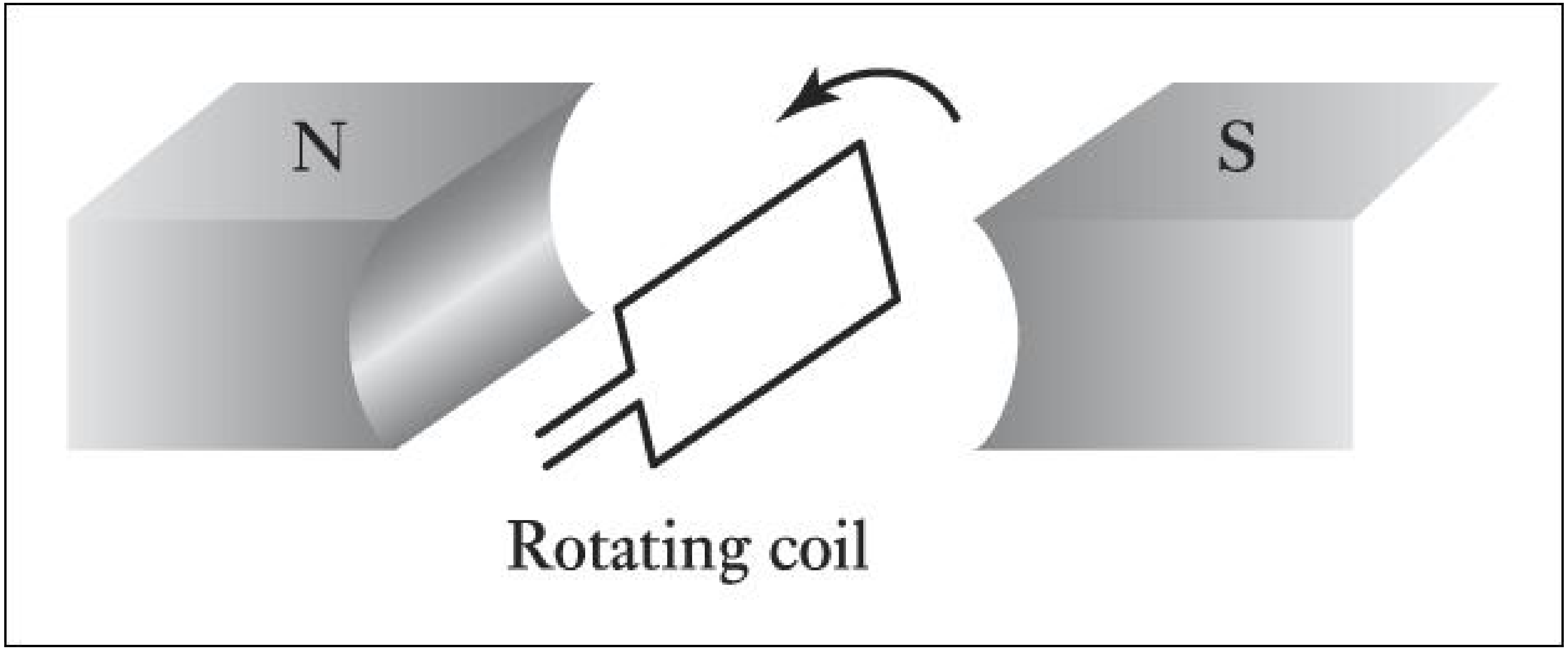


Figure 2.27 A.C. generator form of tachogenerator

2.5 Force

2.5.1 Strain gauge load cell

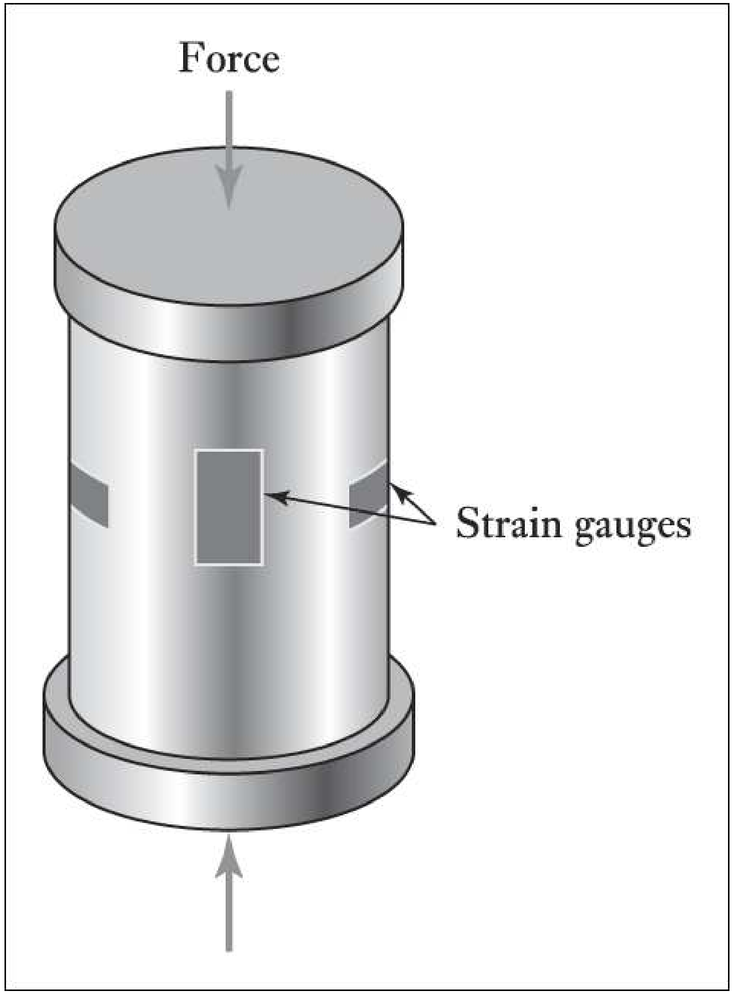


Figure 2.32 Strain gauge load cell

2.6 Fluid pressure

2.6.1 Piezoelectric sensors

- piezoelectric materials
  - When stretched or compressed, generate electric charges with one face of the material becoming positively charged and the opposite face negatively charged → Voltage is produced.

