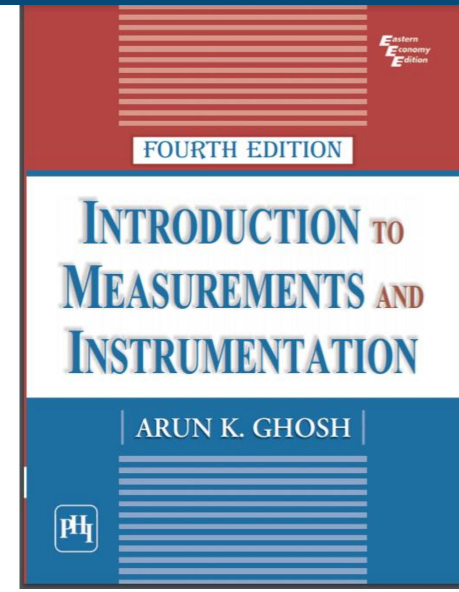
NUST
SCHOOL OF ELECTRICAL ENGINEERING
& COMPUTER SCIENCE

- Course: **EE383 Instrumentation and Measurements**
- Session: Fall 2022
- Class: BEE12 (C)
- **Lectures: Week 14**
- Course Instructor: Dr. Shahzad Younis

INSTRUMENTATION
& MEASUREMENT



Week 14

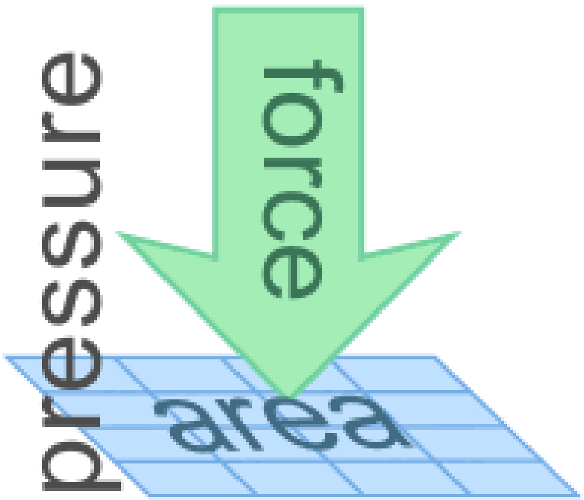
- **Chapter 8**

  Pressure Measurement

Book: Introduction to Measurements and Instrumentation, Arun K. Ghosh

Pressure Measurement

- ❑ **Pressure is converted to force by allowing it to act on an area**
  - ❑ Pressure measurement reduces to force measurement



Pressure Measurement

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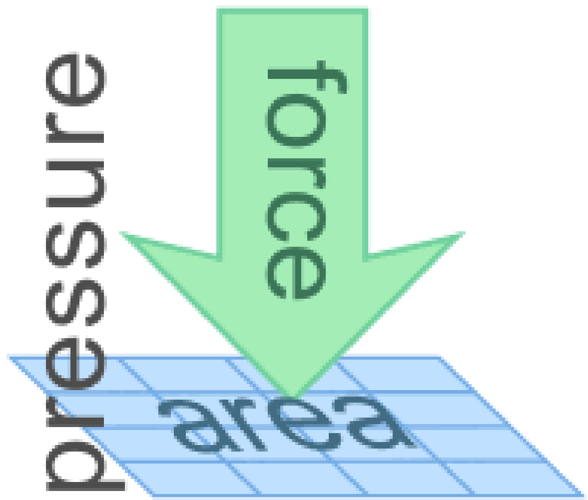
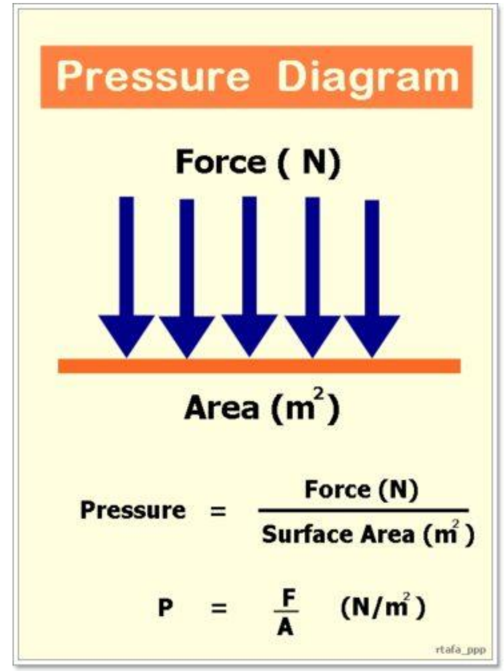


- ❑ **Pressure measurement ---> force measurement**

Pressure Measurement



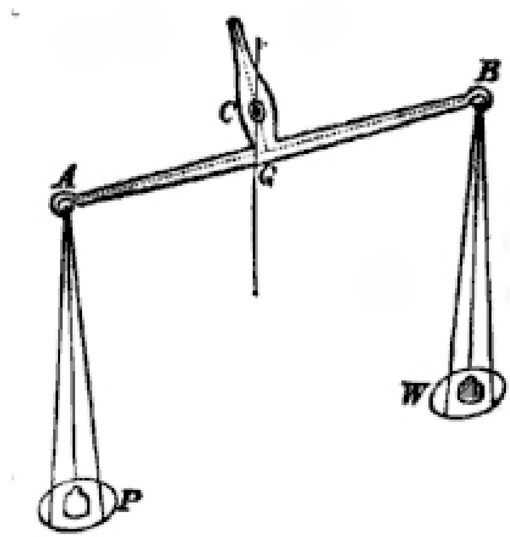
- Pressure is '**force per unit area**'

$$P = \frac{F}{A} \quad or \quad P = \frac{\Delta F}{\Delta A}$$

- Common Units:
  - Pounds per square inch (psi)
  - N/m^2 (Pa)
  - 1 bar = 100 kPa
  - Inches (or mm) of water (or Hg)
  - Atmosphere (1 atm = 760 mm of Hg)
  - 1mm of Hg= 133.33pascals
  - Torr (1 mm of Hg)

Pressure Measurement

- **Weight measurement**
  - In a common balance, the downward force acting on the mass is directly balanced by counterpoising it with an equal mass on the other scale pan



Pressure Measurement

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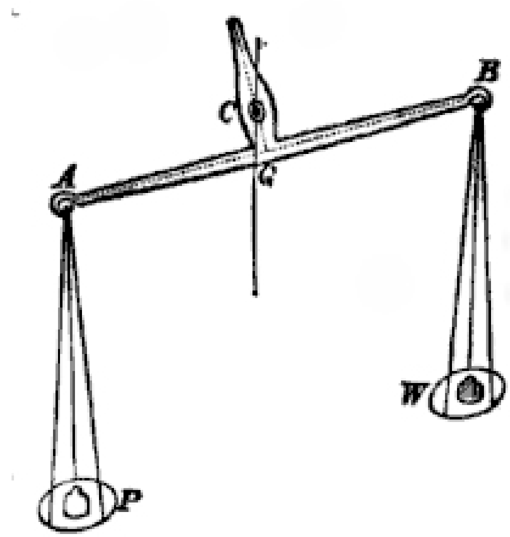
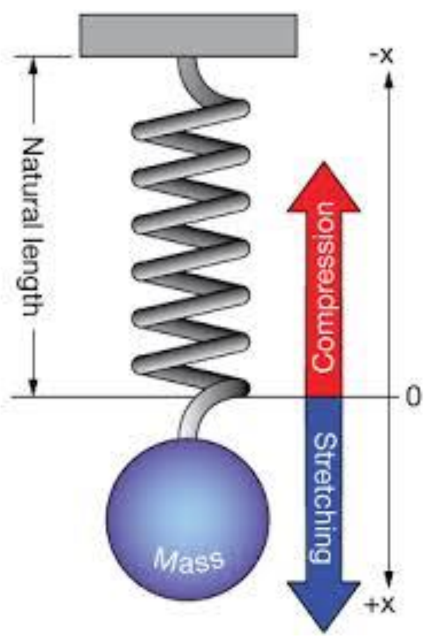


✓ **Comparison with known dead-weights acting on known areas**

Pressure Measurement

- **Weight measurement**
  - In a spring balance, the opposing force exerted by the spring balances the weight
  - The generated elastic force within spring depends on displacement of the end point
  - The displacement constitutes a measure of the weight



Pressure Measurement

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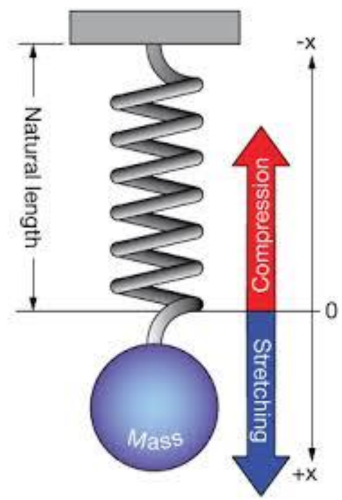
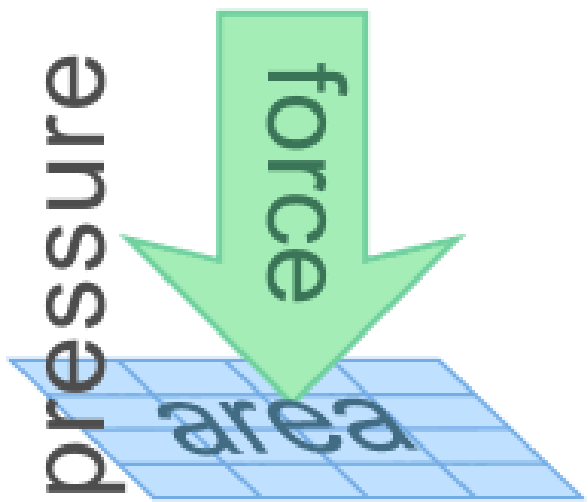


- ✓ **Deflection of elastic elements subjected to unknown weight**

Pressure Measurement

- How to measure pressure?

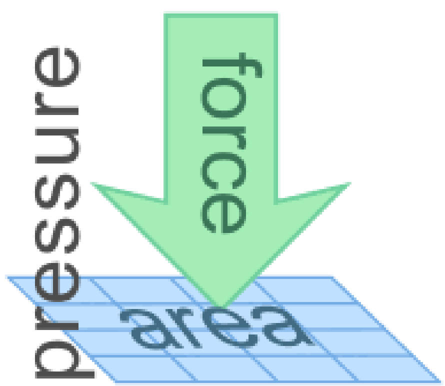


Pressure Measurement

- **How to measure pressure?**

  1. Comparison with known dead-weights acting on known areas

  2. Deflection of elastic elements subjected to unknown pressure



Pressure Measurement

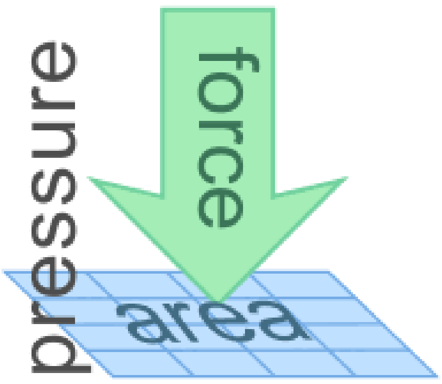
- **How to measure pressure?**

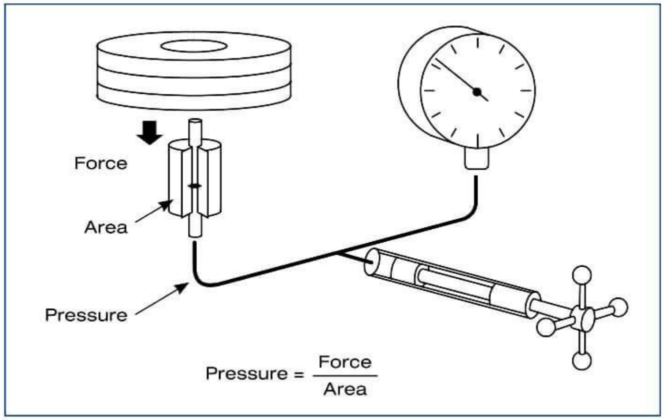
1. Comparison with known dead-weights acting on known areas

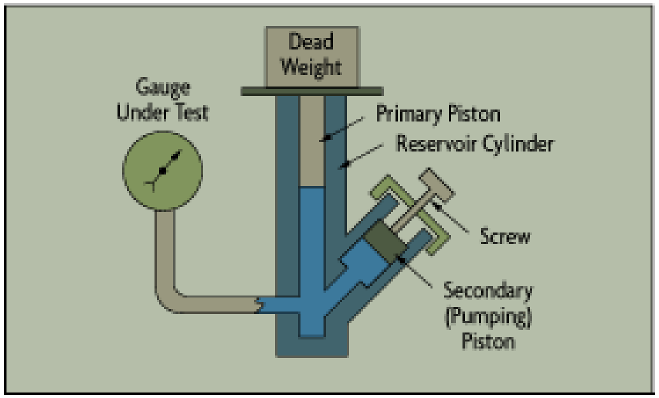
- Dead-weights gauges (DWG)

2. Deflection of elastic elements subjected to unknown pressure

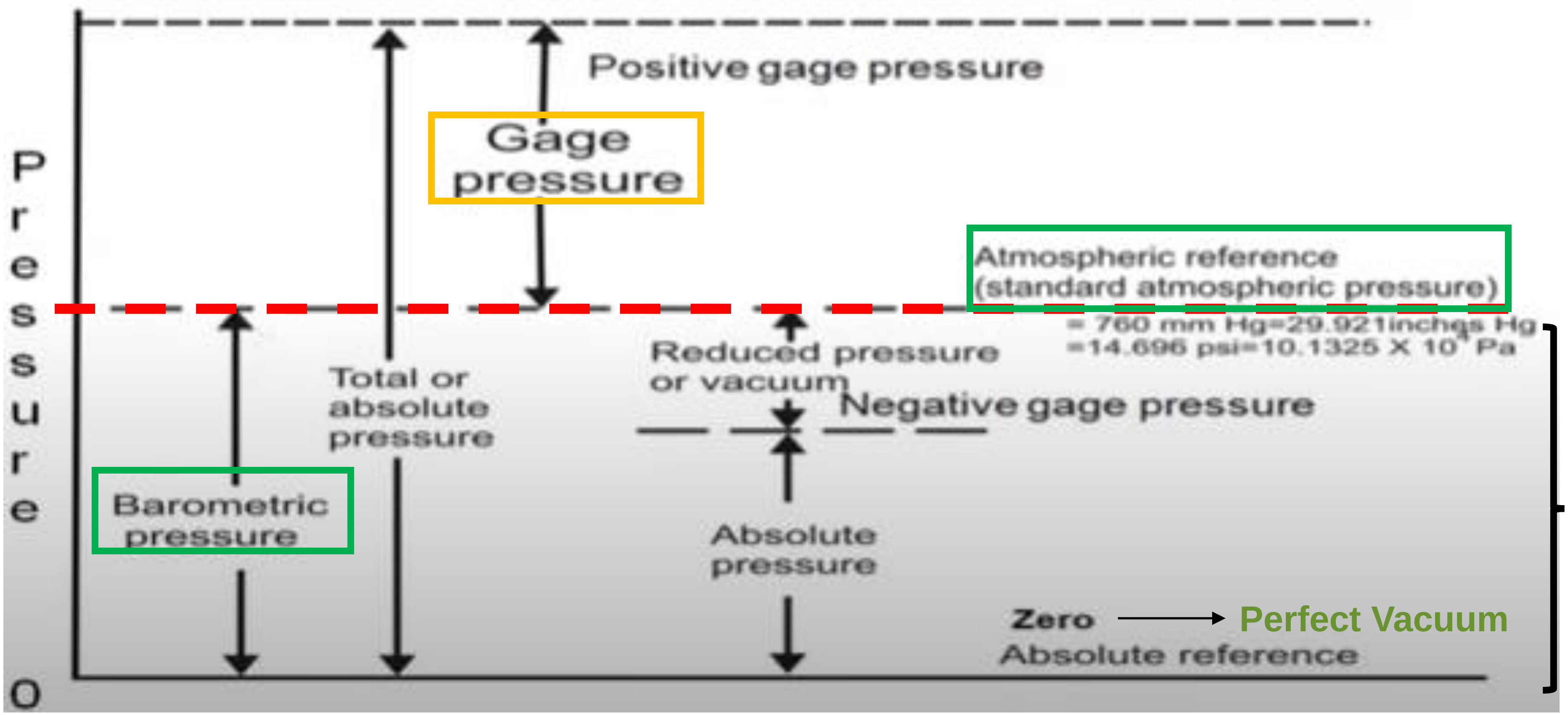
- Force summing devices
- These elastic devices convert applied pressures to forces and then to displacements



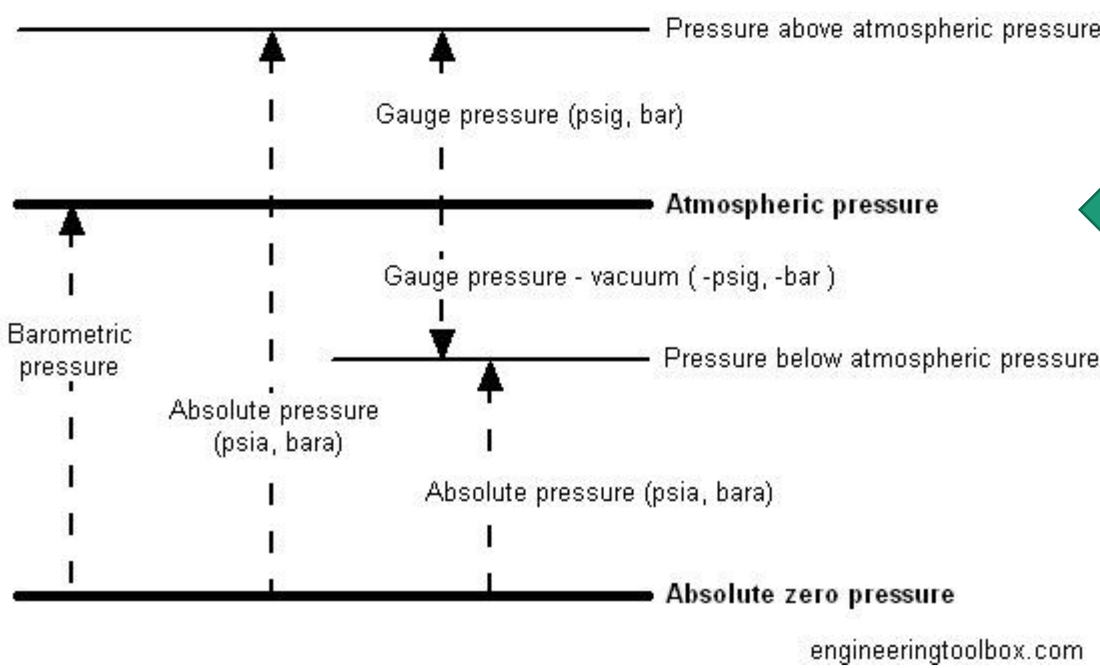




Pressure Measurement



Perfect Vacuum	0 Torr (theoretically impossible)
Outer Space	about 10^{-9} to 10^{-17} Torr
Extreme High Vacuum	about 10^{-13} Torr
Ultra High Vacuum (UHV)	about 10^{-10} to 10^{-11} Torr
High or Hard Vacuum (HV)	about 10^{-5} to 10^{-8} Torr
Medium or Intermediate Vacuum	about 10^{-3} to 10^{-5} Torr
Low, Soft or Rough Vacuum	about 10^{-3} Torr
Atmospheric Pressure	760 Torr



Example: Atmospheric Pressure

- Atmospheric pressure also known as barometric pressure is the pressure within the atmosphere of earth.
- On average, a column of air with a cross sectional area of $1\ cm^2$ measured from mean sea level to the top of earths atmosphere has a mass of about 1.03 kg and exerts a force of about 10.1 N resulting in a pressure of $10.1\ \mathrm{N}/cm^2$.
- $10.1\ \mathrm{N}/cm^2$=$101\ \mathrm{kN}/m^2$=$101\ kPa$ = $1\ atm$.

Pressure Measurement

- **Few Definitions**

  1. **Absolute pressure**
  2. **Gauge pressure**
  3. **Vacuum pressure**

Pressure Measurement

Pressure measurement is a very common requirement for most industrial process control systems.