$$q = kx = SF$$

  - x: displacement
  - k: constant
  - S: constant: charge sensitivity

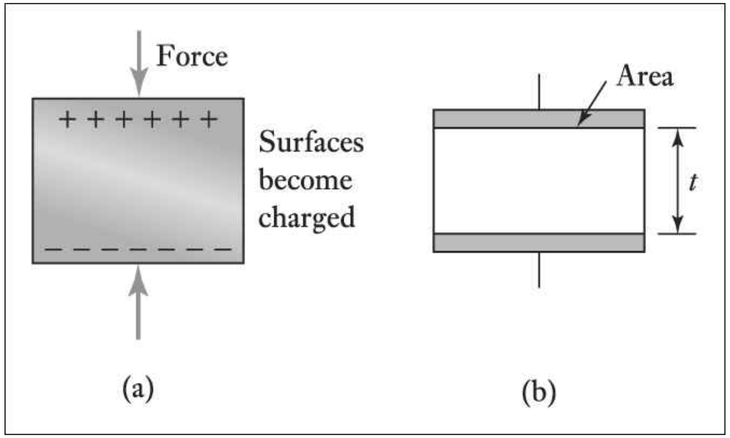


Figure 2.38 (a) Piezoelectricity, (b) piezoelectric capacitor

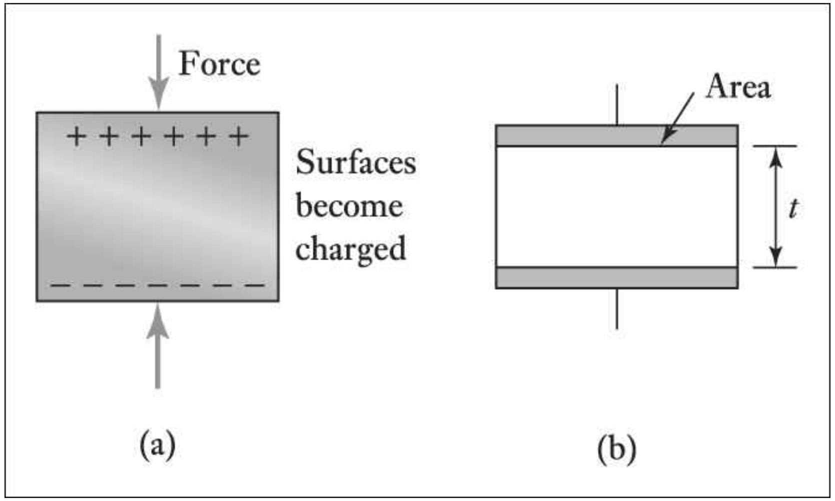
2.6 Fluid pressure

2.6.1 Piezoelectric sensors

- piezoelectric materials
  - When stretched or compressed, generate electric charges with one face of the material becoming positively charged and the opposite face negatively charged → Voltage is produced.

$$q = kx = SF$$

  - x: displacement; k: constant
  - S: constant: charge sensitivity; S_v=voltage sensitivity factor



$$C = \frac{\varepsilon_0 \varepsilon_r A}{t} \qquad q = Cv = SF$$

$$v = \frac{St}{\varepsilon_0 \varepsilon_r A} F \qquad S_v = (S / \varepsilon_0 \varepsilon_r)$$

$$v = S_v tp$$

Figure 2.38 (a) Piezoelectricity, (b) piezoelectric capacitor → Proportional to Pressure

2.6 Fluid pressure
2.6.1 Piezoelectric sensors

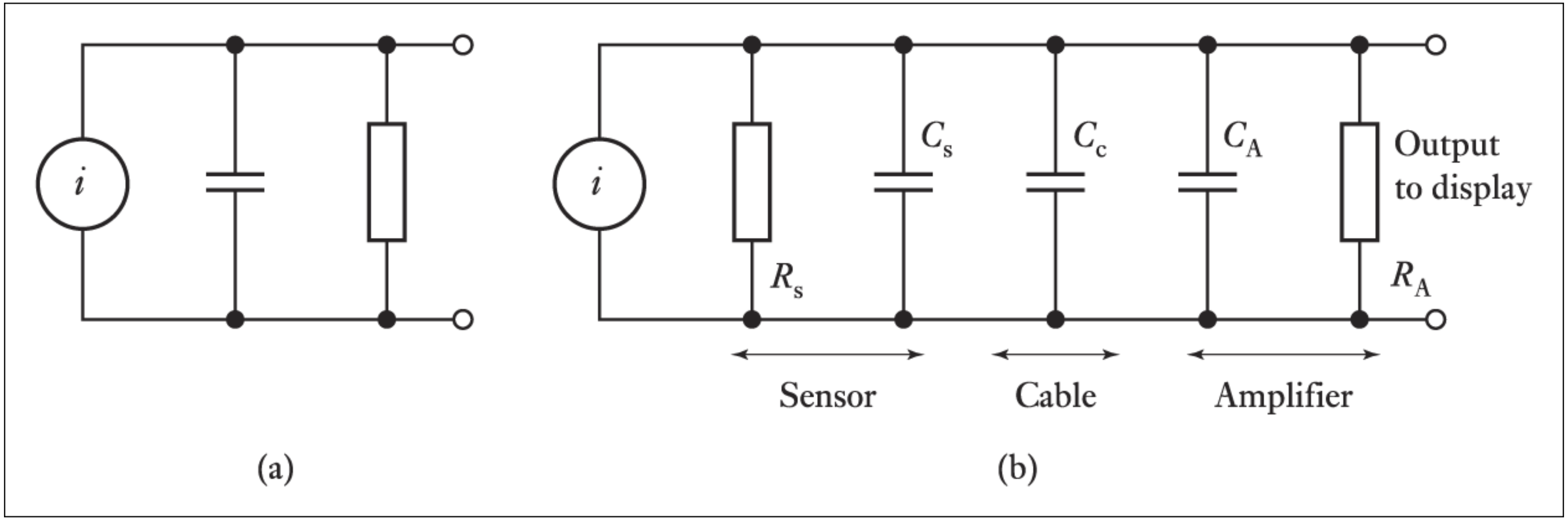


Figure 2.39 (a) Sensor equivalent circuit, (b) sensor connected to charge amplifier

2.6.2 Tactile sensor

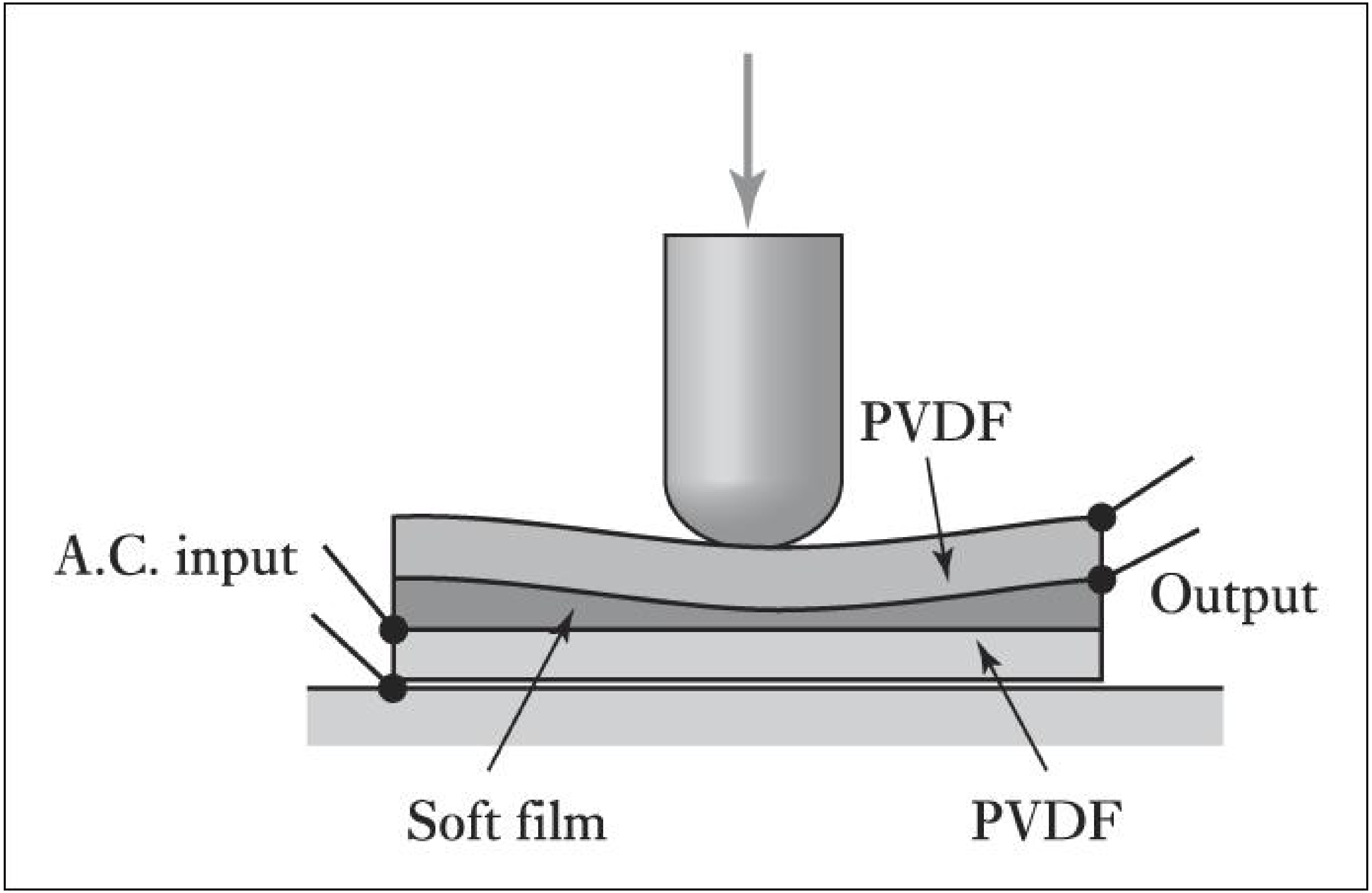


Figure 2.40 PVDF tactile sensor

2.7 Liquid flow

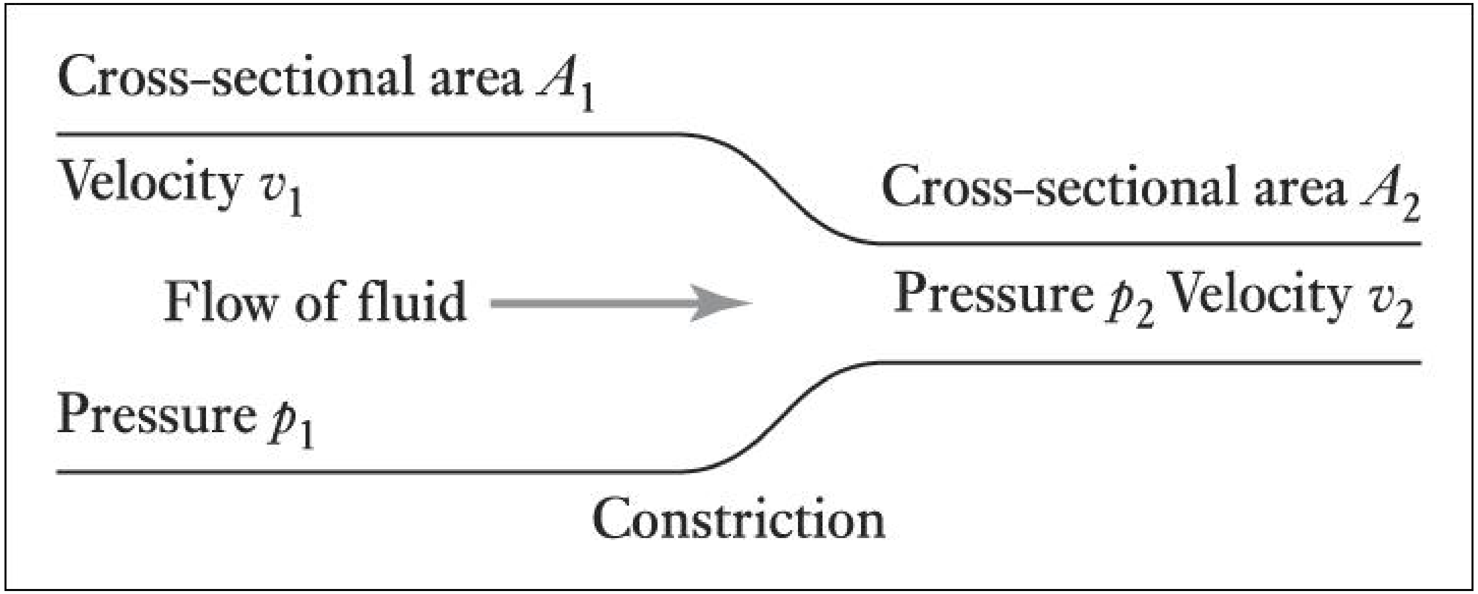


Figure 2.41 Fluid flow through a constriction

$$\frac{v_1^2}{2g}+\frac{P_1}{\rho g}=\frac{v_2^2}{2g}+\frac{P_2}{\rho g}$$

$$A_1 v_1 \rho = A_2 v_2 \rho$$

$$A_1 v_1 = A_2 v_2$$