- **Absolute Pressure**
  - The difference between pressure of the fluid and absolute zero of the pressure

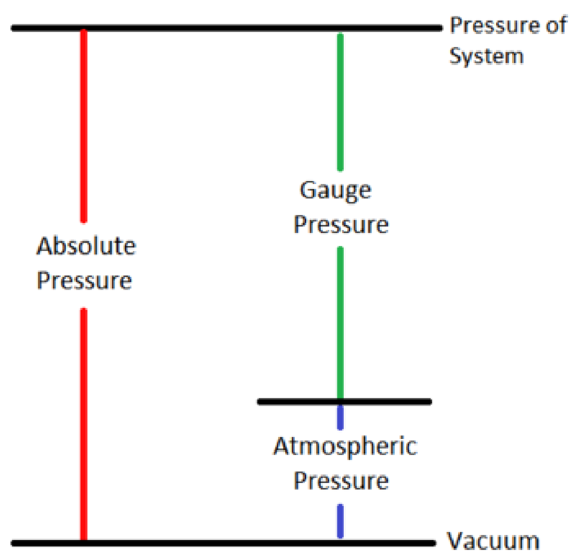
- **Gauge Pressure**
  - The difference between pressure of the fluid and atmospheric pressure

Gauge Pressure = Absolute Pressure - Atmospheric Pressure

- **Differential Pressure**
  - The differential pressure is the difference of pressure between two points.

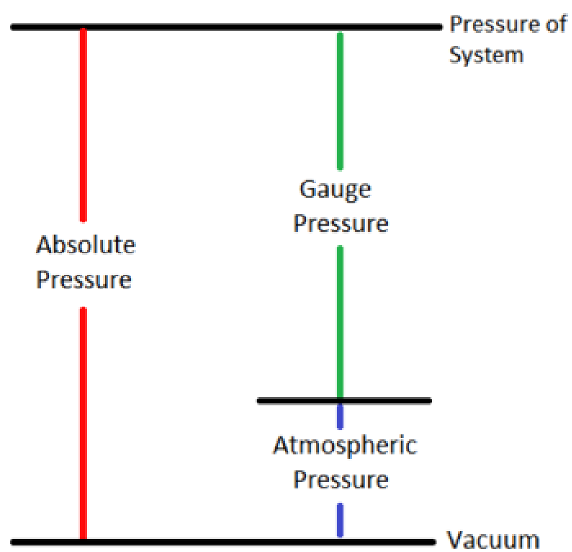
Pressure Measurement

- **Absolute pressure**
  - Absolute pressure is measured relative to a full vacuum



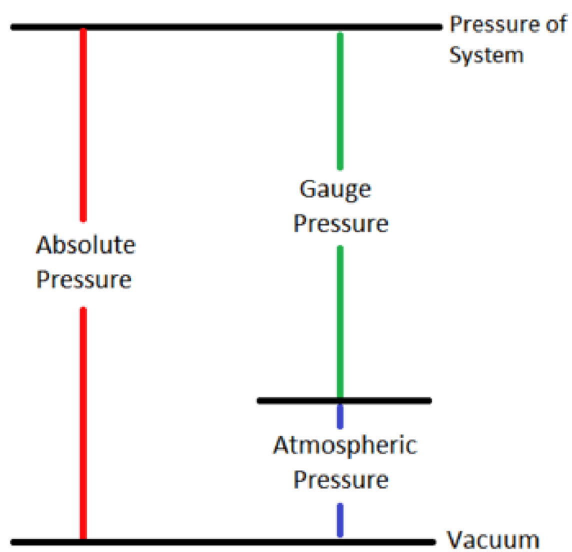
Pressure Measurement

- **Absolute pressure**
  - Absolute pressure is measured relative to a full vacuum
  - ‘a’ is added to the unit descriptor to indicate the absolute pressure
    - e.g., abbreviation for pounds per square inch (absolute) being *psi* (*a*)



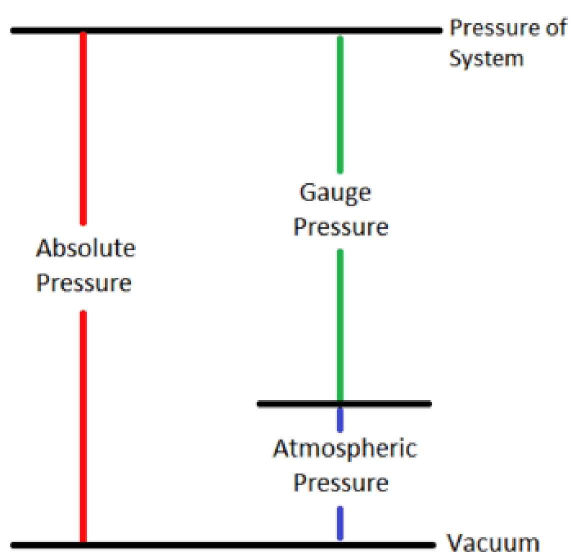
Pressure Measurement

- **Gauge pressure**
  - Measured against atmospheric pressure



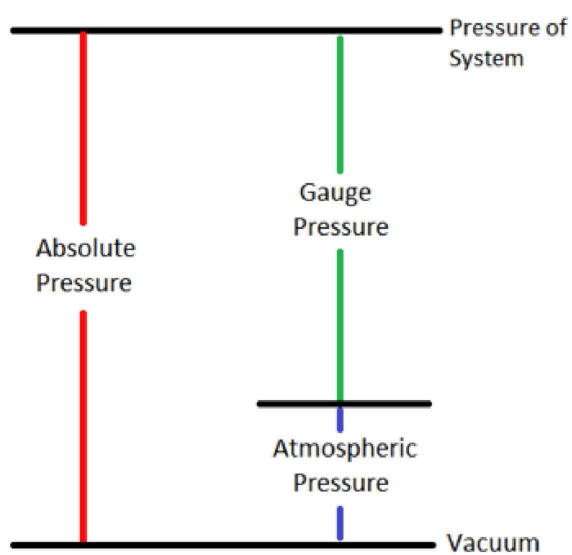
Pressure Measurement

- **Gauge pressure**
  - Measured against atmospheric pressure
  - gauge pressure does not include the atmospheric pressure and, therefore, is lower than the actual fluid pressure
  - absolute pressure can be obtained by adding the local atmospheric pressure to the indicated gauge pressure



Pressure Measurement

- **Gauge pressure**
  - Measured against atmospheric pressure
  - gauge pressure is indicated by adding a ‘g’ to the unit descriptor
  - e.g., pounds per square inch (gauge) is abbreviated as *psi* (*g*)



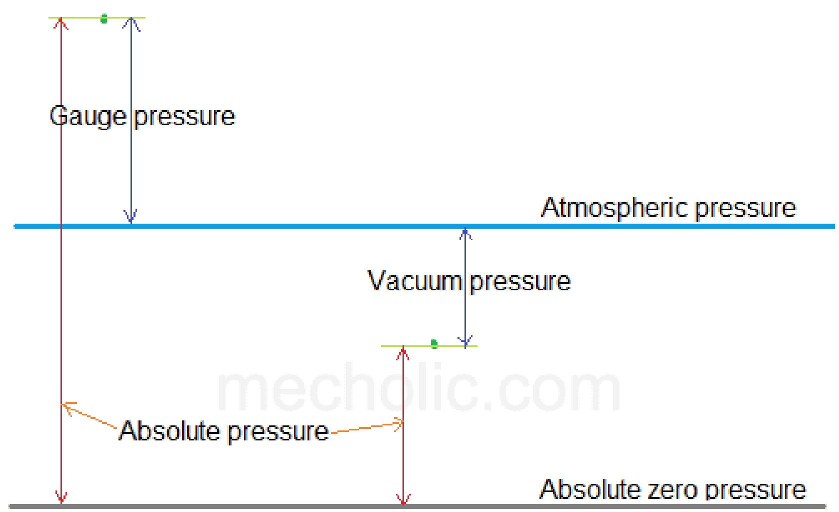
Pressure Measurement

- **Vacuum pressure**
  - **What is a vacuum?**

Pressure Measurement

- **Vacuum pressure**
  - Vacuum pressure is the difference between the atmospheric pressure and the absolute pressure
  - The pressure corresponding to that lower than the atmospheric pressure is expressed as *a vacuum of* so many Torr [1]

[1] The pressure exerted by a 1 mm column of Hg.



Pressure Measurement

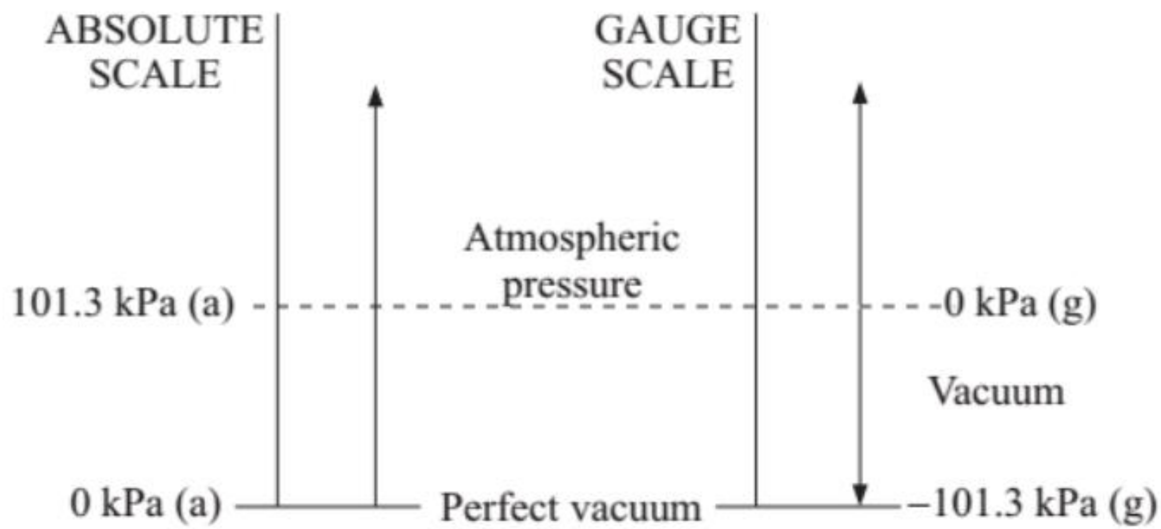


Fig. 8.1 Absolute and gauge pressure scales.

Pressure Measurement

Table 8.1 Difference between absolute pressure and gauge pressure

Absolute pressure	*Gauge pressure*
1. Reference point is absolute vacuum	1. Reference point is atmospheric pressure
2. Indicated by an affix 'a', such as kPa (a)	2. Indicated by an affix 'g', such as kPa (g)
3. Value at mean sea level is 101.3 kPa (a)	3. Value at mean sea level is 0 kPa (g)
4. Always has a positive value	4. Value below atmospheric pressure is negative and indicates a vacuum condition
5. Equals (gauge pressure + atmospheric pressure)	5. Equals (absolute pressure − atmospheric pressure)

Pressure Measurement

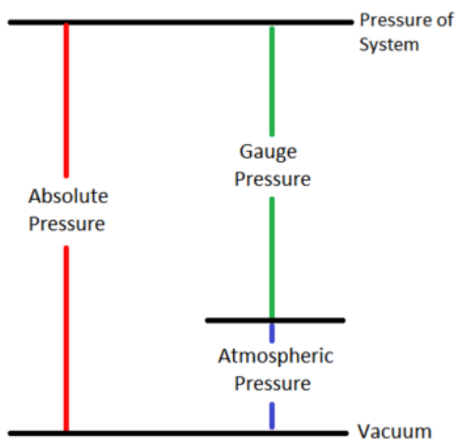
Example 8.1
Calculate the gauge pressure and absolute pressure in kg/cm^2 at the depth of 20 m in a water tank.

Solution
Assuming that the density ρ of water is 1000 kg/m^3, the gauge pressure is

$$p_{\text{gauge}} = h\rho = (25)(1000)\ \text{kg/m}^2 = 2.5\ \text{kg/cm}^2$$

And, the absolute pressure is

$$p_{\text{abs}} = p_{\text{gauge}} + p_{\text{atmos}} = 2.5 + 1.03 = 3.53\ \text{kg/cm}^2$$



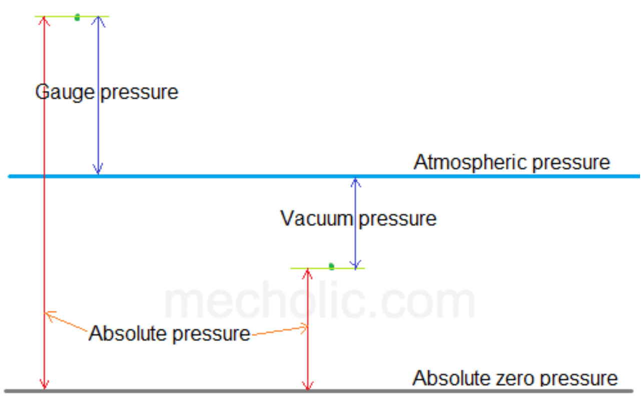
Pressure Measurement

- **Vacuum pressure**
  - Vacuum pressure is the difference between the atmospheric pressure and the absolute pressure.

Example 8.2
If the measurement indicates a vacuum of 150 Torr, what are the gauge and absolute pressures?

Solution
The vacuum of 150 Torr actually indicates 150 Torr below atmospheric pressure. So,

$$p_{\text{gauge}} = -150 \text{ Torr}$$
$$p_{\text{abs}} = p_{\text{atmos}} - 150 = 760 - 150 = 610 \text{ Torr}$$



Note: The specification is *vacuum of* 150 Torr, not *pressure of* 150 Torr. A vacuum is thus always a *negative* quantity if expressed as a gauge pressure.

Pressure Measurement

- **Definitions**
  1. **Absolute pressure**
  2. **Gauge pressure**
  3. **Vacuum pressure**

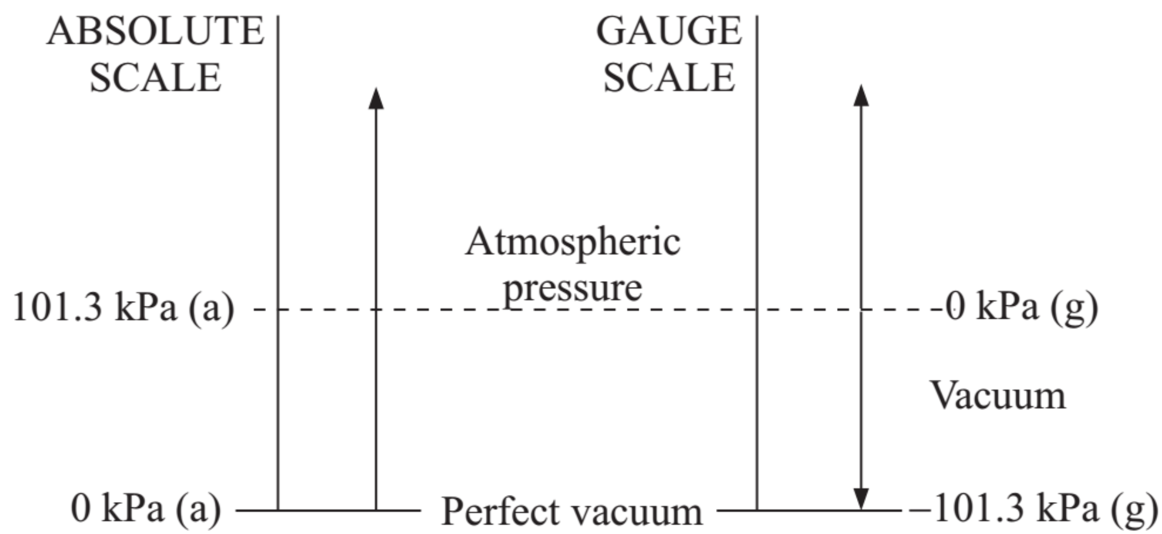


Fig. 8.1 Absolute and gauge pressure scales.

Pressure Measurement

❑ Absolute and Gauge pressure

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4. Always has a positive value	4. Value below atmospheric pressure is negative and indicates a vacuum condition
5. Equals (gauge pressure + atmospheric pressure)	5. Equals (absolute pressure − atmospheric pressure)

Pressure Measurement

8.2 Pressure Units and Their Conversions

The basic SI unit of pressure is pascal (Pa) which is defined as a force of 1 newton acting on area of 1 m^2, or

$$1 \text{ Pa} = 1 \text{ N/m}^2$$

Since pascal is a small unit, it is customary to use kPa or MPa. Quite a number of other units are used to report pressure readings. A conversion table helps to interrelate them. Table 8.2 lists such conversions.

Table 8.2 Conversion factors for pressures in various systems of units

	Pa	mbar	Torr	at[a]	atm[b]	psi
Pa	1	1×10^{-2}	7.5×10^{-3}	1.02×10^{-5}	9.87×10^{-6}	14.5×10^{-5}
mbar	1.0×10^{2}	1	7.5×10^{-1}	1.02×10^{-3}	9.87×10^{-4}	14.5×10^{-3}
Torr	1.33×10^{2}	1.33	1	1.36×10^{-3}	1.32×10^{-3}	19.3×10^{-3}
at[a]	9.80×10^{4}	9.80×10^{2}	7.36×10^{2}	1	9.68×10^{-1}	14.5
atm[b]	1.01×10^{5}	1.01×10^{2}	7.60×10^{2}	1.03	1	14.7
psi	6.8×10^{3}	0.68	51.8	6.9×10^{-2}	6.8×10^{-2}	1
mmWG/ mmWC[c]	9.8	9.8×10^{-2}	7.35×10^{-2}	10^{-4}	9.67×10^{-5}	1.42×10^{-3}

[a] Technical atmosphere
[b] Physical atmosphere
[c] Full forms are *mm water gauge* or *mm water column*. 1 mmWG or mmWC is the pressure required to support a 1 mm column of water at normal temperature.

Applications of Pressure Measuring Instrument

Altimeter: Used in hiking, climbing, sky diving, Aircrafts

Barometer: Used in weather forecast

Applications of Pressure Measuring Instrument

Depth gage: Used in submarines and by underwater divers

Pitot tube: Used for measuring aircraft speed.

Applications of Pressure Measuring Instrument

Sphygmomanometer: Used for blood pressure measurement.

Tire pressure gage.

Applications of Pressure Measuring Instrument

Accurately measuring pressure is crucial for many industrial processes to operate safely, efficiently and with optimum quality control.