$$Q=\frac{A}{\sqrt{1-(A_2/A_1)^2}}\sqrt{\frac{2(P_1-P_2)}{\rho}}$$

2.7.1 Orifice plate

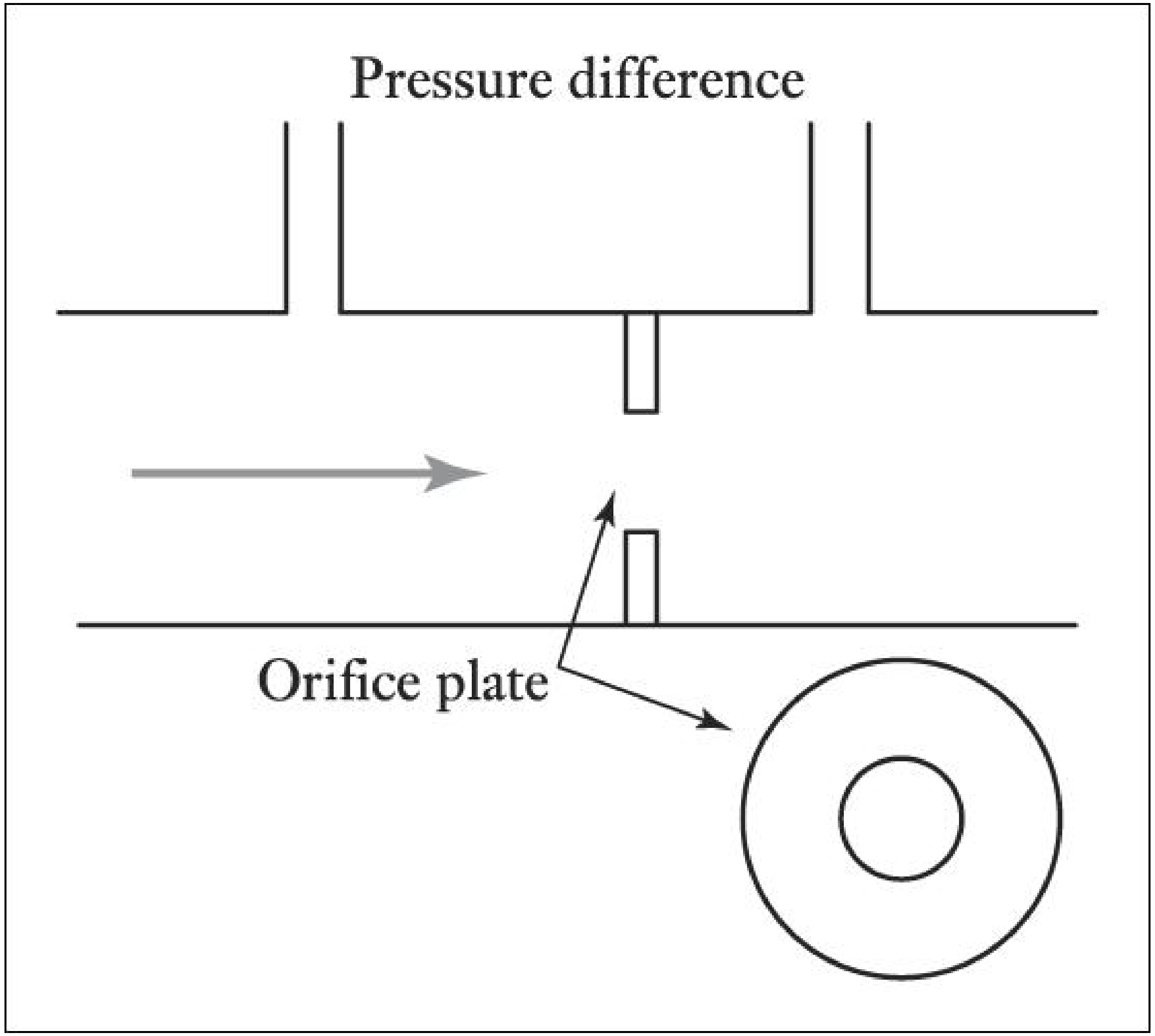


Figure 2.42 Orifice plate

2.7.2 Turbine meter

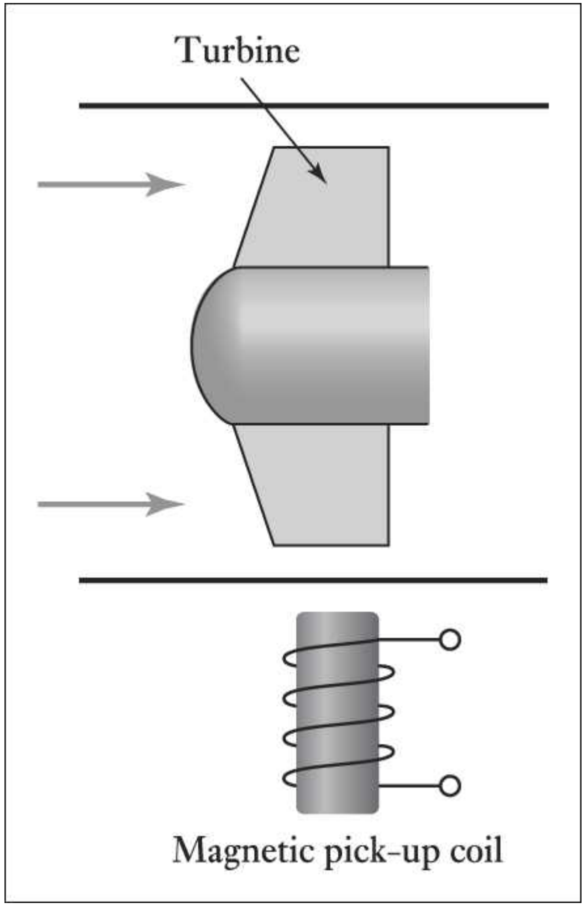


Figure 2.43 Turbine flowmeter

2.8 Liquid level

2.8.1 Floats

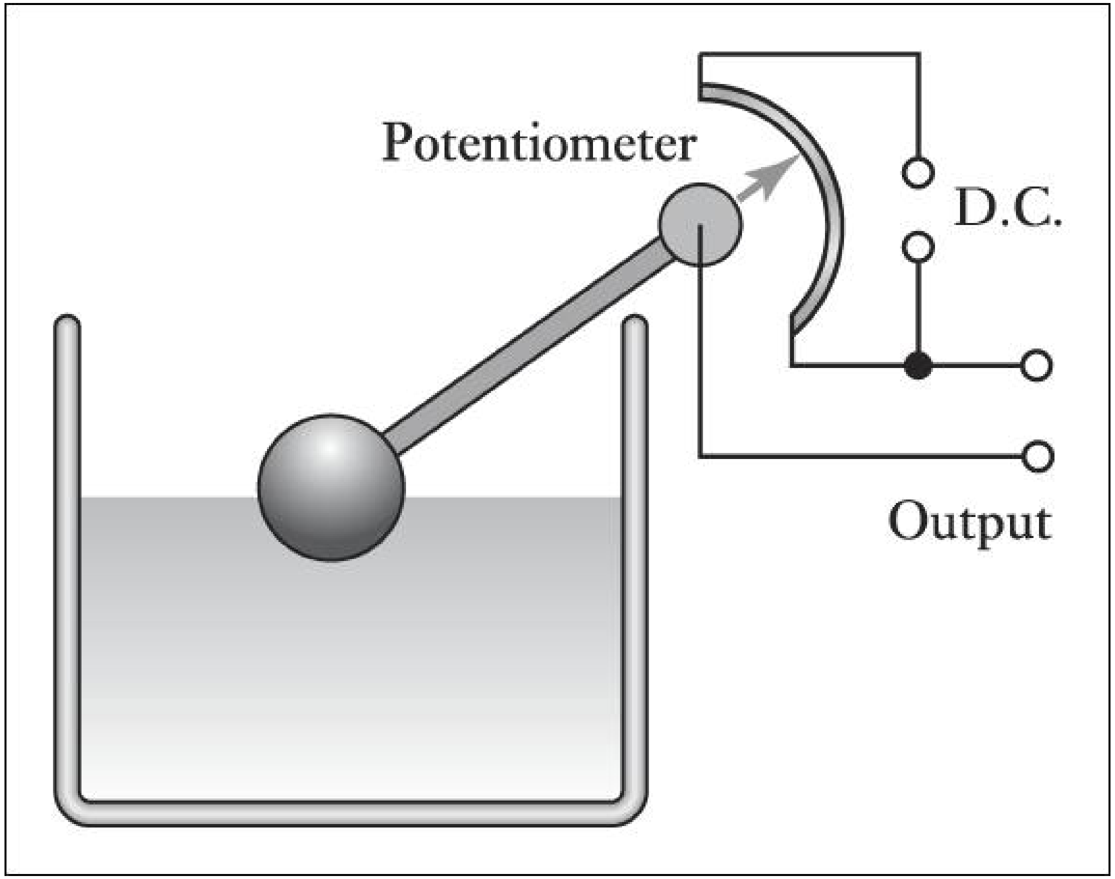


Figure 2.44 Float system

2.8 Liquid level

2.8.2 Differential pressure