Pressure measuring instruments have many indirect application in industry

- **Flow rates**
- **Fluid Levels**
- **Product Density**

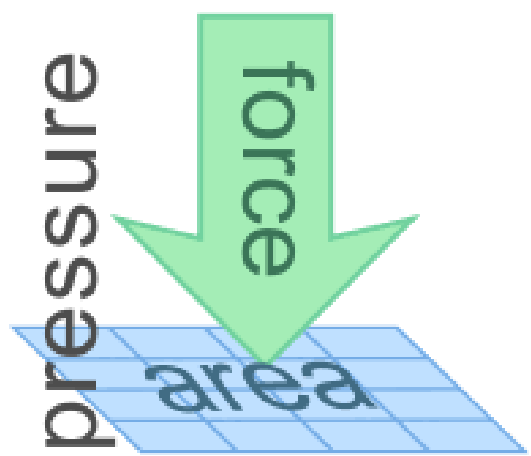
Pressure Measurement

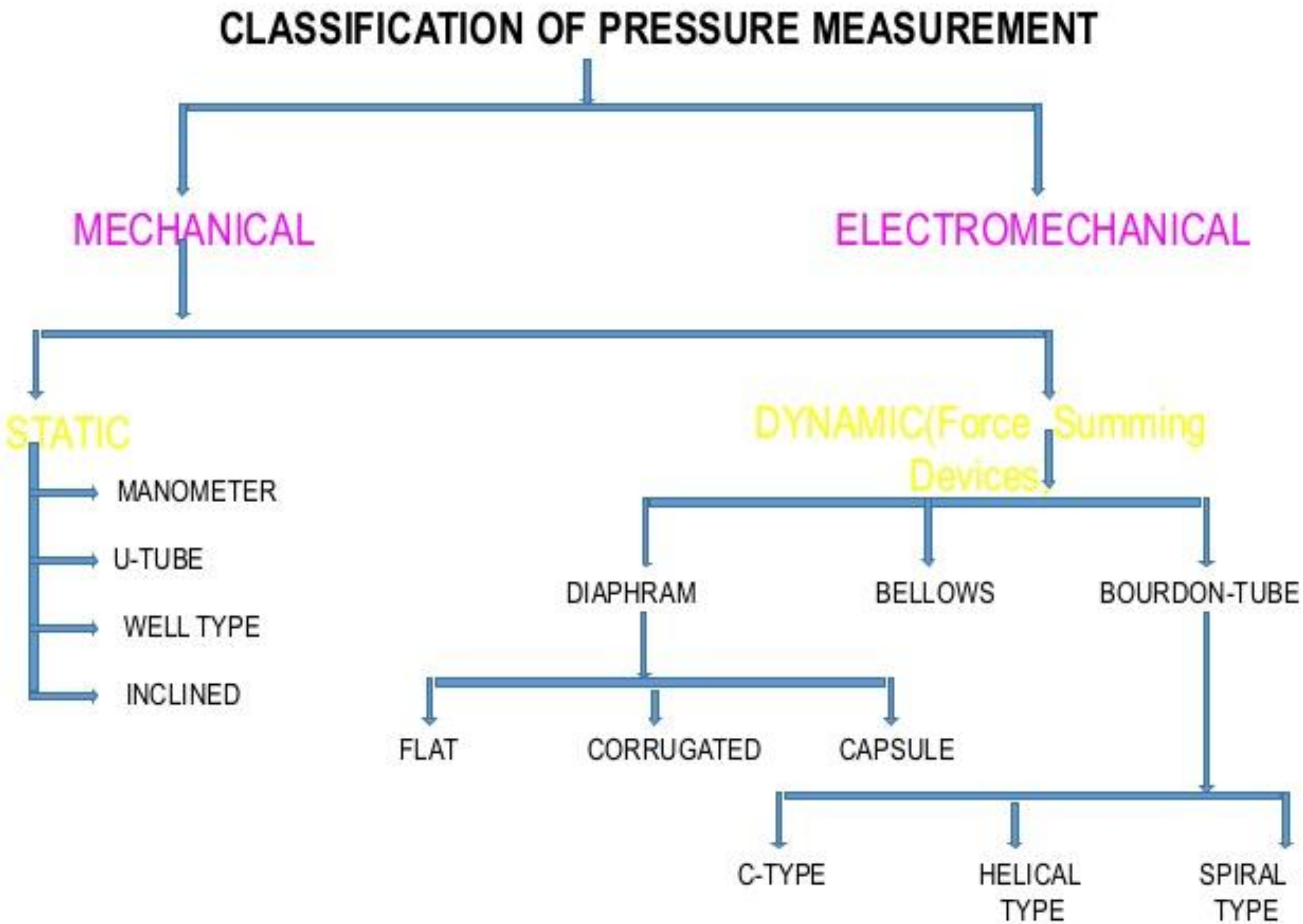
- **Pressure measurement : force measurement**

- **How to measure pressure?**

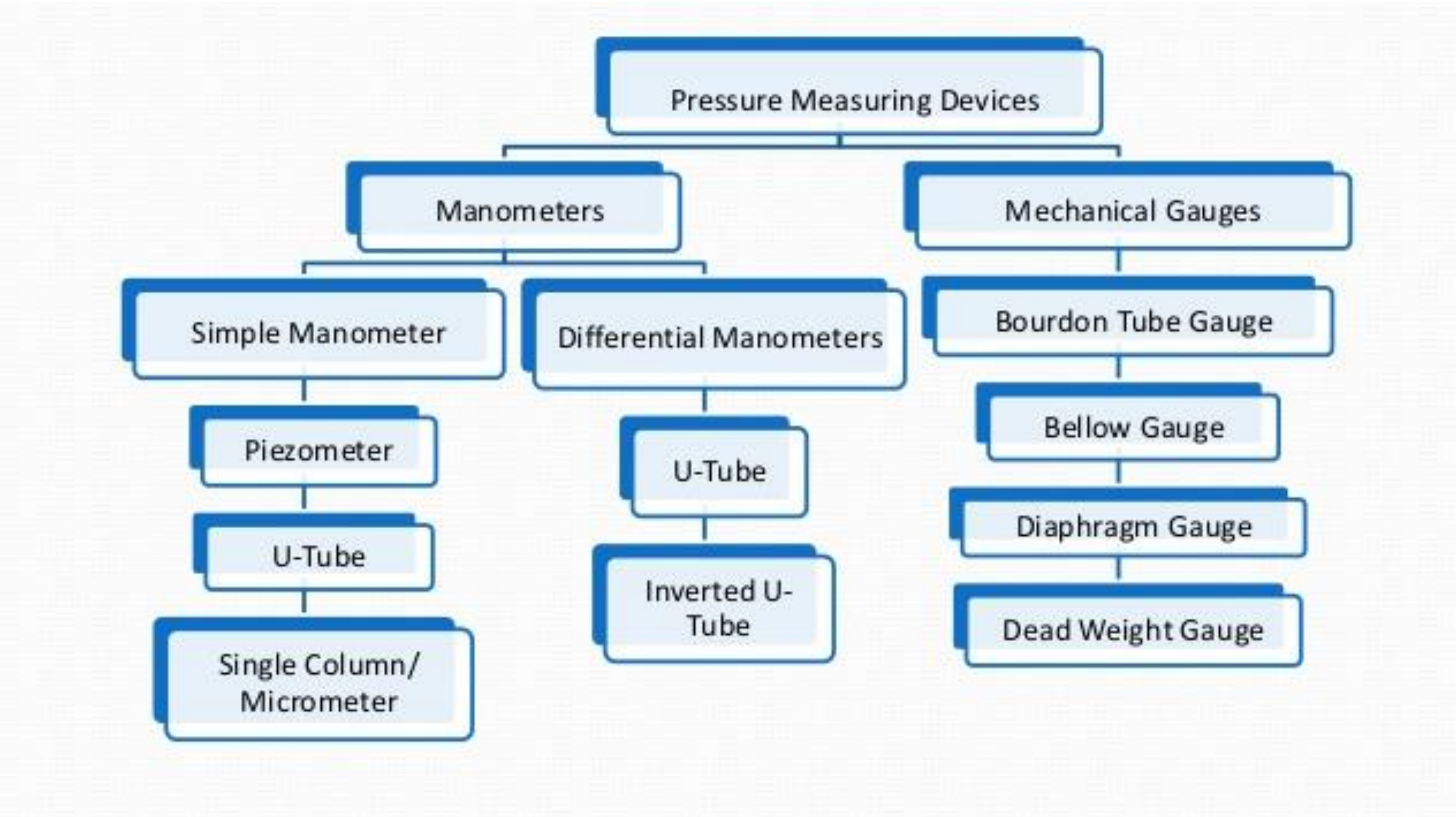
  1. Dead-weights gauges (DWG)

  2. Force summing devices




CLASSIFICATION OF PRESSURE MEASUREMENT
MECHANICAL
ELECTROMECHANICAL
STATIC
MANOMETER
U-TUBE
WELL TYPE
INCLINED
DYNAMIC(Force Summing Devices)
DIAPHRAM
BELLOWS
BOURDON-TUBE
FLAT
CORRUGATED
CAPSULE
C-TYPE
HELICAL TYPE
SPIRAL TYPE

Types of Pressure Measuring Devices



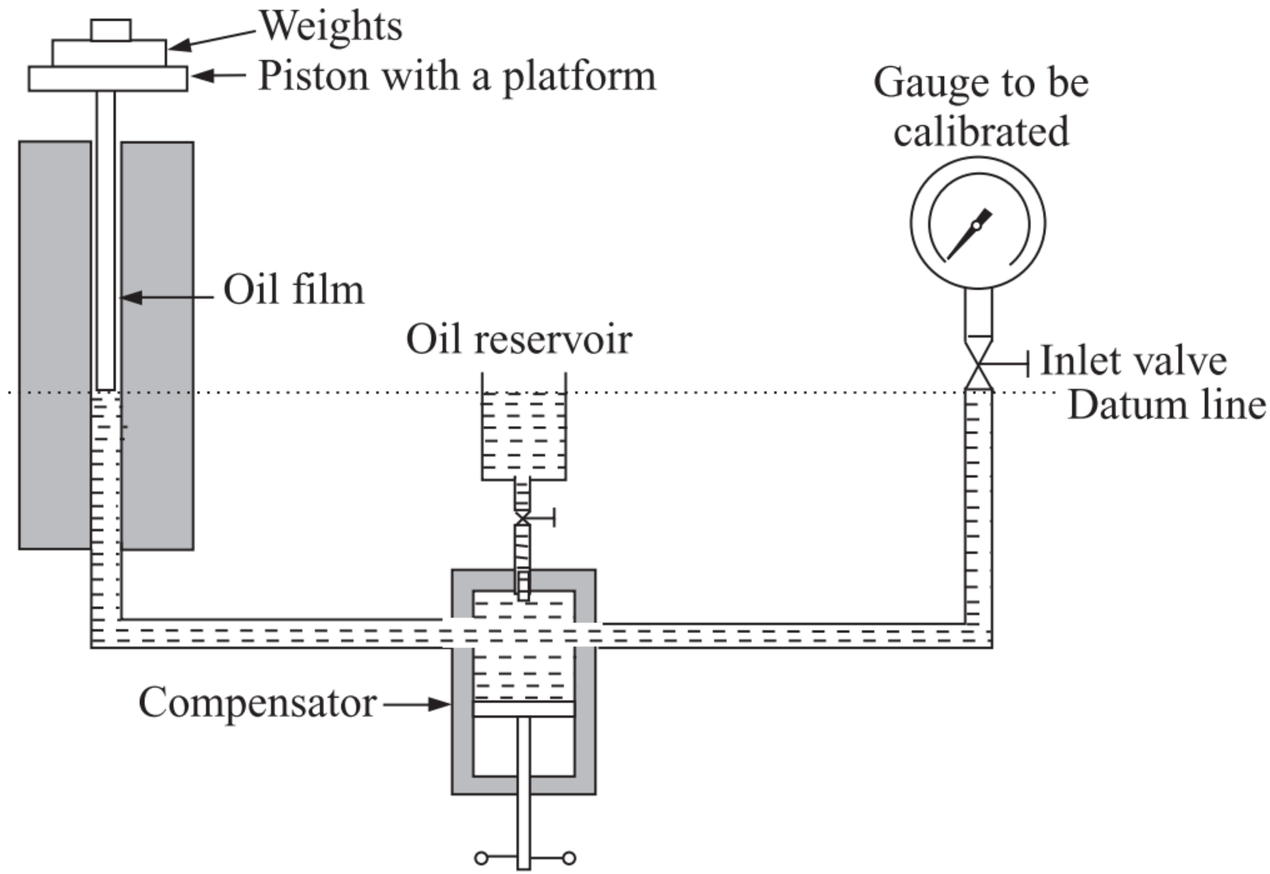
Pressure Measurement

- **Comparison with Known Dead-weights**

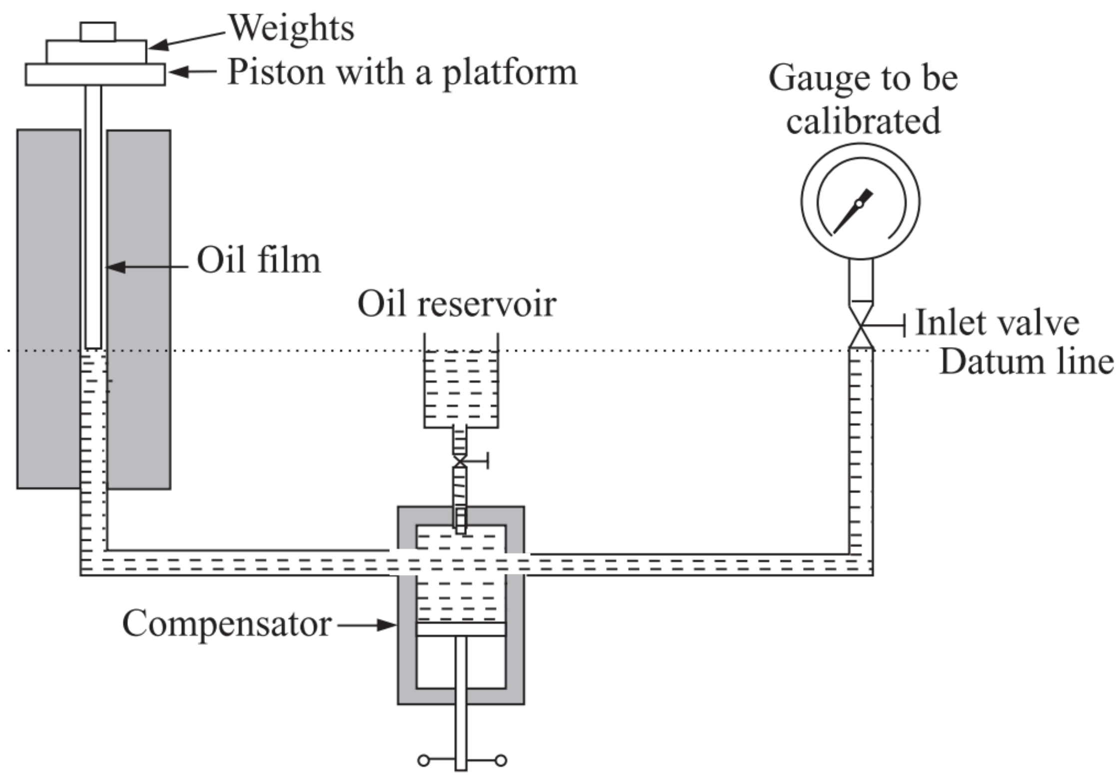
    1. Dead-weight Gauge

    2. Manometers

Dead-weight Gauge

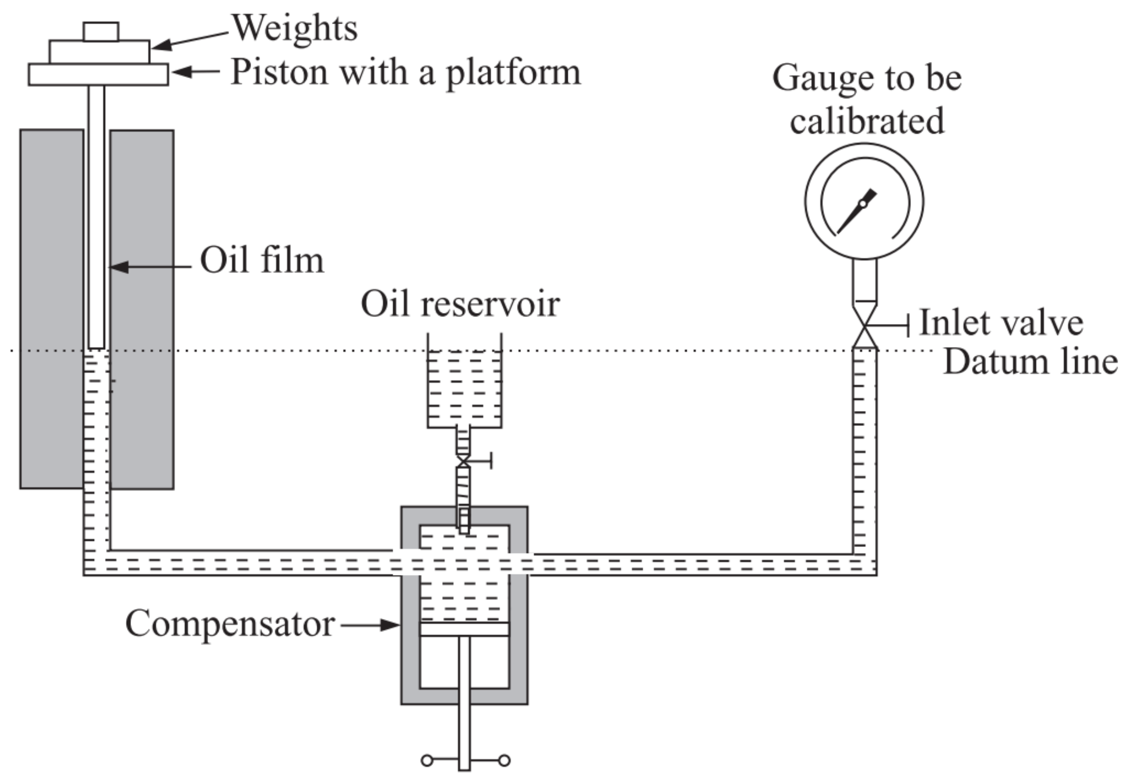


Dead-weight Gauge



- ❑ An hollow cylinder and a close-fitting piston with a top platform
  - ❑ accurately known weights in the form of discs can be placed on the top platform
- ❑ Another similar cylinder connected to the former through a reservoir
- ❑ The gauge to be calibrated is connected to the cylinder

Dead-weight Gauge



- Working
- By the piston arrangement shown at the bottom, the fluid pressure is gradually increased until the piston-weight arrangement just freely floats
  - An equal pressure appears at the inlet valve of the opposite cylinder
- The pressure is applied to the Gauge to be calibrated using the Inlet valve
  - Calibration is achieved using comparison

Dead-weight Gauge

If p is the fluid pressure

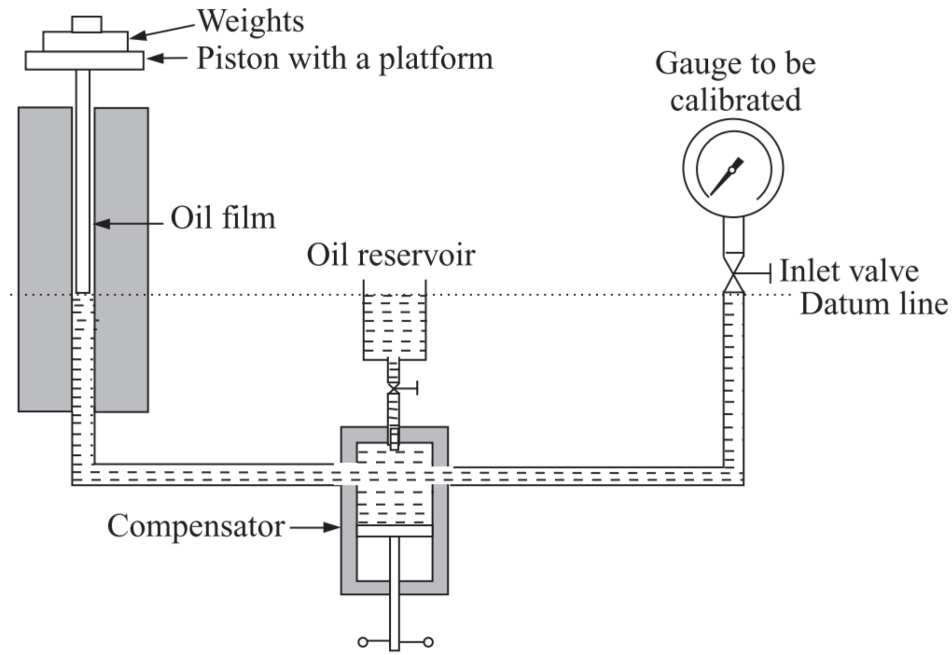
p_A is the atmospheric pressure acting on the weights

M_t is the tare (or mass of the piston assembly)

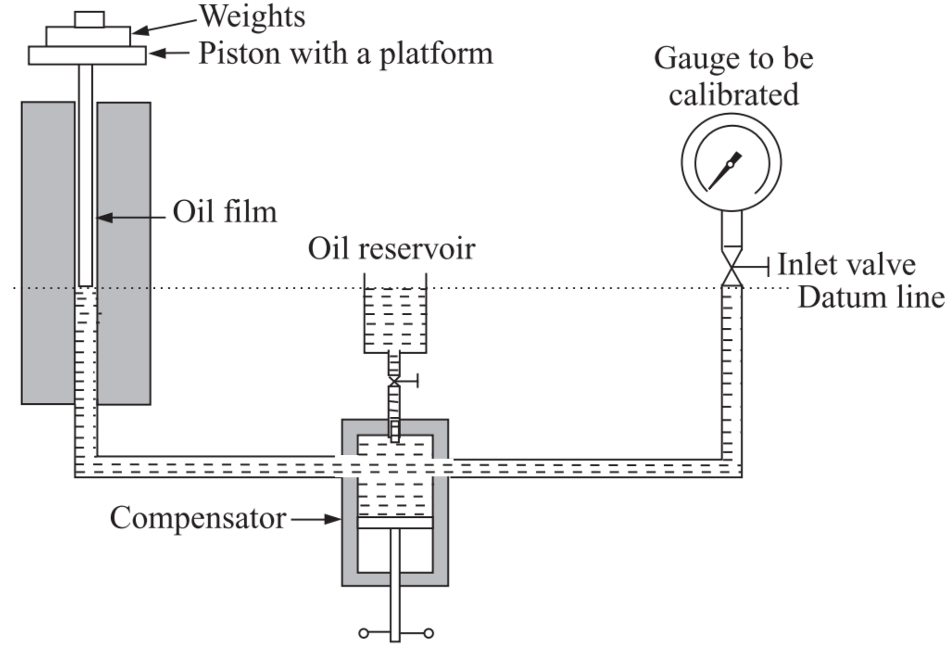
M_c is the extra mass placed on top of the piston to calibrate pressure

A is the equivalent area of the piston

g is the acceleration due to gravity



Dead-weight Gauge



If p is the fluid pressure
p_A is the atmospheric pressure acting on the weights
M_t is the tare (or mass of the piston assembly)
M_c is the extra mass placed on top of the piston to calibrate pressure
A is the equivalent area of the piston
g is the acceleration due to gravity

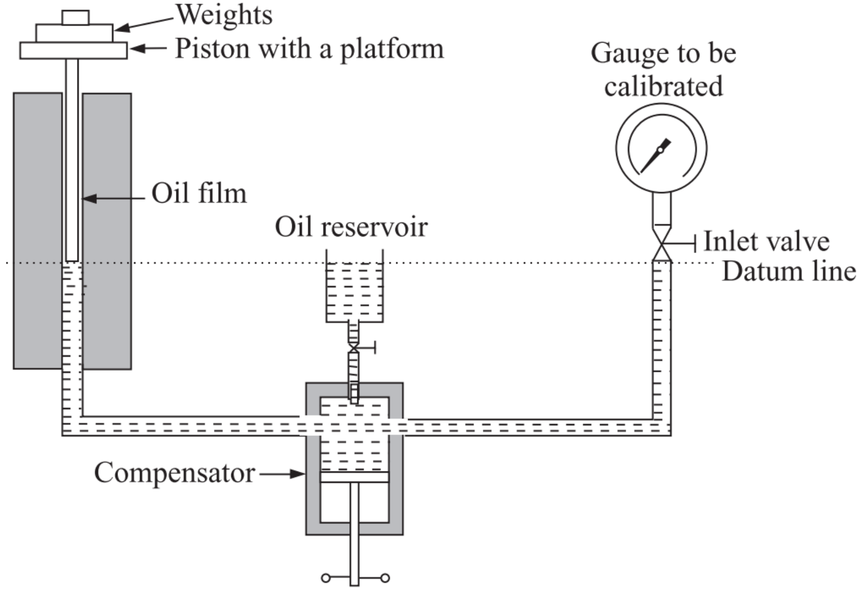
$$p = p_A + \frac{(M_t + M_c)g}{A}$$

$$p - p_A = \frac{(M_t + M_c)g}{A}$$

- "g" is assumed acting vertically downwards, which demands a strict verticality of the piston and the cylinder

Dead-weight Gauge

❑ Dead-weight Gauge



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$$p = p_A + \frac{(M_t + M_c)g}{A}$$

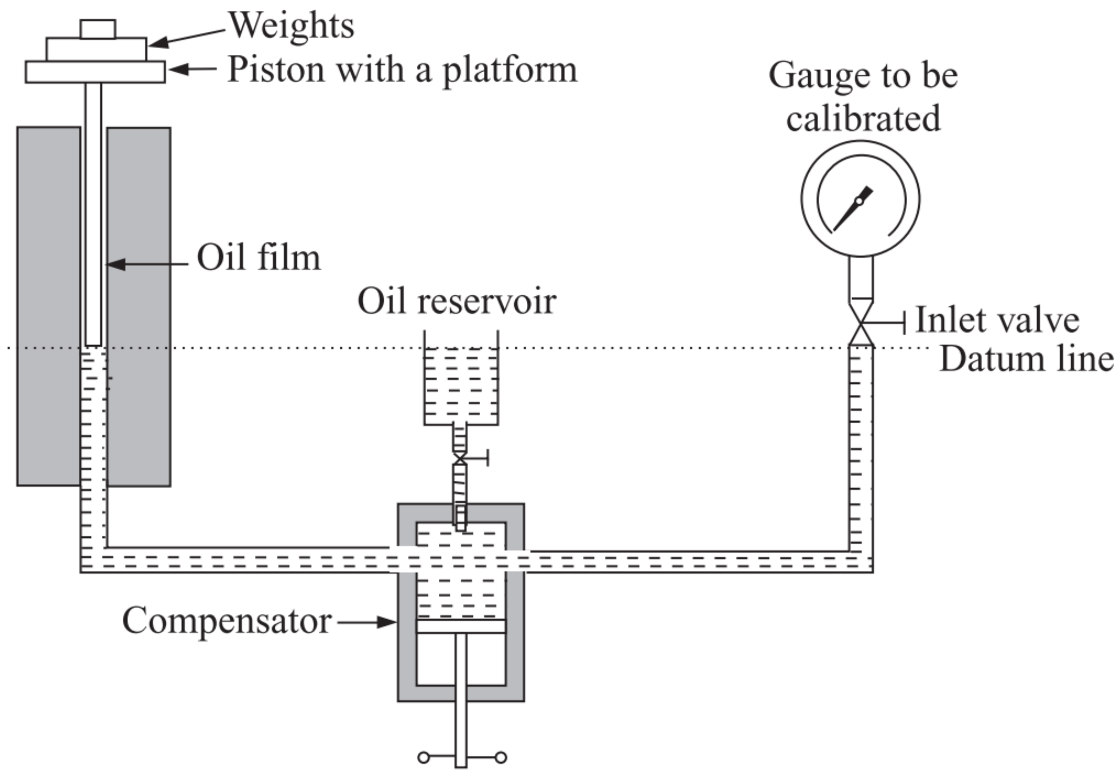
$$p - p_A = \frac{(M_t + M_c)g}{A}$$

❑ Features

- ❑ High accuracy: maximum attainable accuracy ~0.01%
- ❑ Minimum pressure that such a gauge can measure is

$$M_t g / A$$

Dead-weight Gauge



- ❑ **Features**
- ❑ Direct pressure measurement is rarely done with dead-weight gauges
  - ❑ mainly used to calibrate direct reading dial-type pressure gauges

Classification of Pressure Measuring Instrument Based on Pressure-Levels

High Vacuum Measuring Instruments

- Mcleod gage
- Thermal conductivity gauge
  - Thermocouple gage
  - Pirani Gage
- Ionization gauge

Low Pressure Measuring Instruments

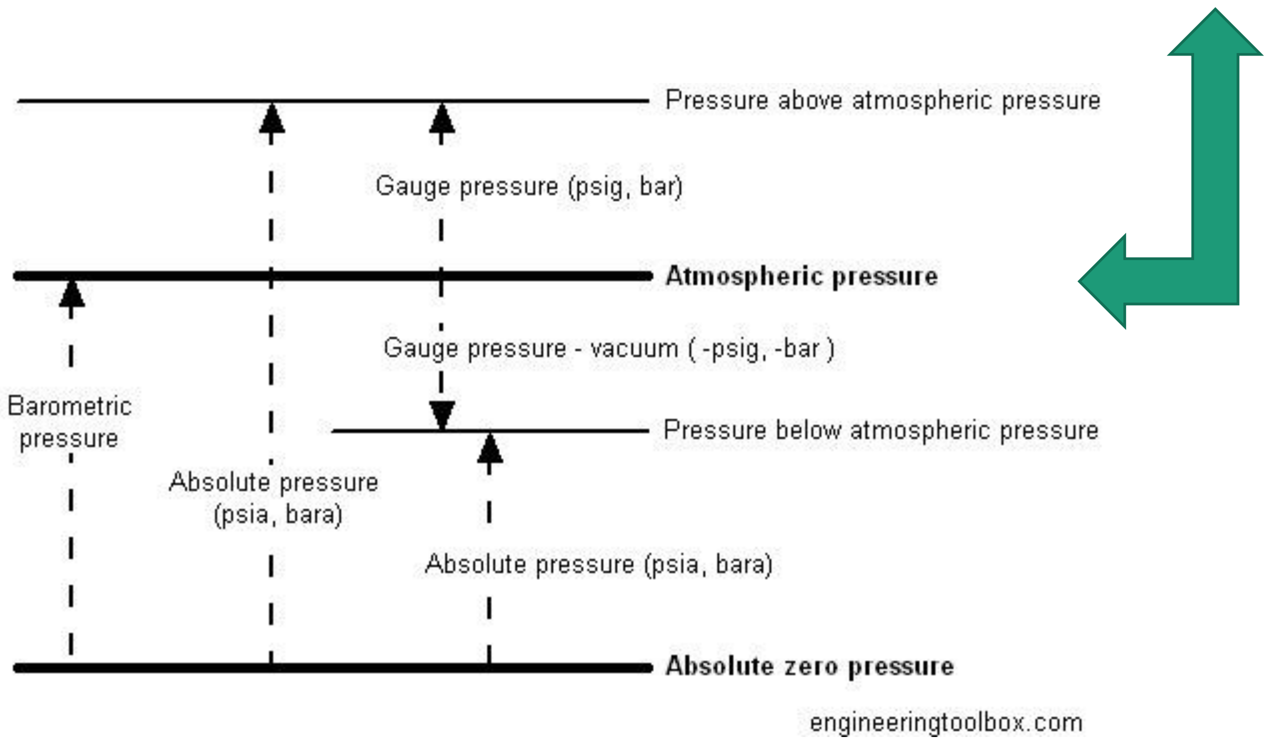
- Manometer

Moderate pressure measuring instrument

- Elastic pressure transducer
  - Bourdon tube pressure gage
  - Diaphragm type gage
  - Bellows gage

Recall….

Perfect Vacuum	0 Torr (theoretically impossible)
Outer Space	about 10^{-9} to 10^{-17} Torr
Extreme High Vacuum	about 10^{-13} Torr
Ultra High Vacuum (UHV)	about 10^{-10} to 10^{-11} Torr
High or Hard Vacuum (HV)	about 10^{-5} to 10^{-8} Torr
Medium or Intermediate Vacuum	about 10^{-3} to 10^{-5} Torr
Low, Soft or Rough Vacuum	about 10^{-3} Torr
Atmospheric Pressure	760 Torr



Classification of Pressure Measuring Instrument Based on Pressure-Levels

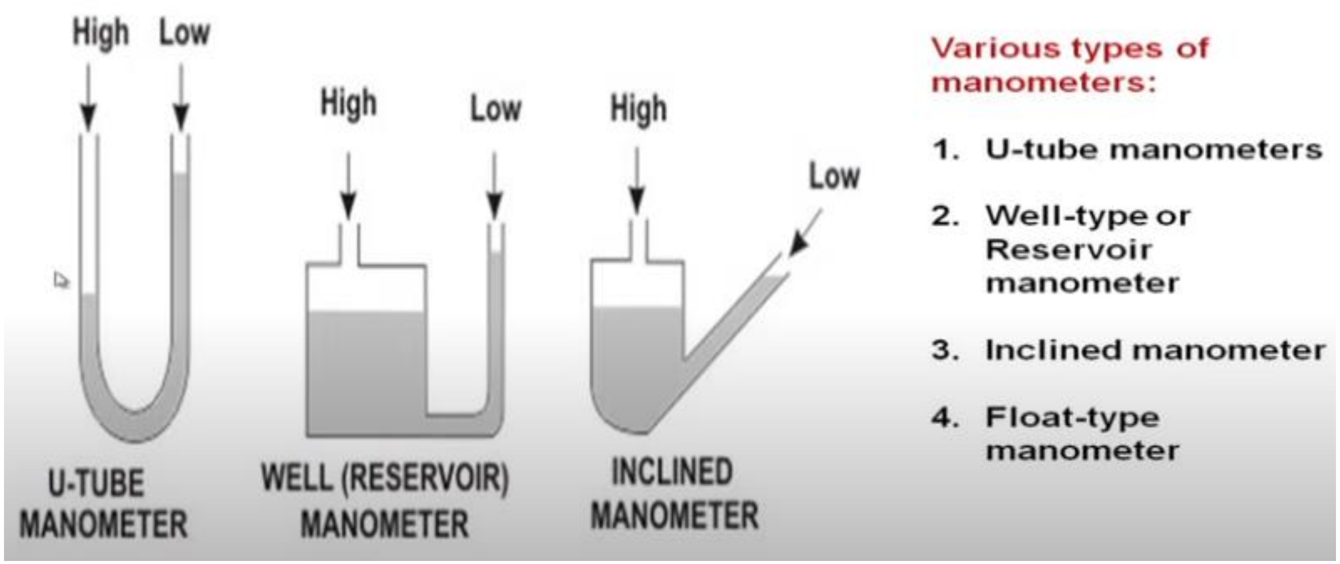
Type of pressure to be measured	Pressure Measuring instrument to be used
Low pressure	Manometer
High and medium pressure	Bourdon tube pressure gauge. Diaphragm gauge. Bellows Gauges.
Low vacuum and ultra high vacuum	Mcleod vacuum gauge thermal conductivity gauges. Ionisation gauges.
Very high pressure	Bourdon tube pressure gauge. Diphragm gauge. Bulk modulus pressure gauge.

- Low pr (Below 1 mm of Hg)- manometer and low pr gauges
- Medium and low (between 1mm of Hg 1000 atm)- Bourdon gauge and Diaphragm gauges
- Low vacuum and ultra high vacuum(760 torr to 10 raise to -9 torr and beyond)- McLeod, thermal conductivity and ionisation gauge
- Very high pr (1000 atm and above)- Bourdon gauge,Diaphragm and electrical pr gauges

Low Pressure Measurement

Types of Manometers

- Various types of manometers are used.



U-Tube Manometers

Manometers Types *(w.r.t text book)*

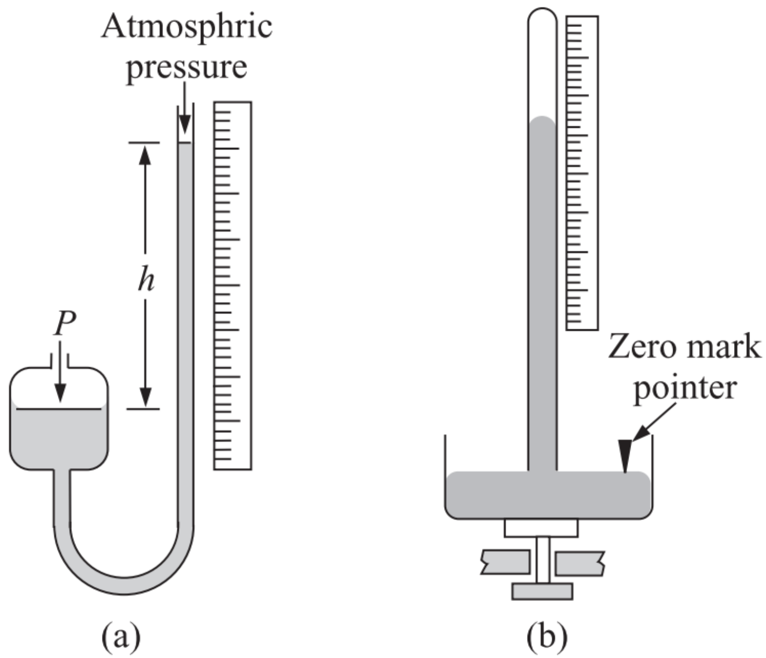
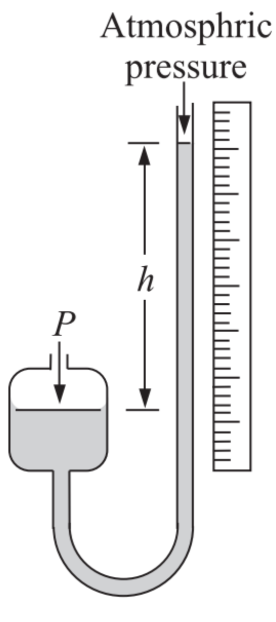


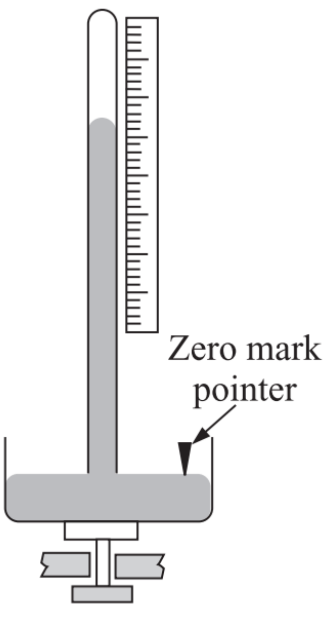
Fig. 8.3 Manometers of different kinds: (a) well-type manometer, and (b) barometer.

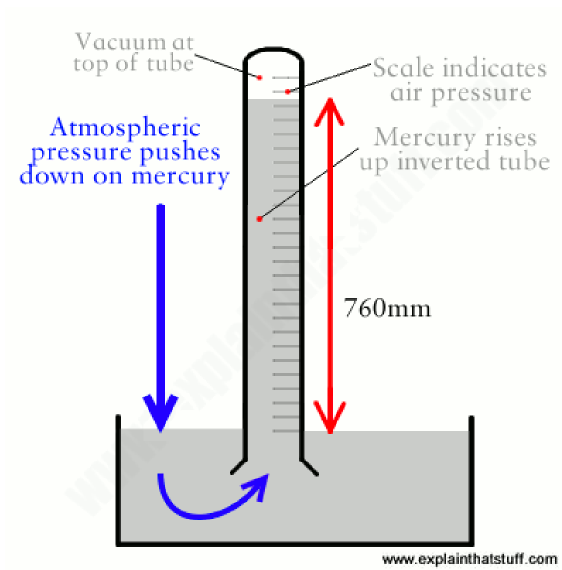
Manometers

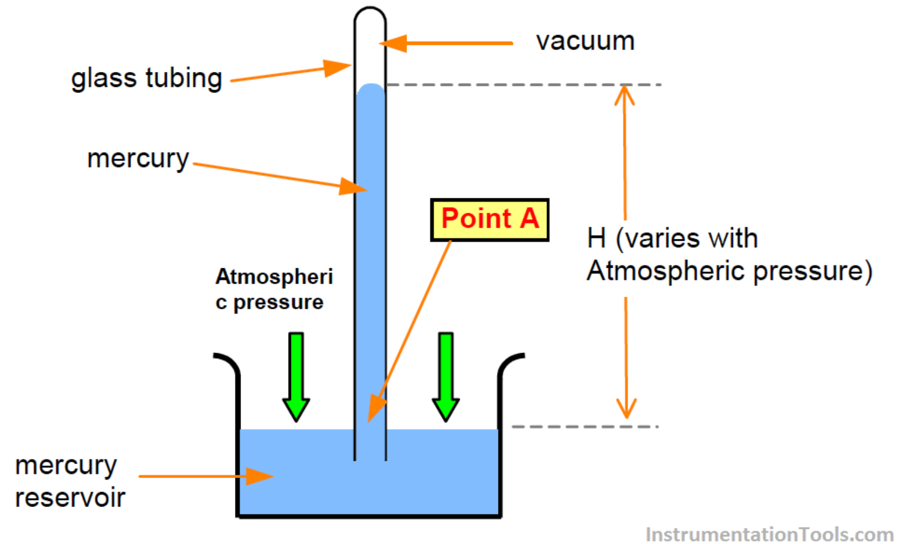


- ❑ **Well-type**
  - ❑ reading of a single leg gives the desired pressure reading

Manometers







- ❑ **Barometric type**
  - ❑ end of the reading tube is evacuated and sealed
  - ❑ gives absolute pressure readings

Manometers

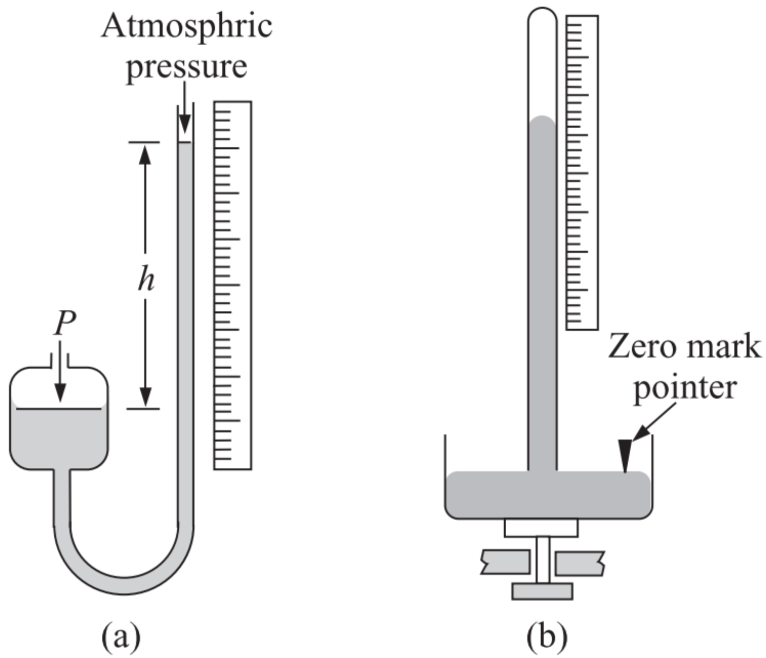


Fig. 8.3 Manometers of different kinds: (a) well-type manometer, and (b) barometer.