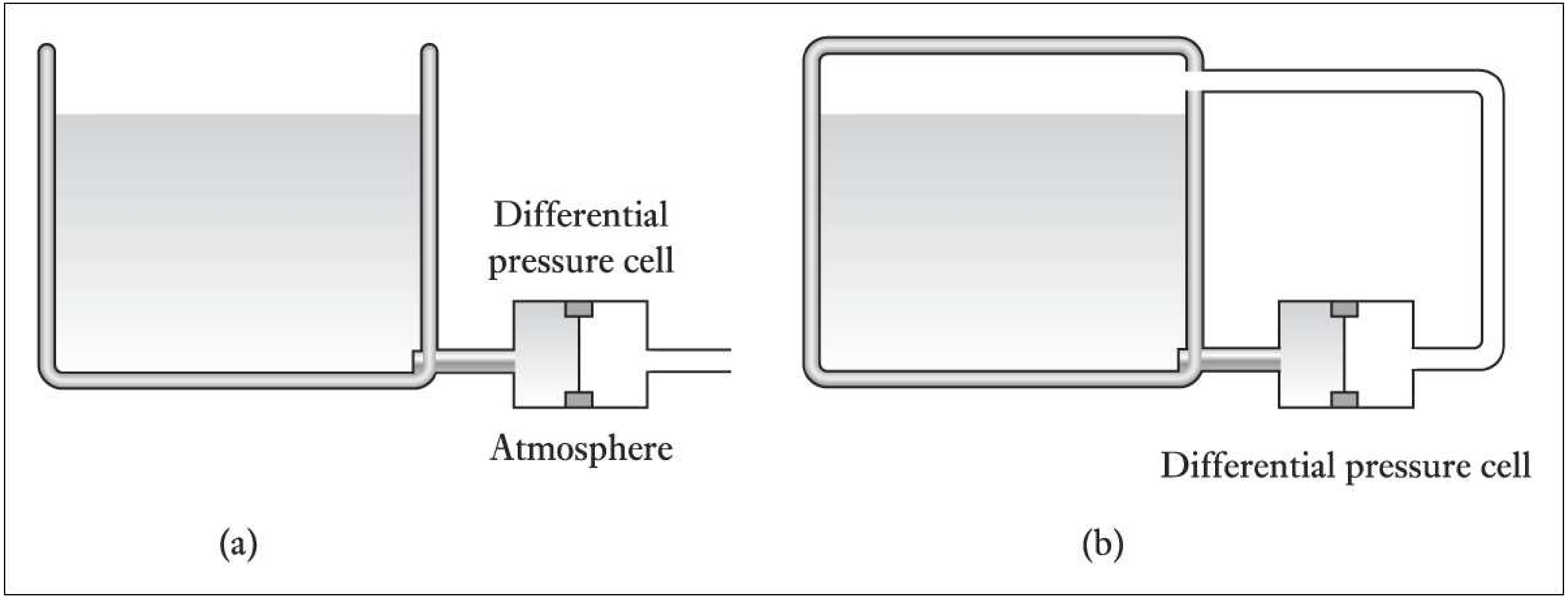


Figure 2.45 Using a differential pressure sensor

2.9 Temperature

2.9.1 Bimetallic strips

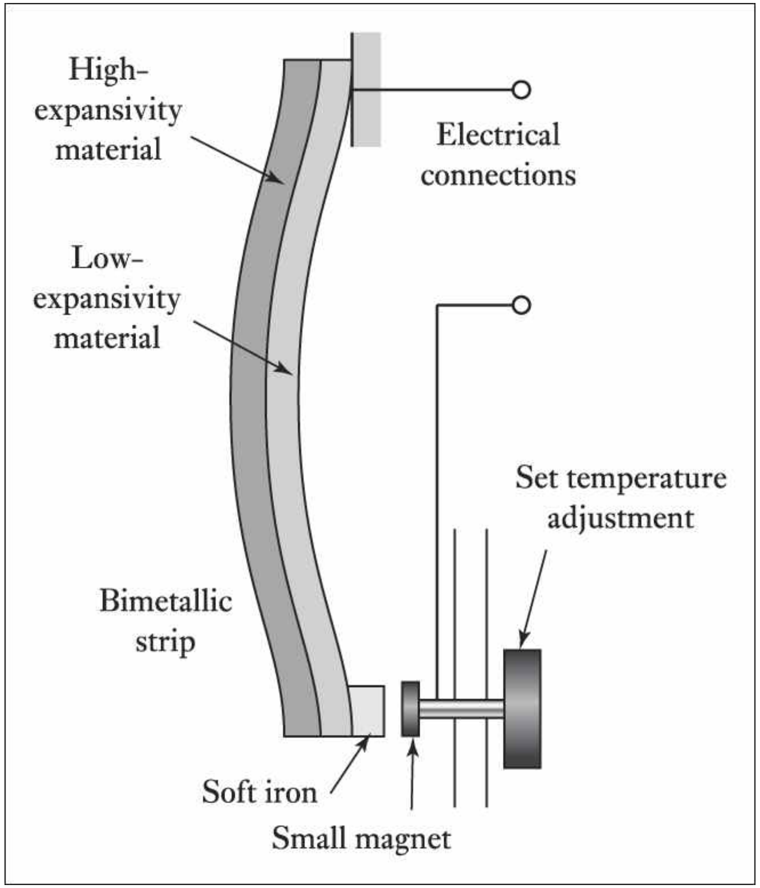
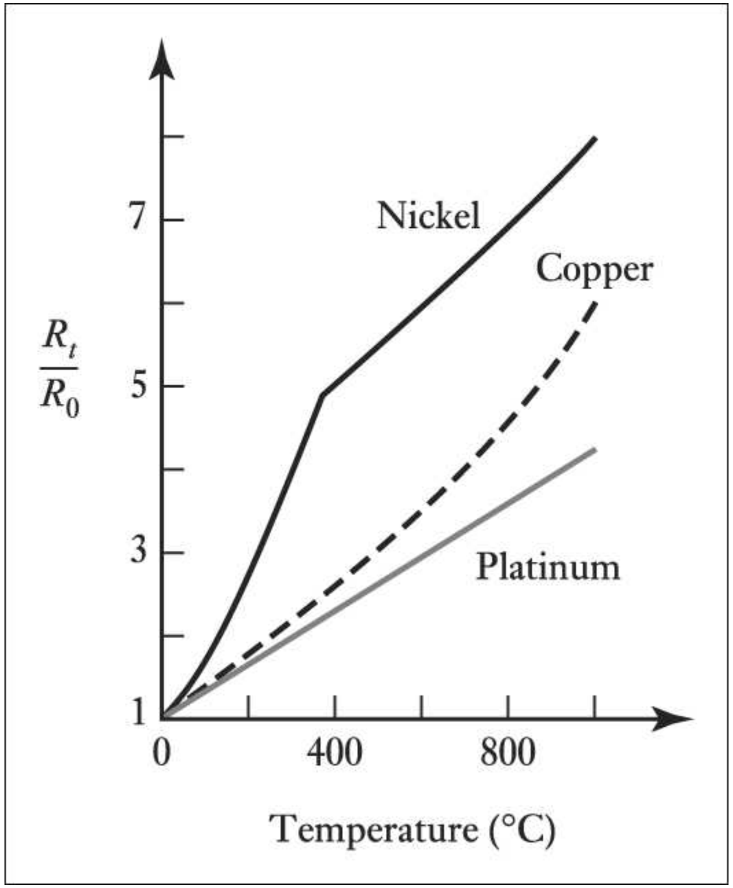


Figure 2.46 Bimetallic thermostat

2.9 Temperature

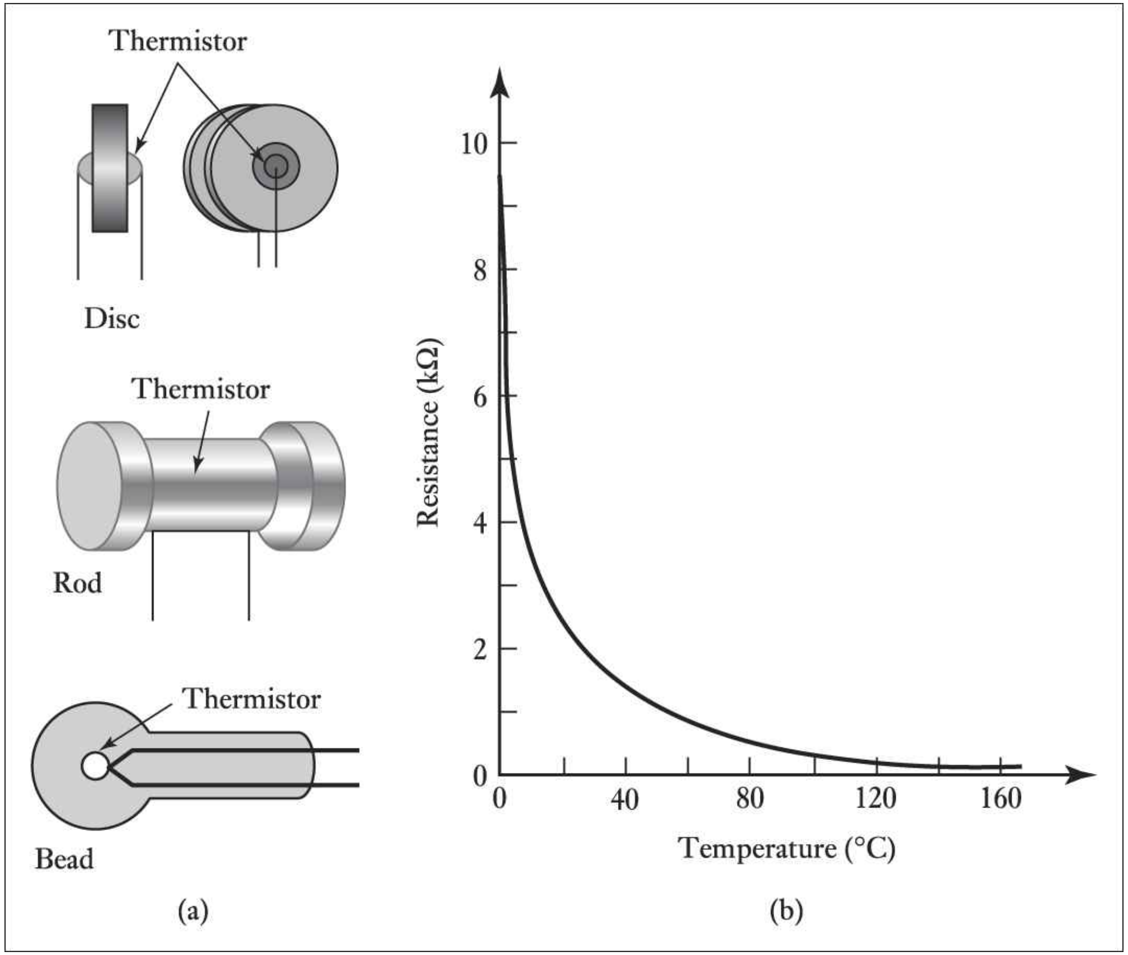
2.9.2 Resistance temperature detectors(RTDs)



$$R_t = R_0(1 + \alpha t)$$

Figure 2.47 Variation of resistance with temperature for metals

2.9.3 Thermistors



$$R_t = Ke^{\beta / t}$$

Figure 2.48 Thermistors: (a) common forms, (b) typical variation of resistance with temperature

2.10 Light sensors

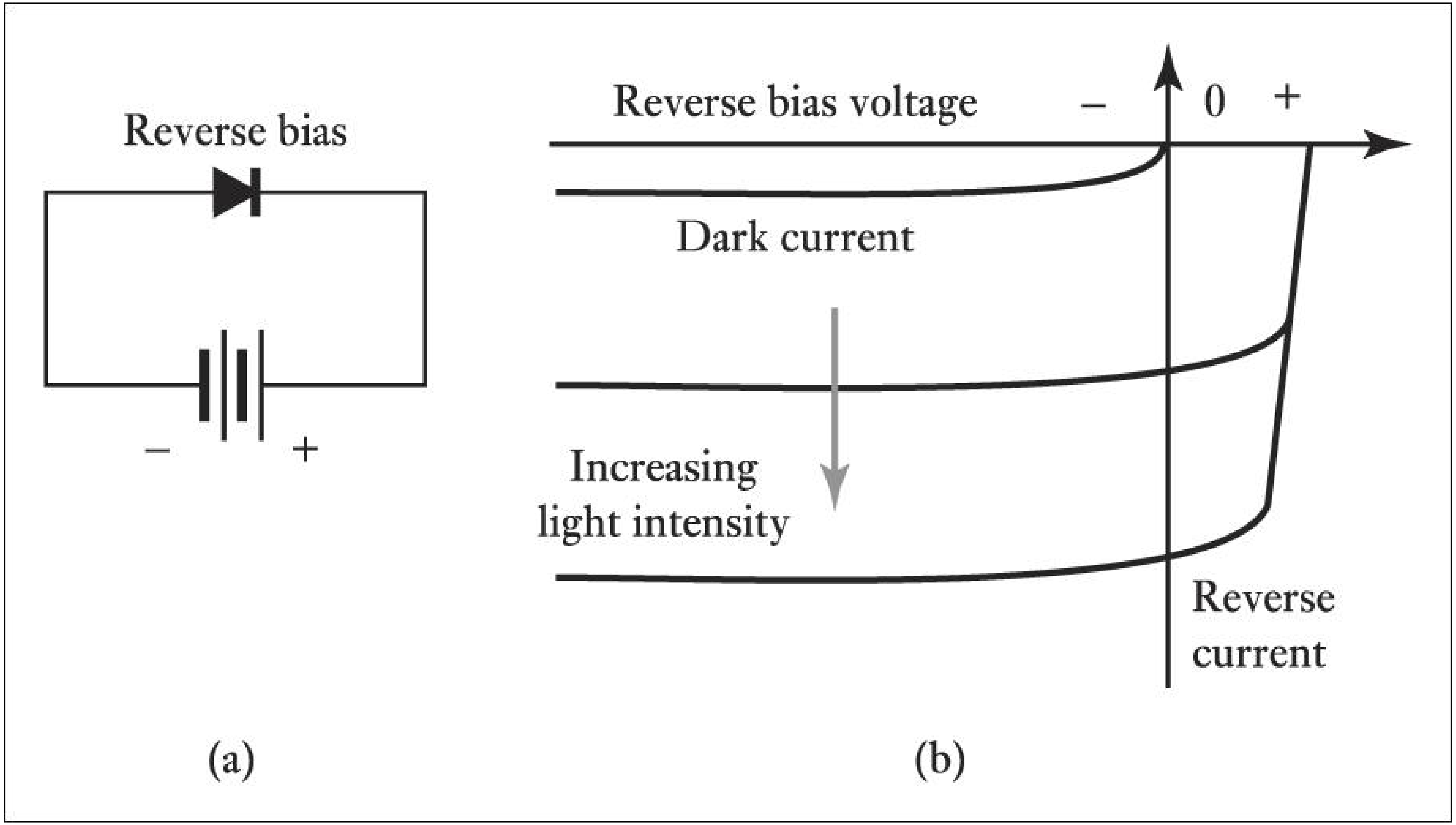


Figure 2.52 Photodiode

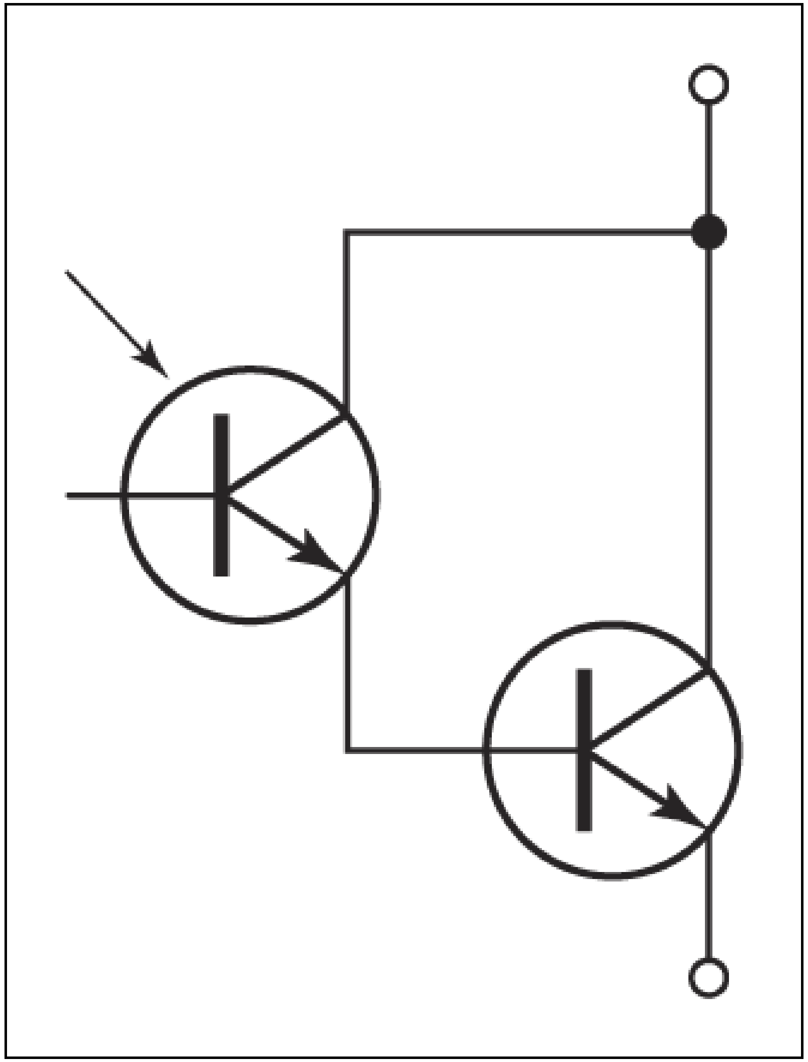


Figure 2.53 Photo Darlington

2.11 Selection of sensors

- 1. The nature of the measurement:
  - Variable to be measured
  - nominal value, range of values, accuracy required, required speed, reliability required, environmental conditions