- **Features**
  - Comparable accuracy to deadweight gauges at lower pressures
  - Higher pressure measurements with manometer are impractical because of the length of liquid columns involved

Manometers

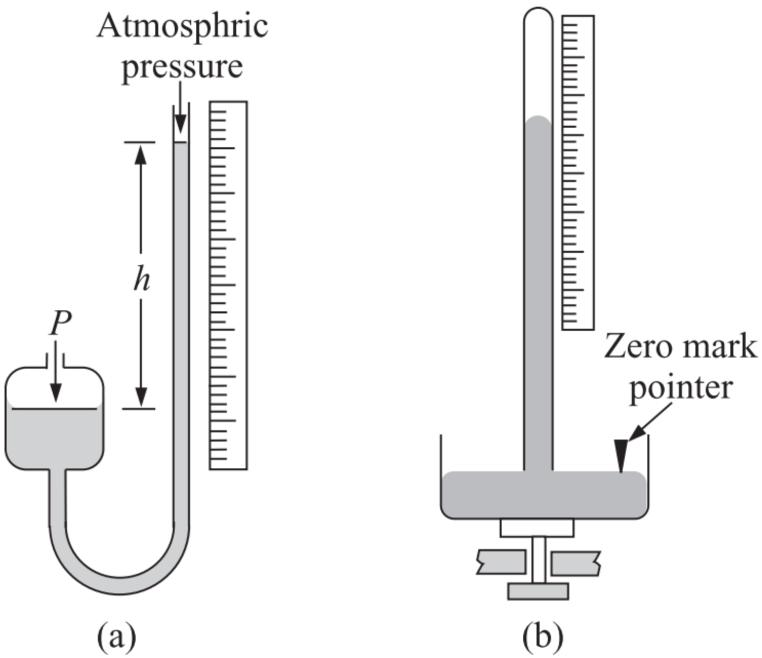


Fig. 8.3 Manometers of different kinds: (a) well-type manometer, and (b) barometer.

- **Unlike dead-weight gauges,**
  - self-balancing, deflection-type rather than null-type instruments
  - have a continuous rather than stepwise readout

Manometers

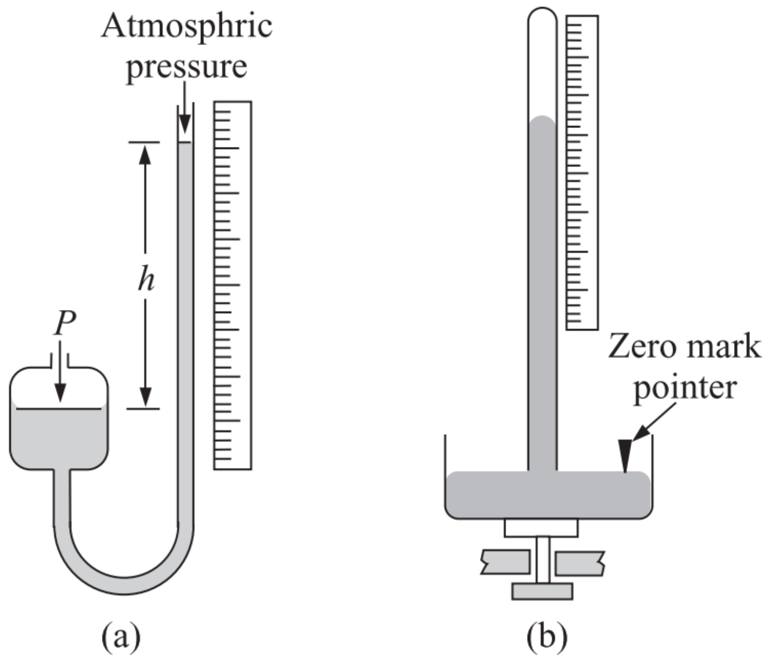


Fig. 8.3 Manometers of different kinds: (a) well-type manometer, and (b) barometer.

- **Disadvantages**
  - being large, not well suited for integration into automatic control loops
  - usually found in the laboratory or used as local indicators

Manometers

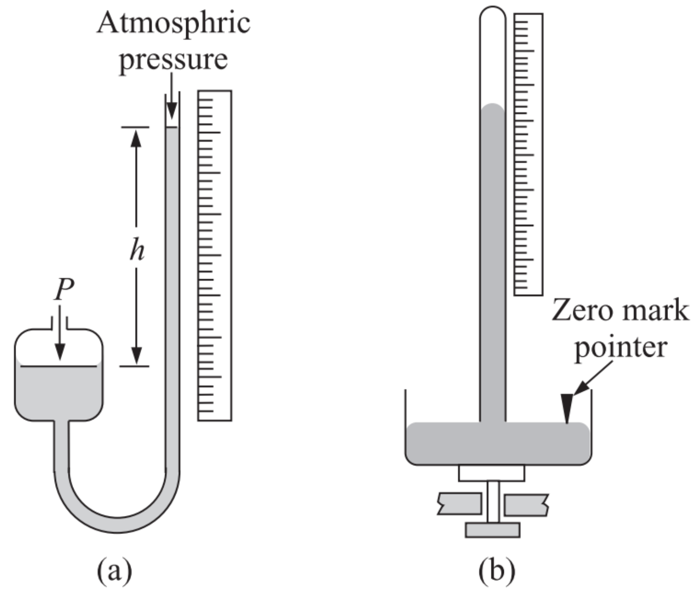
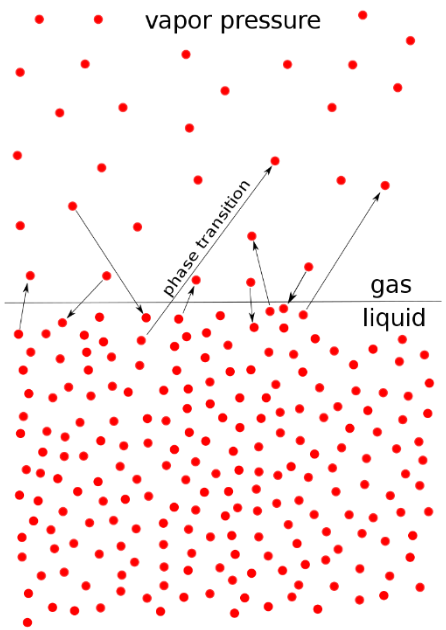


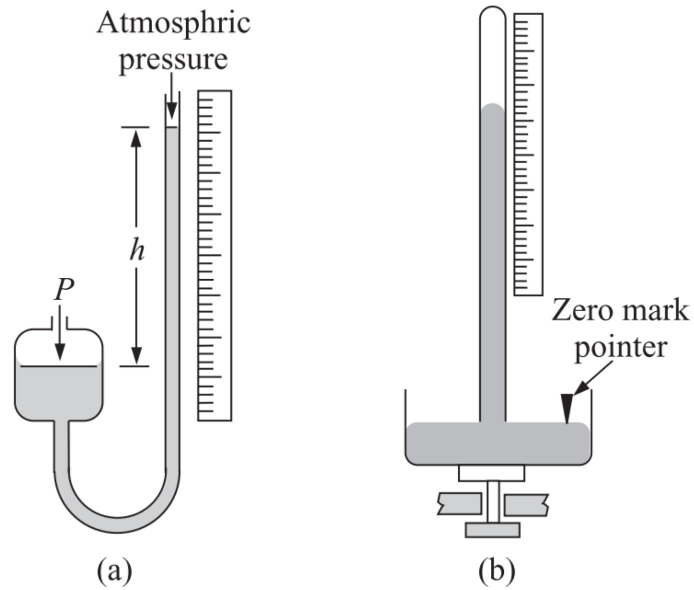
Fig. 8.3 Manometers of different kinds: (a) well-type manometer, and (b) barometer.

Characteristics of manometer fluid

1. Manometer fluid should not wet the wall of the container.
2. It should not absorb gas or chemically react with it.
3. It should be of reasonably high density so that the pressure balancing column stays within a desirable limit.
4. It should have low vapour pressure at the operating temperature.
5. It should freely move in the limbs of the manometer.
6. It should not be compressible.

Manometers





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Inclined-limb Manometer

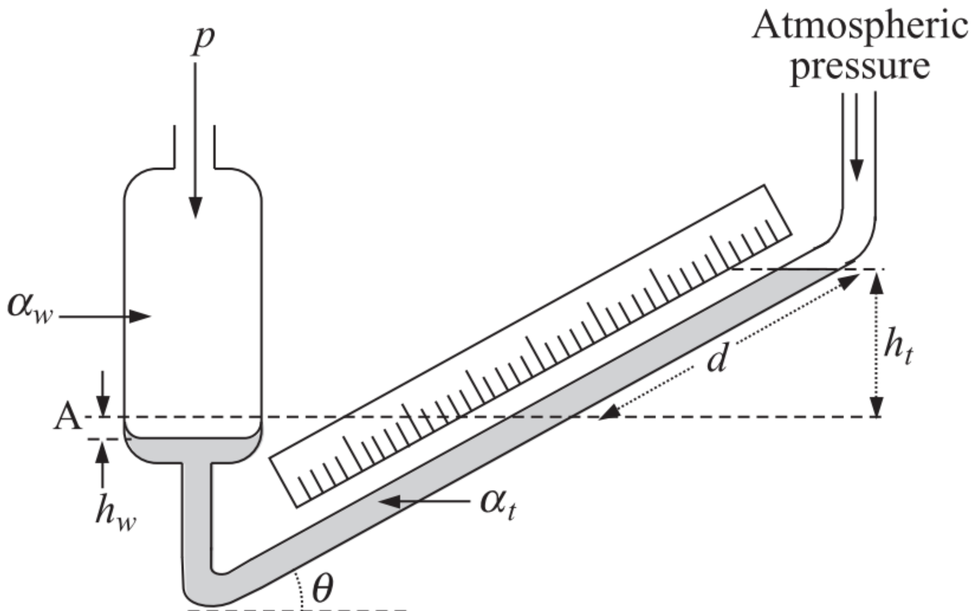


Fig. 8.4 Inclined-limb manometer.

- **If one of the limbs of a manometer is inclined at an angle *θ*, its sensitivity increases**

Inclined-limb Manometer

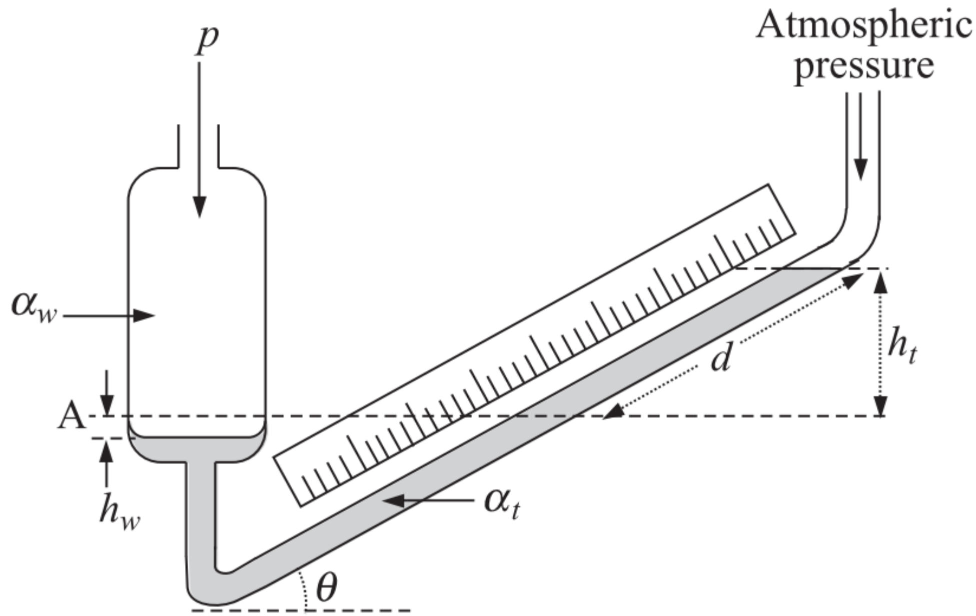


Fig. 8.4 Inclined-limb manometer.

- ❑ **Working**
- ❑ with no pressure difference Δp applied between the limbs of the manometer, the meniscus in each limb is at the same level A
- ❑ With a pressure difference Δp applied, the tube meniscus goes up by a height h_t while the well meniscus goes down by h_w

Inclined-limb Manometer

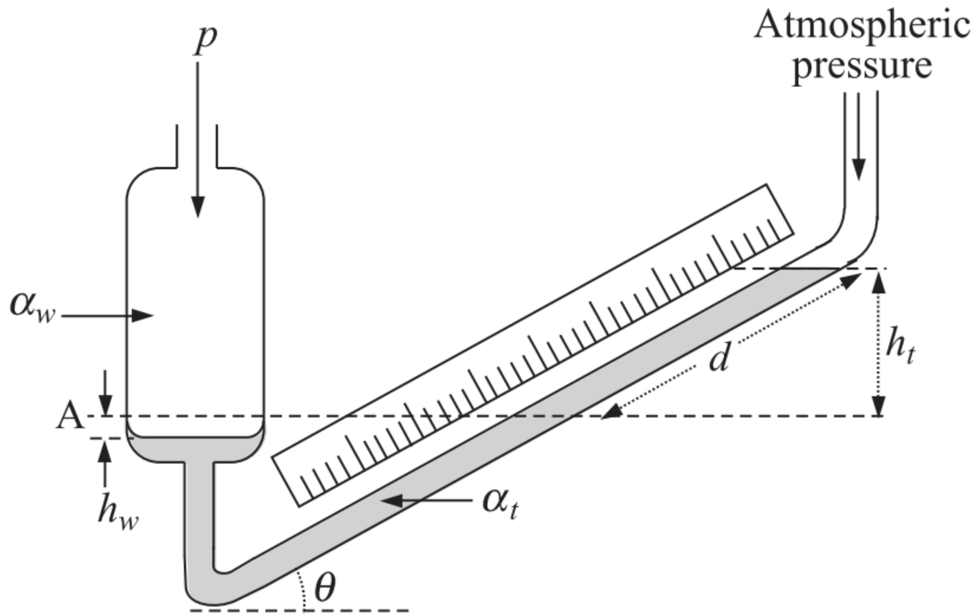


Fig. 8.4 Inclined-limb manometer.

$$\Delta p = (h_t + h_w)\rho g$$

where, ρ is the density of the manometric fluid and g is the acceleration due to gravity.

Inclined-limb Manometer

$$\Delta p = (h_t + h_w)\rho g$$

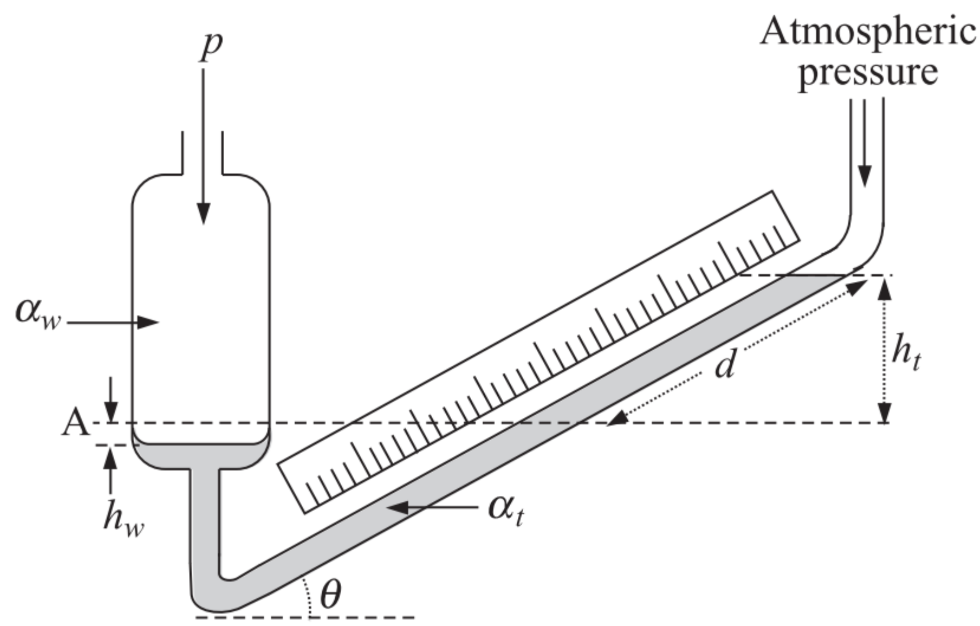


Fig. 8.4 Inclined-limb manometer.

Now, if α_t and α_w are cross-sectional areas of the tube and well respectively, and d is the distance moved by the meniscus in the tube, we get from the continuity of volume,

$$\alpha_w h_w = \alpha_t d = \alpha_t \frac{h_t}{\sin\theta} \qquad [\because\ h_t = d\sin\theta]$$

Inclined-limb Manometer

$$\begin{cases} \Delta p = (h_t + h_w)\rho g \\ \alpha_w h_w = \alpha_t d = \alpha_t \dfrac{h_t}{\sin\theta} \end{cases} \qquad [\because\ h_t = d\sin\theta]$$

- **Combining two, we get**

$$\Delta p = d\left(\sin\theta + \frac{\alpha_t}{\alpha_w}\right)\rho g$$

$$\cong d\rho g \sin\theta \qquad [\text{since } \alpha_w \gg \alpha_t]$$

$$= h_t \rho g$$

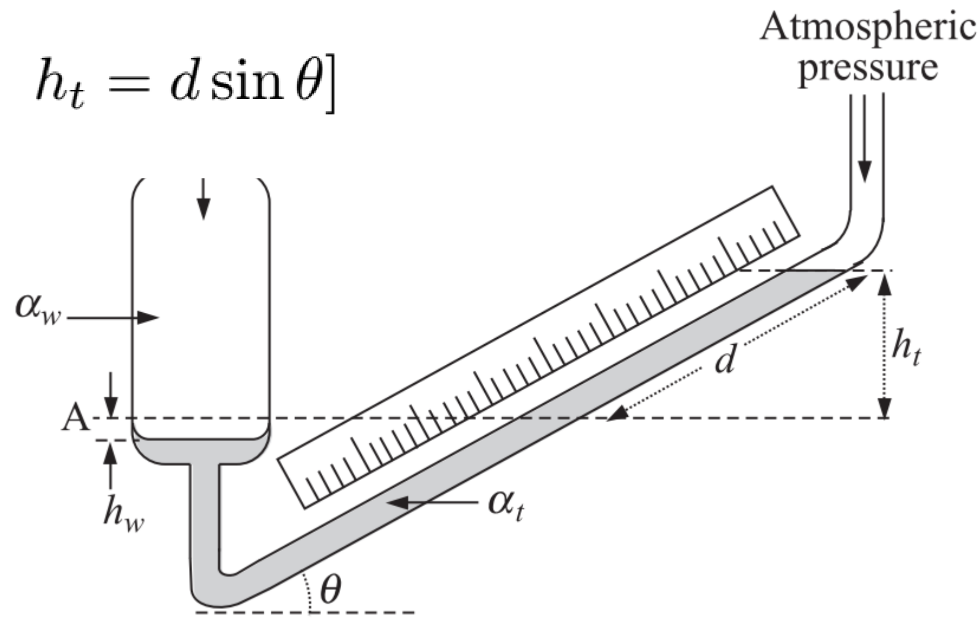


Fig. 8.4 Inclined-limb manometer.

Inclined-limb Manometer

$$\Delta p = (h_t + h_w)\rho g$$

$$\Delta p = d\left(\sin\theta + \frac{\alpha_t}{\alpha_w}\right)\rho g$$

$$\cong d\rho g \sin\theta \qquad\qquad [\text{since } \alpha_w \gg \alpha_t]$$

$$= h_t \rho g$$

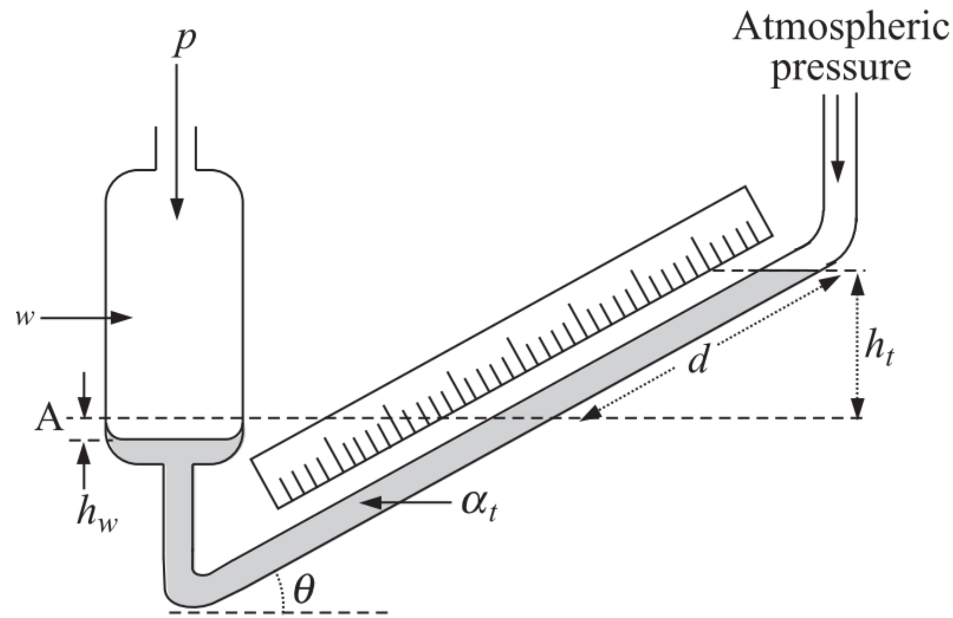


Fig. 8.4 Inclined-limb manometer.