- 2. The nature of the output required from the sensor:
  - signal conditioning requirements

- 3. Selection of sensor:
  - Range, accuracy, linearity, speed of response, reliability, maintainability, life, poser supply requirements, ruggedness, availability , cost

2.12 Inputting data by switches

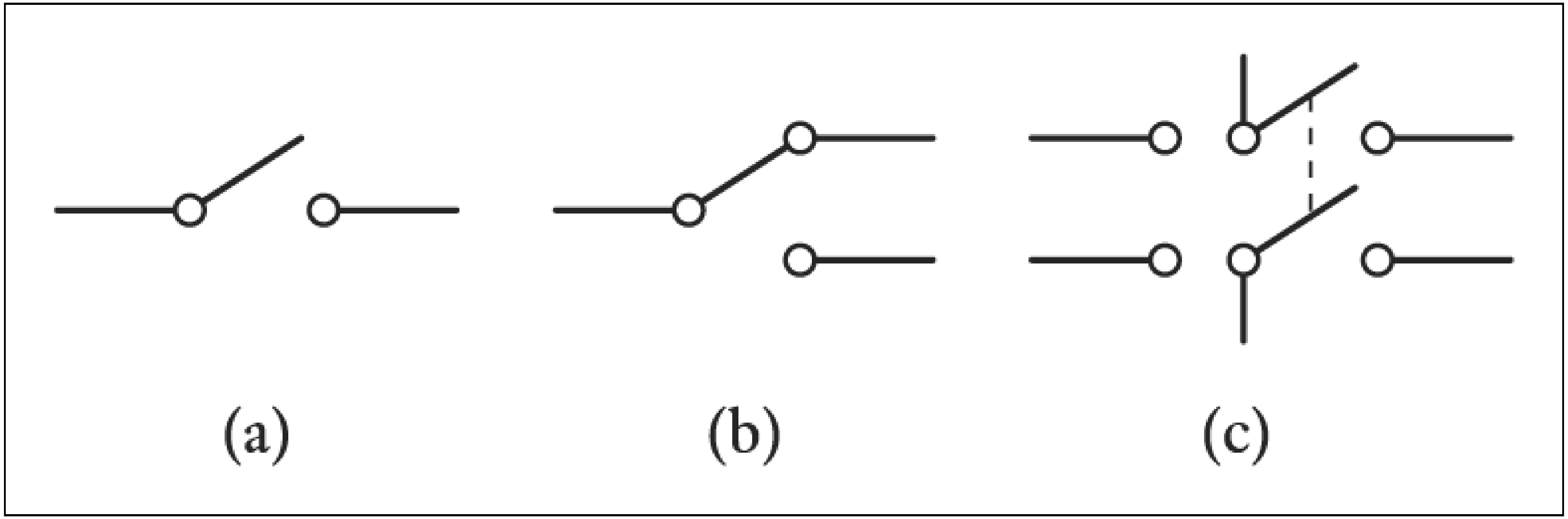


Figure 2.54 Switches: (a) SPST, (b) SPDT, (c) DPDT

(a) SPST: Single pole – single throw

(b) SPDT: Single pole – double throw

(c) DPDT: double pole – double throw

2.12.1 Debouncing

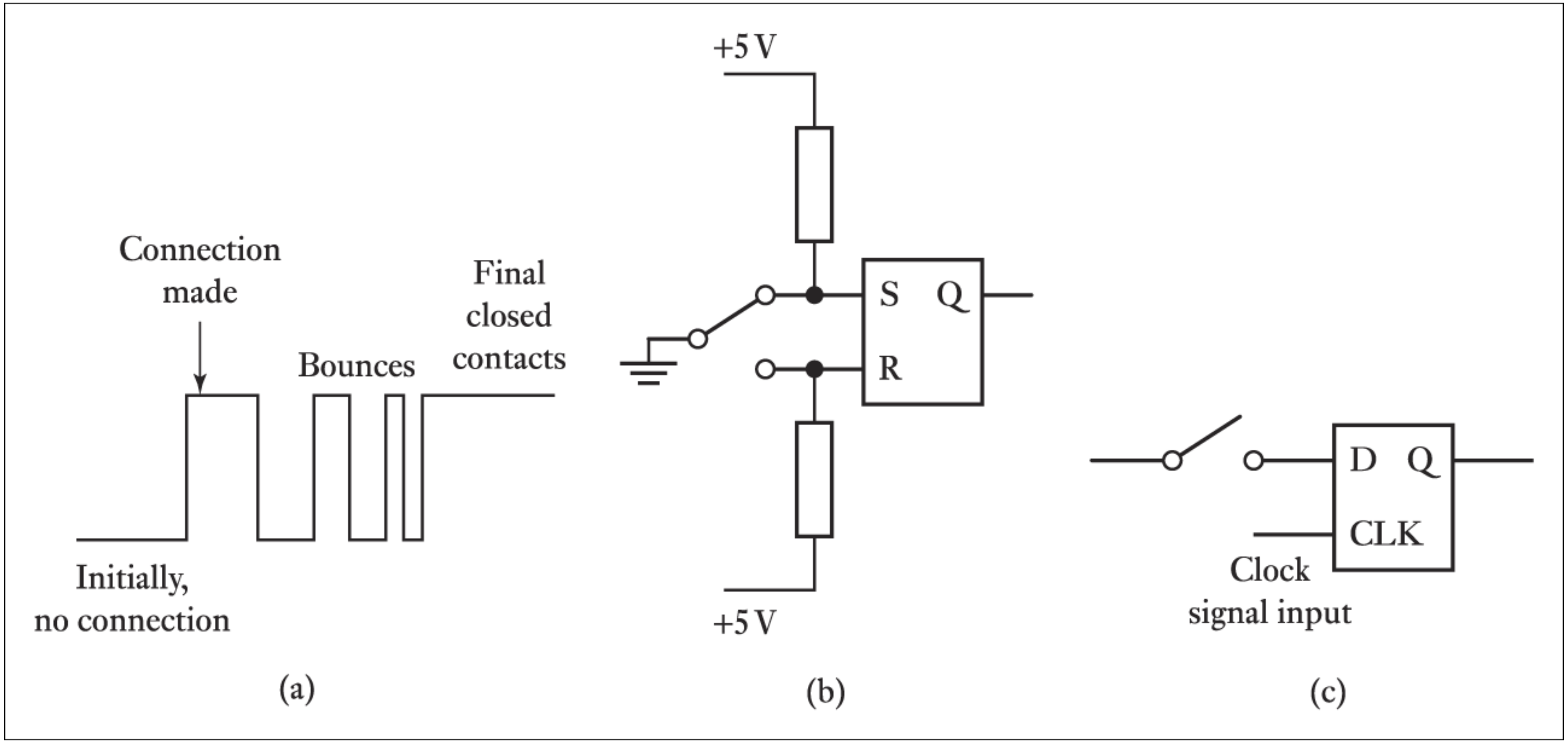


Figure 2.55 (a) Switch bounce on closing a switch, (b) debouncing using an SR flip-flop, (c) debouncing using a D flip-flop