- Pressure difference can be measured by measuring either h_t or d
- Since, $h_t = d \sin\theta$, if θ is 30º, $d = 2h_t$ for the same Δp,
  - measuring d will increase the sensitivity of the instrument

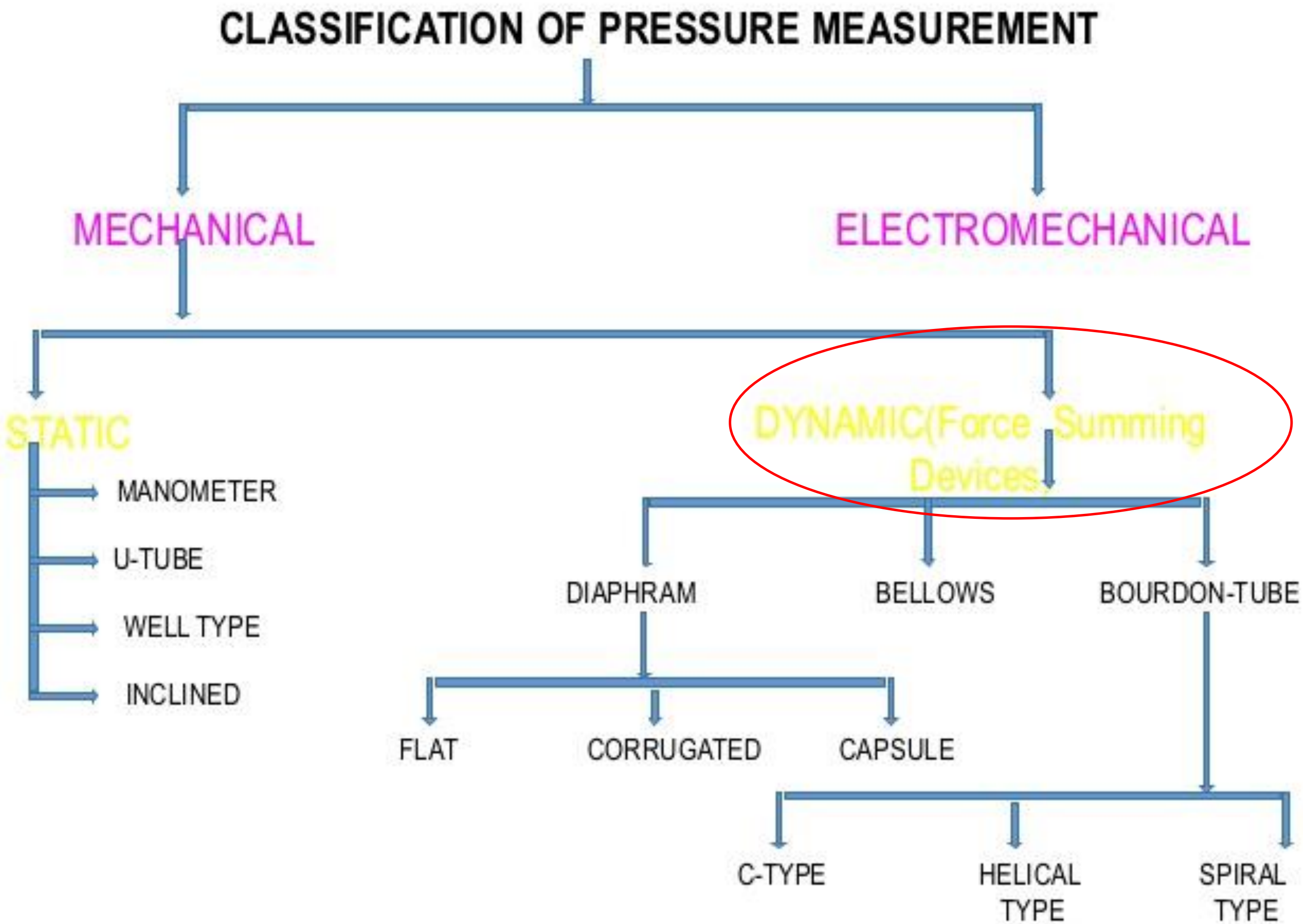
Manometers

Advantages of manometers

1. Manometers are considered as standards of pressure by many standardising institutions.
2. They are simple and low cost devices.
3. Suitable sensors such as capacitance or sonar devices can be used to provide better precision in their readouts.

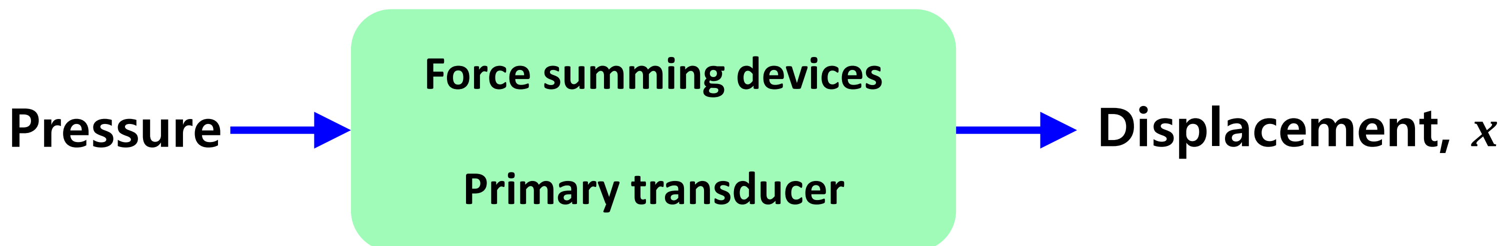
Sources of error in using manometers

1. Surface tension of manometer fluids, causing capillary effects, may give wrong readings.
2. Thermal expansion of the fluid as well as of the readout scale may cause error.
3. Compressible fluid may change calibration.
4. Evaporated fluid at low pressure and high temperature can interfere in measurement.


CLASSIFICATION OF PRESSURE MEASUREMENT
MECHANICAL
ELECTROMECHANICAL
STATIC
MANOMETER
U-TUBE
WELL TYPE
INCLINED
DYNAMIC(Force Summing Devices)
DIAPHRAM
BELLOWS
BOURDON-TUBE
FLAT
CORRUGATED
CAPSULE
C-TYPE
HELICAL TYPE
SPIRAL TYPE

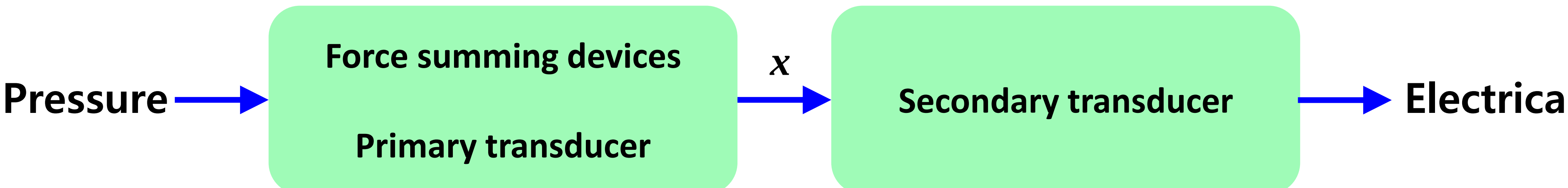
Pressure Measurement

- Force-summing Devices
    - Convert the applied pressures to displacements
        - primary transducers



Pressure Measurement

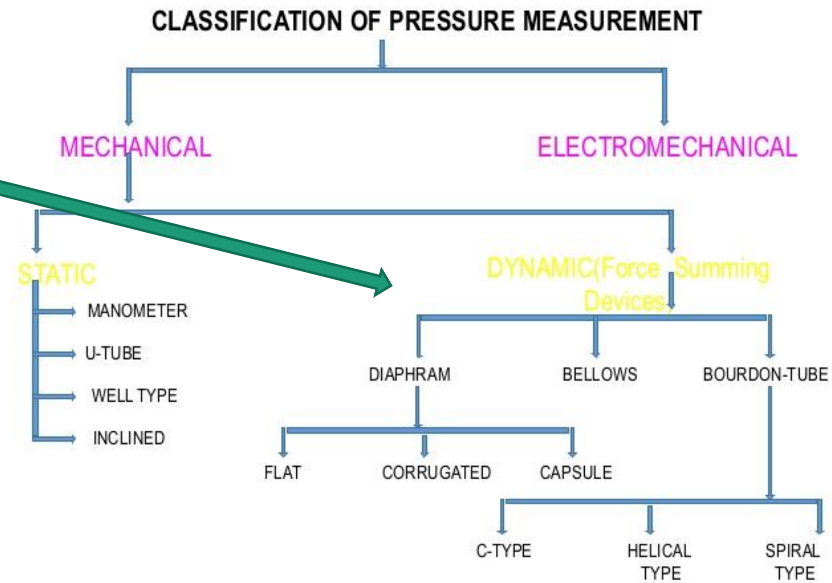
- **Force-summing Devices**
  - Convert the applied pressures to displacements
    - primary transducers
- **Generated displacements may be measured by secondary transducers**
  - secondary transducers



Pressure Measurement

- ❑ **Force Summing Devices**
  - ❑ **Convert the applied pressures to displacements**
    - ❑ **Primary transducers**

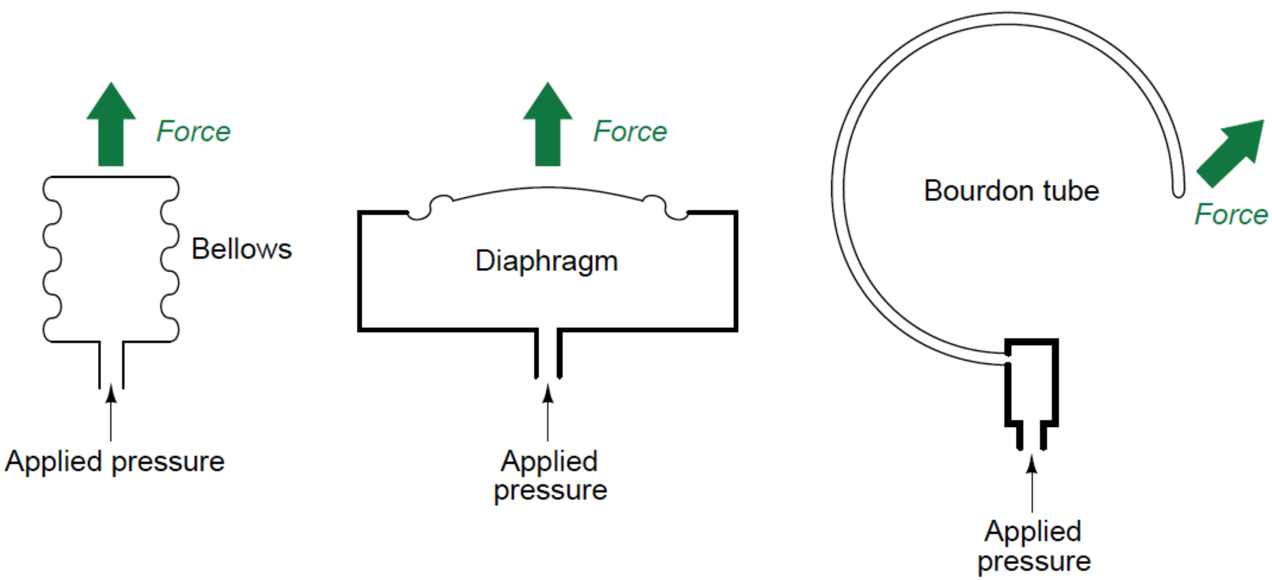
1. Diaphragms
2. Bellows
3. Bourdon gauge



Pressure Measurement

- **Force Summing Devices**
  - **Convert the applied pressures to displacements**
    - **Primary transducers**

1. Diaphragms
2. Bellows
3. Bourdon gauge



Moderate Pressure Measurement

Classification of Pressure Measuring Instrument

Type of pressure to be measured	Pressure Measuring instrument to be used
Low pressure	Manometer
High and medium pressure	Bourdon tube pressure gauge. Diaphragm gauge. Bellows Gauges.
Low vacuum and ultra high vacuum	Mcleod vacuum gauge thermal conductivity gauges. Ionisation gauges.
Very high pressure	Bourdon tube pressure gauge. Diphragm gauge. Bulk modulus pressure gauge.

- Low pr (Below 1 mm of Hg)- manometer and low pr gauges
- Medium and low (between 1mm of Hg 1000 atm)- Bourdon gauge and Diaphragm gauges
- Low vacuum and ultra high vacuum(760 torr to 10 raise to -9 torr and beyond)- McLeod, thermal conductivity and ionisation gauge
- Very high pr (1000 atm and above)- Bourdon gauge,Diaphragm and electrical pr gauges

Force Summing Devices

- **Diaphragms**
  - Circular metal discs
  - Flexible elements such as rubber, plastic or leather
    - transmitter of pressure to an opposing element such as a spring

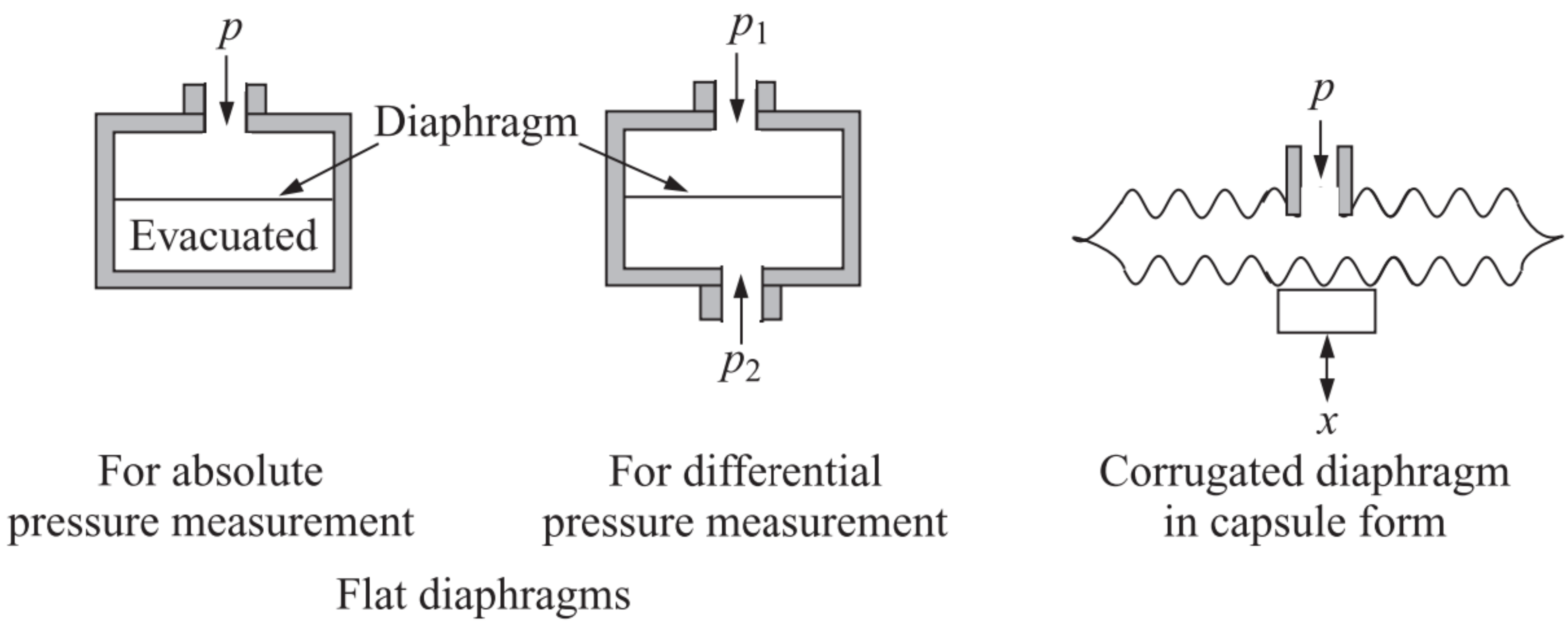
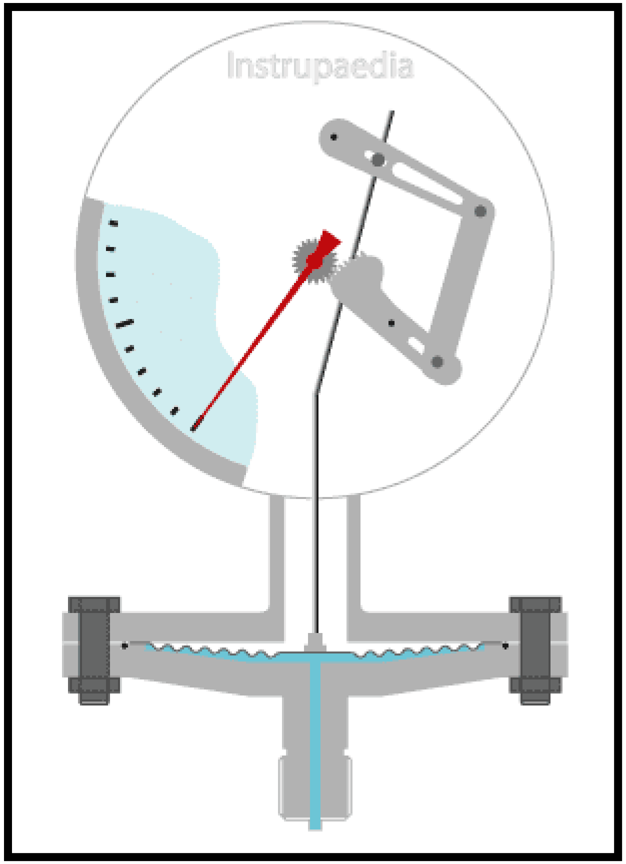
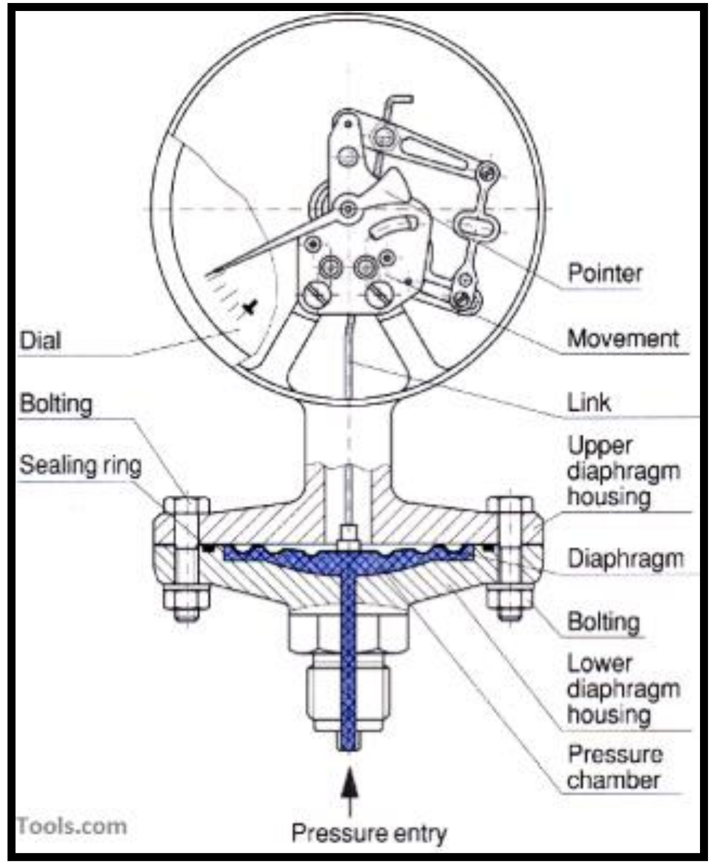


Fig. 8.8 Diaphragms of different kinds.

Elastic Transducer: Diaphragms





Elastic Transducer: Diaphragms

- Theoretical relationship between displacement of diaphragm and pressure is.

$$x \propto \Delta \mathrm{P} \quad \text{for } x < \frac{\mathrm{d}}{3}$$

  - ‘d’ is a thickness of the diaphragm
  - ‘x’ is its deflection owing to the application of pressure
  - Pressure applied is ΔP.

- Displacement can be experimentally calibrated against the pressure.

- Diaphragm can measure pressures up to 7 MPa.

Force Summing Devices

- **Diaphragms**
  - Corrugated diaphragms give a larger displacement
  - two of them can be soldered together at the outer edges to form capsules
  - For a given pressure, a capsule generates a displacement which is twice as large as that of a single diaphragm

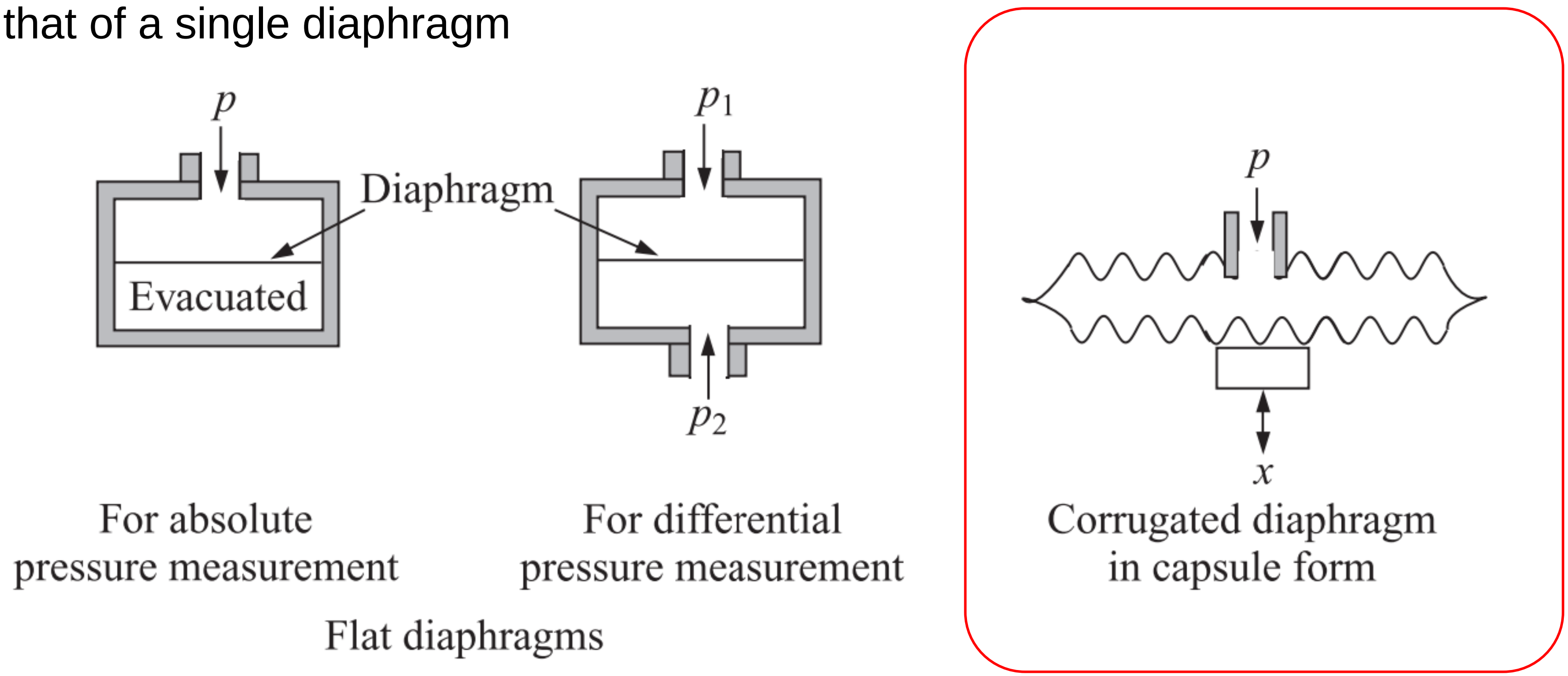


Fig. 8.8 Diaphragms of different kinds.

Force Summing Devices

- ❑ **Diaphragms**

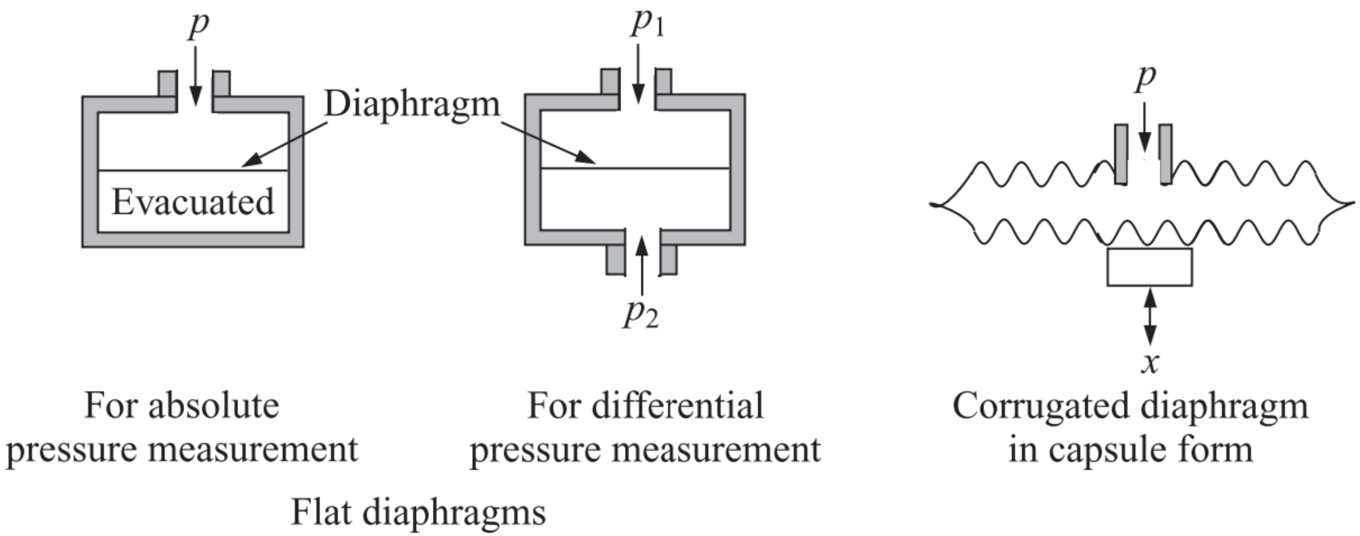


Fig. 8.8 Diaphragms of different kinds.

- ❑ **Features**

- ❑ Diaphragms sensors are very sensitive up to 0.01 MPA to rapid pressure change
- ❑ metal type can measure pressures up to 7 MPa
- ❑ elastic type can have ranges from 0–0.1 kPa to 0–2.2 MPa
  - ❑ can be in corrosive environments or extreme over-pressure situations

Force Summing Devices

- **Bellows**
  - thin-walled cylindrical shells with deep convolutions and sealed at one end
  - sealed end suffers axial displacement with pressure applied at the open **end**

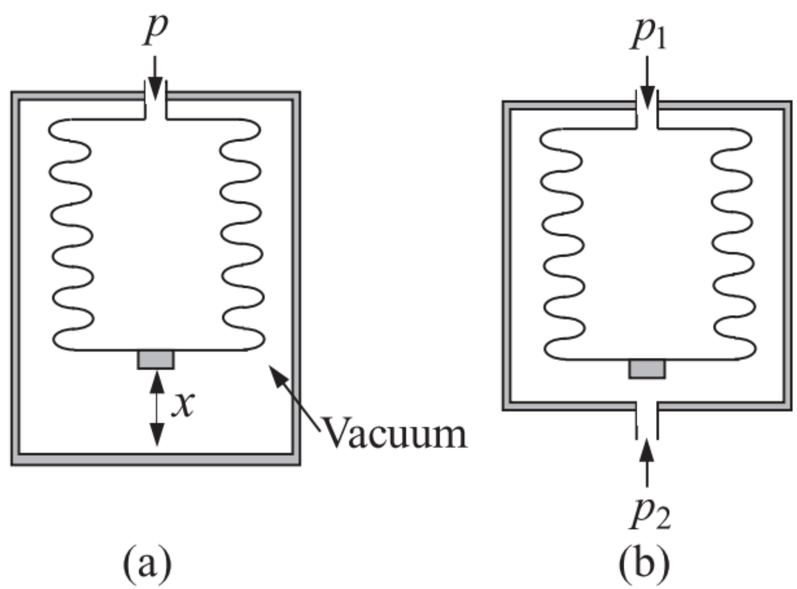


Fig. 8.10 Schematic view of bellows: (a) for absolute pressure measurement, and (b) for differential pressure measurement.

Force Summing Devices

- **Bellows**

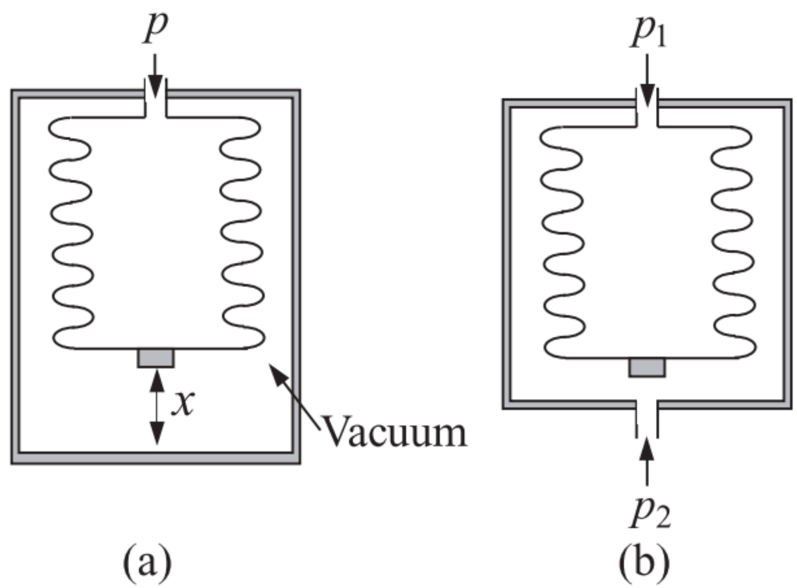


Fig. 8.10 Schematic view of bellows: (a) for absolute pressure measurement, and (b) for differential pressure measurement.

- Absolute Pressure
- can be measured by evacuating either the exterior or interior space of the bellows and then measuring the pressure at the opposite side

Force Summing Devices

- **Bellows**

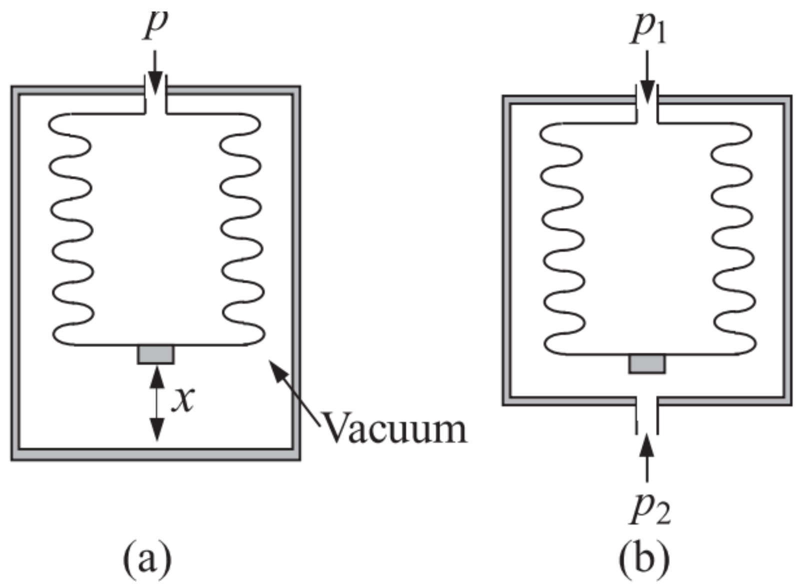
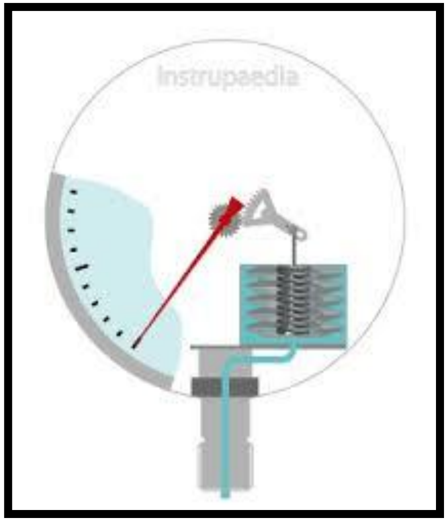
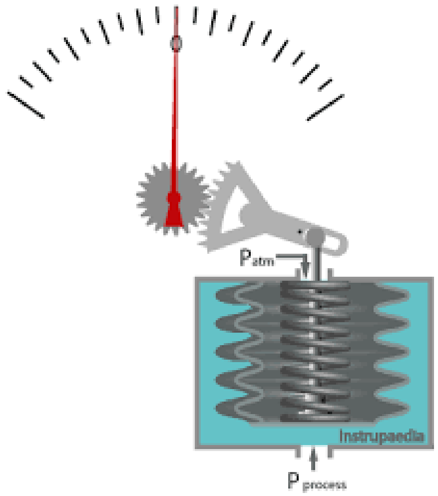


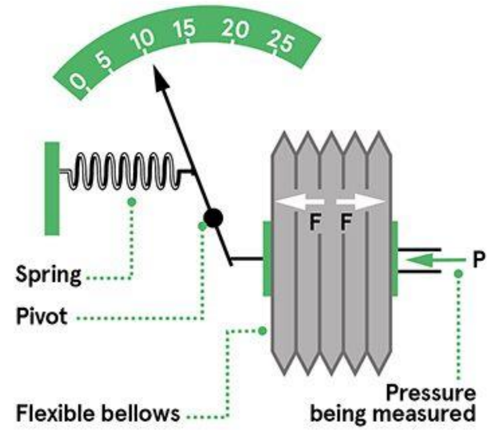
Fig. 8.10 Schematic view of bellows: (a) for absolute pressure measurement, and (b) for differential pressure measurement.

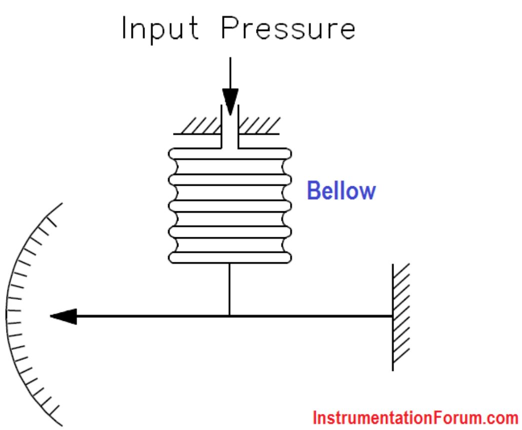
- Features
- Bellows can only be connected to an on/off switch or potentiometer
- used at low pressures, < 0.2 MPa

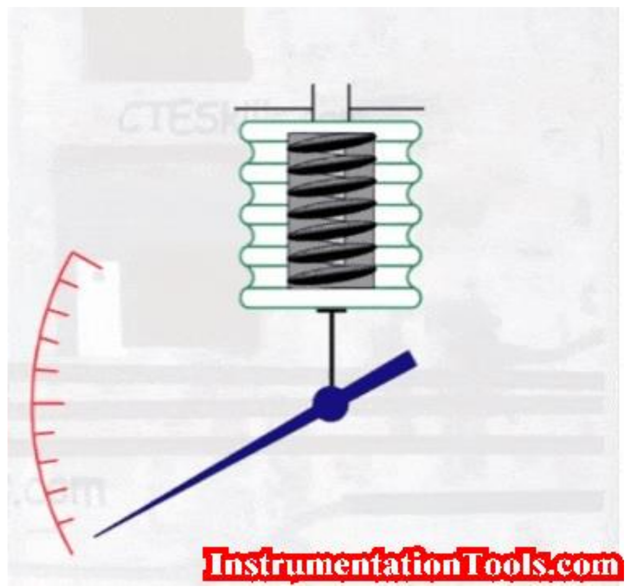
Elastic Transducer: Bellows











https://instrumentationtools.com/bellows-pressure-sensors-working-principle-animation/

Force Summing Devices

- **Bourdon Tubes**
  - they are constructed of tubes of non-circular cross-section

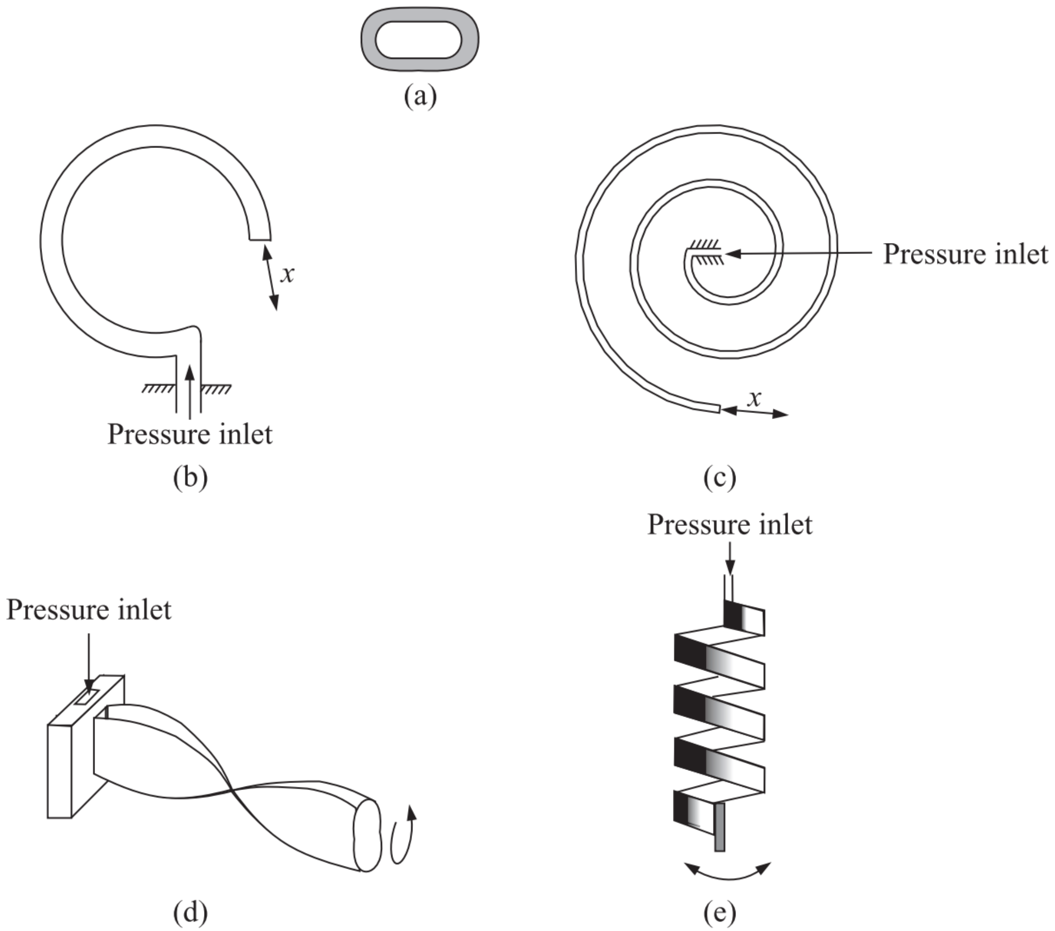
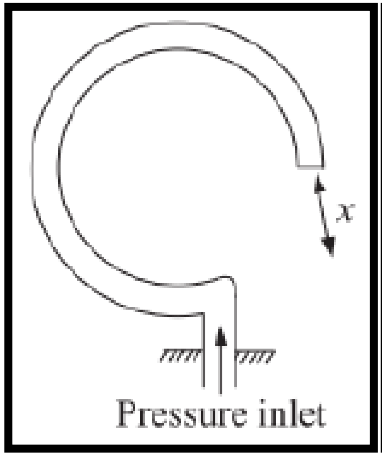
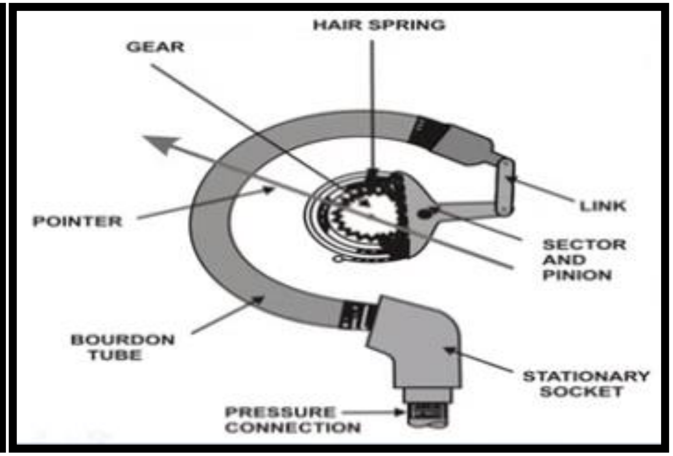
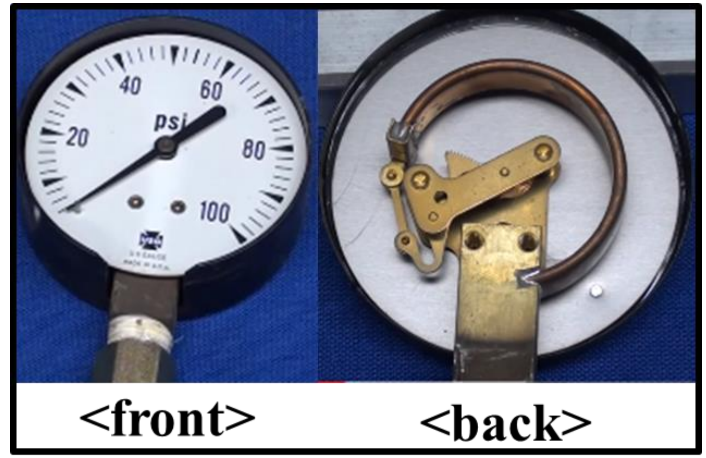


Fig. 8.12 (a) Non-circular cross-section of Bourdon tubes. Bourdon tubes of different shapes: (b) C-type, (c) spiral type (d) twisted-tube type, and (e) helical type.