2.12.1 Debouncing

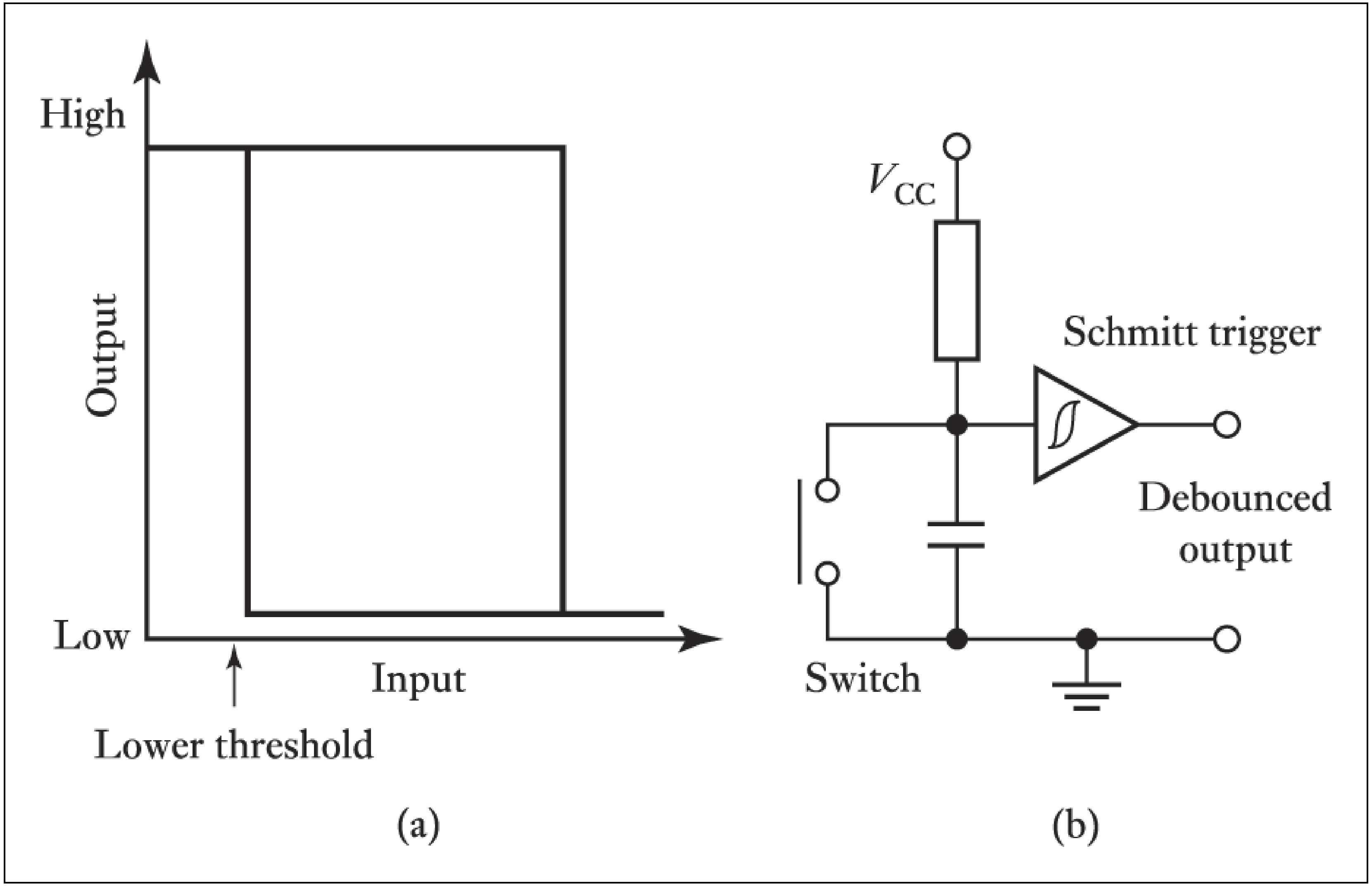


Figure 2.56 Schmitt trigger: (a) characteristics, (b) used for debouncing a switch

2.12.2 Keypads

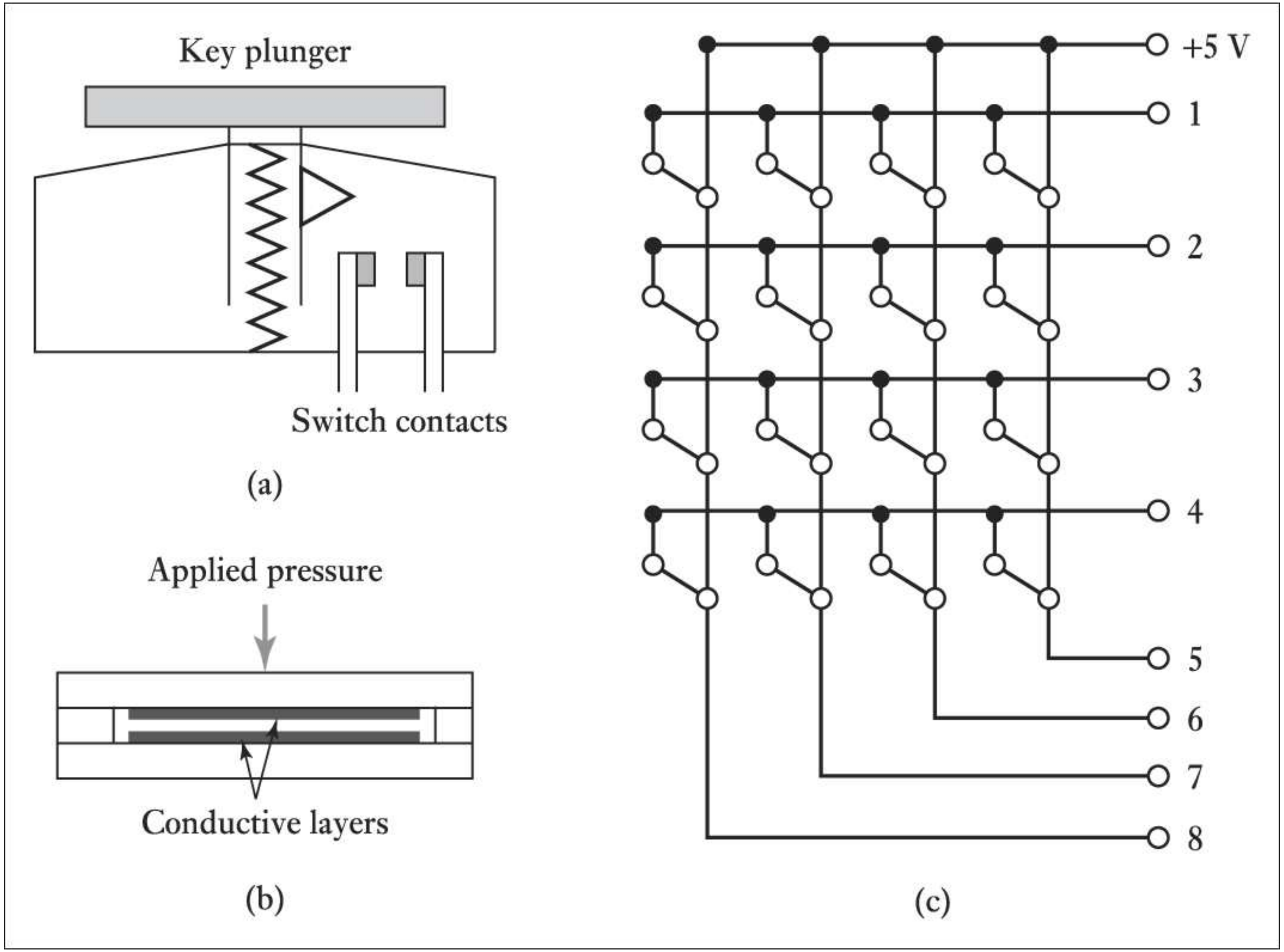


Figure 2.57 (a) Contact key, (b) membrane key, (c) 16-way keypad