Elastic Transducer: C Type Bourdon Tube







- Bourdon tube has a hollow , elliptical cross section.
- It is closed at one end and pressure is applied at the open end.
- When pressure is applied, its cross section becomes more circular, causing the tube to straighten out until the fluid pressure is balanced by the elastic resistance of the tube material.
- Open end of the tube is fixed whereas the closed end moves upon application of pressure.

Force Summing Devices

- **Bourdon Tubes**

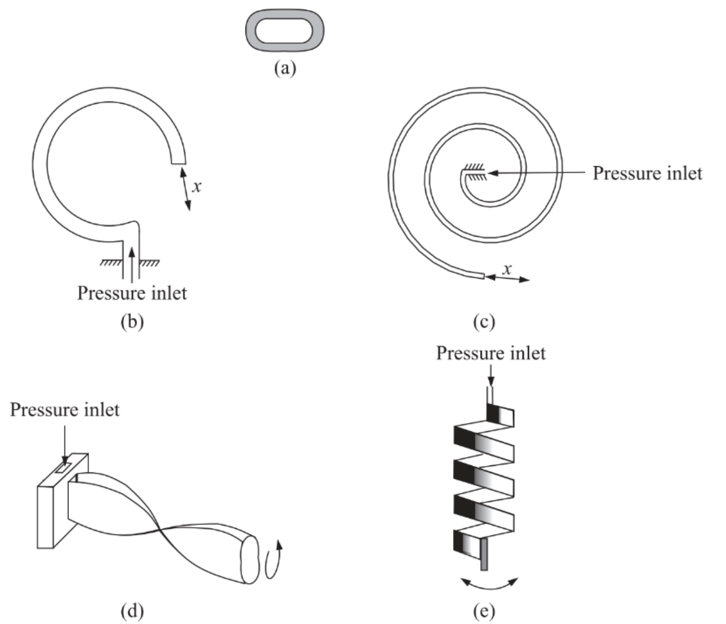


Fig. 8.12 (a) Non-circular cross-section of Bourdon tubes. Bourdon tubes of different shapes: (b) C-type, (c) spiral type (d) twisted-tube type, and (e) helical type.

- Construction materials
- stainless steel is used to construct tubes for ordinary ranges
- for higher ranges phosphor bronze is used

Force Summing Devices

- **Bourdon Gauge**
  - C-type Bourdon tube
  - Pressure is applied to fixed end
  - Opposite, sealed end moves to give pressure readings

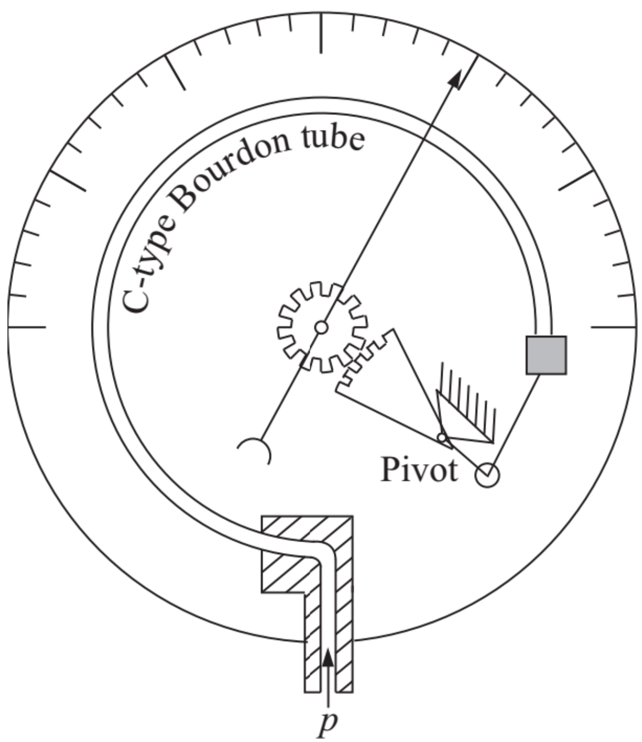


Fig. 8.13 Schematic diagram of a pressure gauge using a C-type Bourdon tube.

Force Summing Devices

- **Bourdon Gauge**

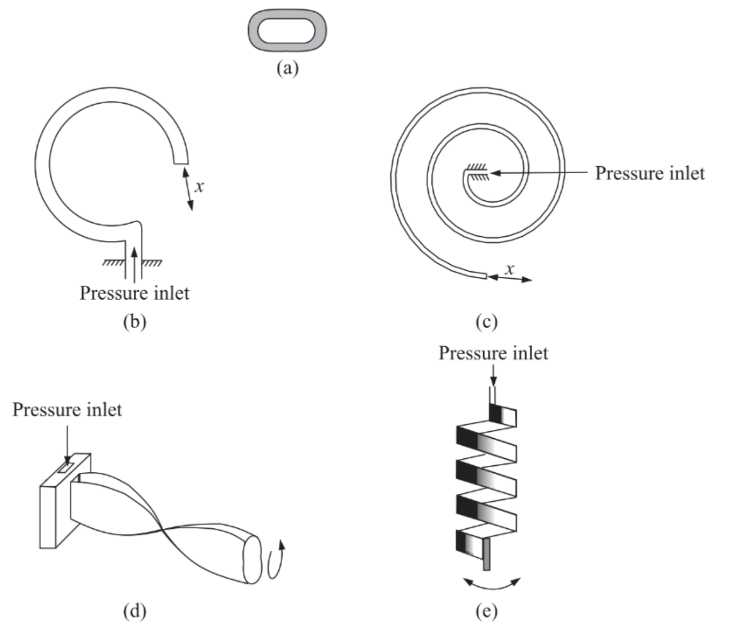


Fig. 8.12 (a) Non-circular cross-section of Bourdon tubes. Bourdon tubes of different shapes: (b) C-type, (c) spiral type (d) twisted-tube type, and (e) helical type.

- Range

- a pressure range from 0.1 to 700 Mpa

Force Summing Devices

- ❑ **Bourdon Gauge**

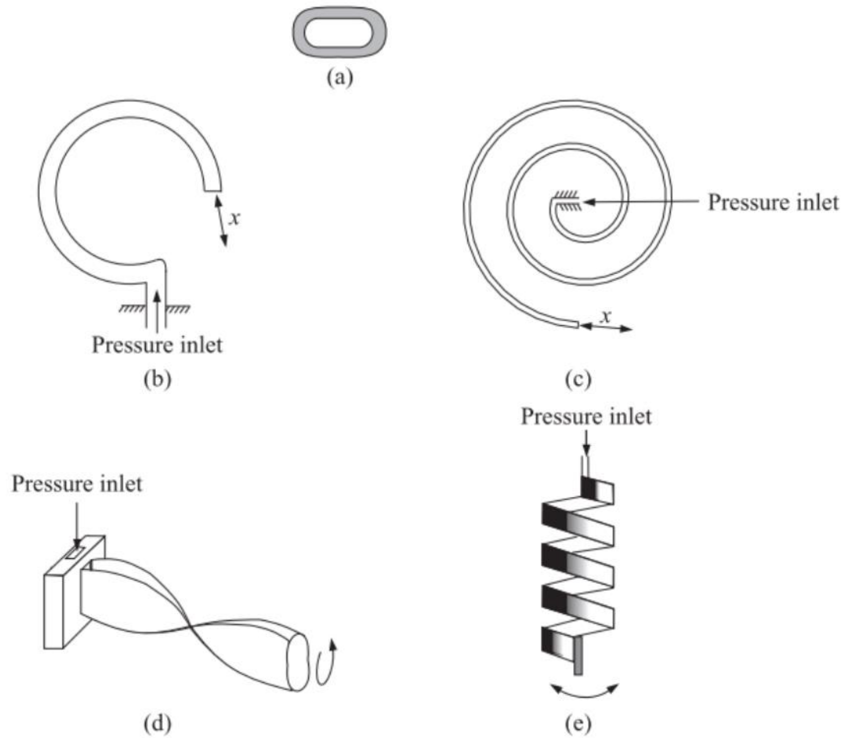


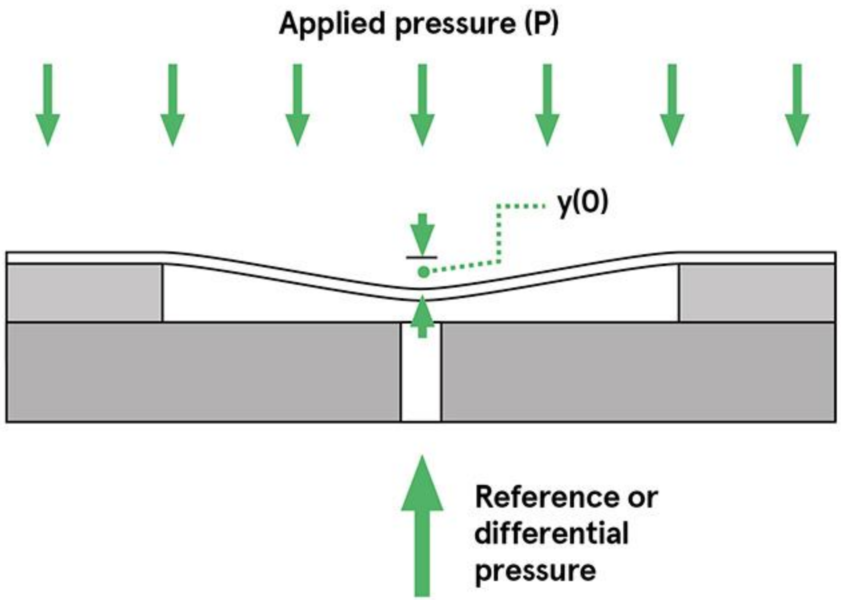
Fig. 8.12 (a) Non-circular cross-section of Bourdon tubes. Bourdon tubes of different shapes: (b) C-type, (c) spiral type (d) twisted-tube type, and (e) helical type.

Features

- ❑ measures gauge pressure
- ❑ vacuum is sensed as a reverse motion
- ❑ portable and require little maintenance

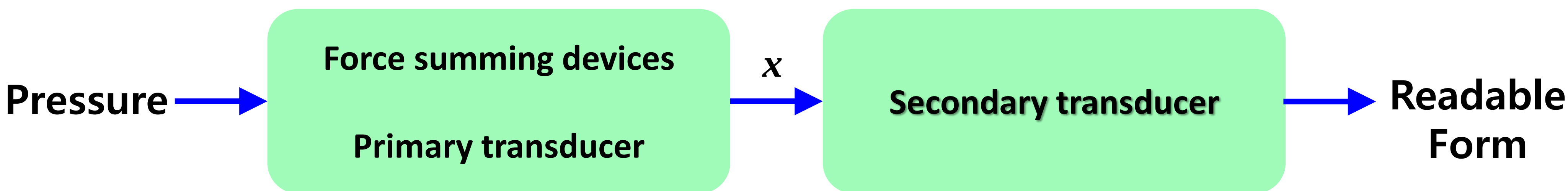
Force Summing Devices

- **MEMS Membrane**
  - **converts pressure into displacement**



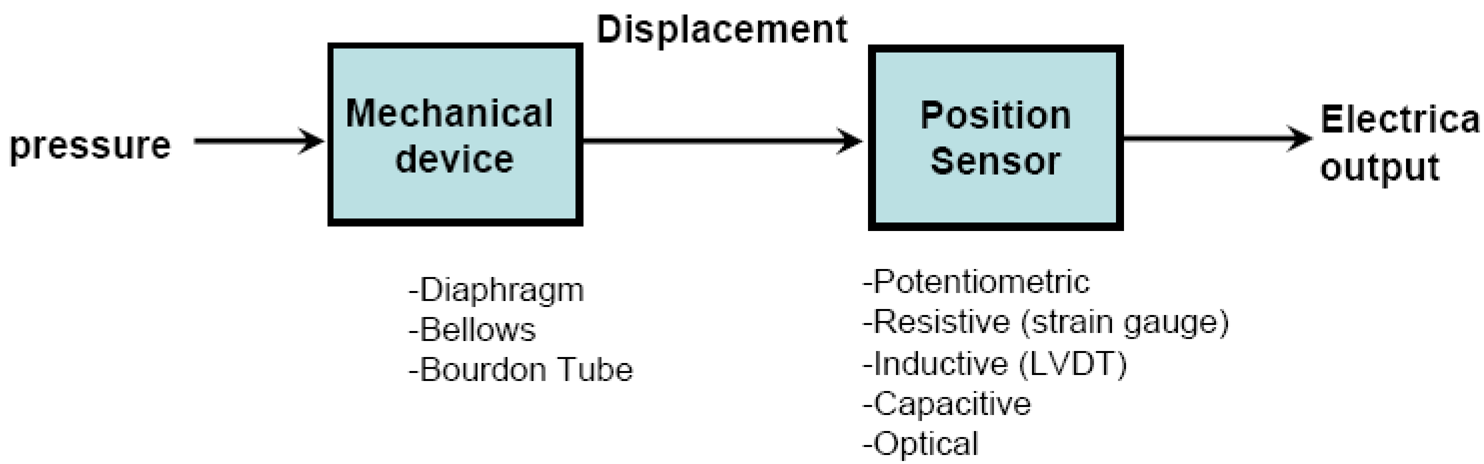
Pressure Measurement

- **Secondary Transducers**
  - **Convert the displacement produced by force-summing devices into a readable format**



Secondary Transducers

- Elastic transducers convert pressure into displacement.
- Displacement is converted into readable output using secondary transducers such as.
  - **Mechanical**
  - **Resistive**
  - **Inductive**
  - **Capacitive**



Pressure Measurement

- **Secondary Transducers**
  - **Convert the displacement produced by force-summing devices into a readable format**

1. Mechanical
2. Resistive
3. Inductive
4. Capacitive
5. Photoelectric
6. Piezoelectric
7. Hall effect based
8. Vibrating element
9. Surface acoustic wave type

Secondary Transducers: Mechanical

- Utilize the displacement generated by force-summing devices to mechanically rotate a pointer in front of a dial
- Can be utilized with a Bourdon tube, a diaphragm or a bellows

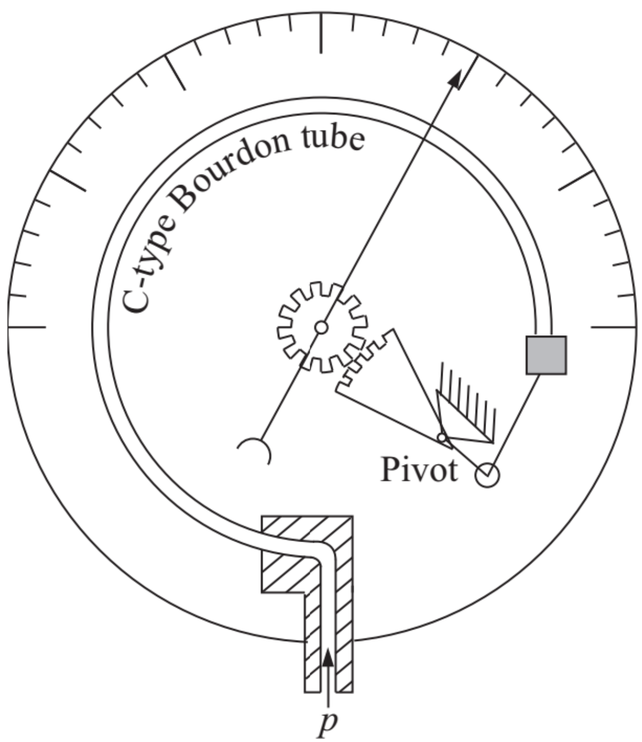


Fig. 8.13 Schematic diagram of a pressure gauge using a C-type Bourdon tube.

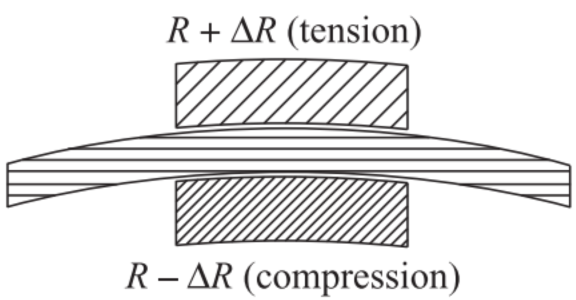
Secondary Transducers: Resistive

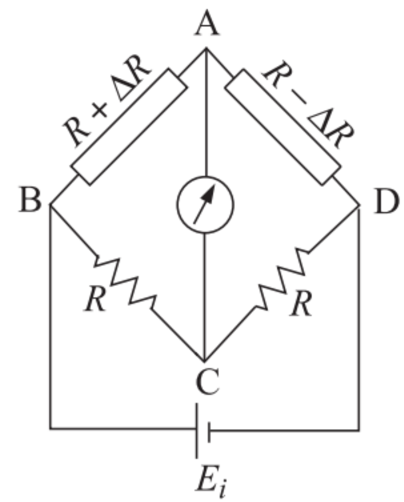
- The resistive secondary transducers are generally of two types:

  1. strain gauge
  2. potentiometer

Secondary Transducers: Resistive

- Strain gauge type
- Bonding two strain gauges, one on the top and another at the bottom side, to a diaphragm
- Connecting to two arms of a Wheatstone bridge in a half-bridge arrangement





Secondary Transducers: Resistive

- Strain gauge type
- Bonding two strain gauges, one on the top and another at the bottom side, to a diaphragm
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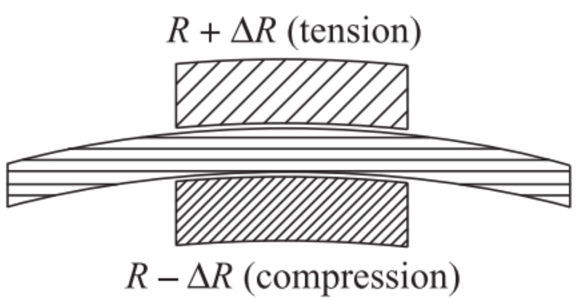
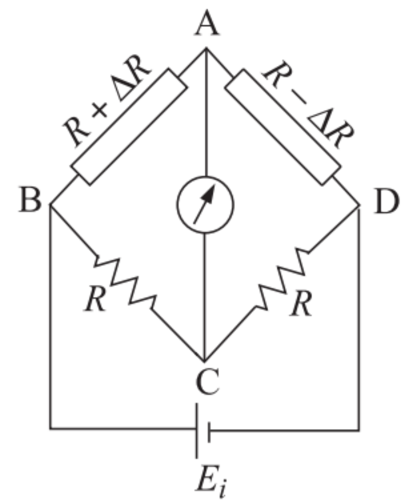




$$\Delta E_o = \left[\frac{R+\Delta R}{(R+\Delta R)+(R-\Delta R)} - \frac{1}{2}\right] E_i$$

$$= \frac{\Delta R}{2R} E_i$$

$$= \frac{G_f \varepsilon}{2} E_i$$

Secondary Transducers: Resistive

- Strain gauge type
  - Wire wound

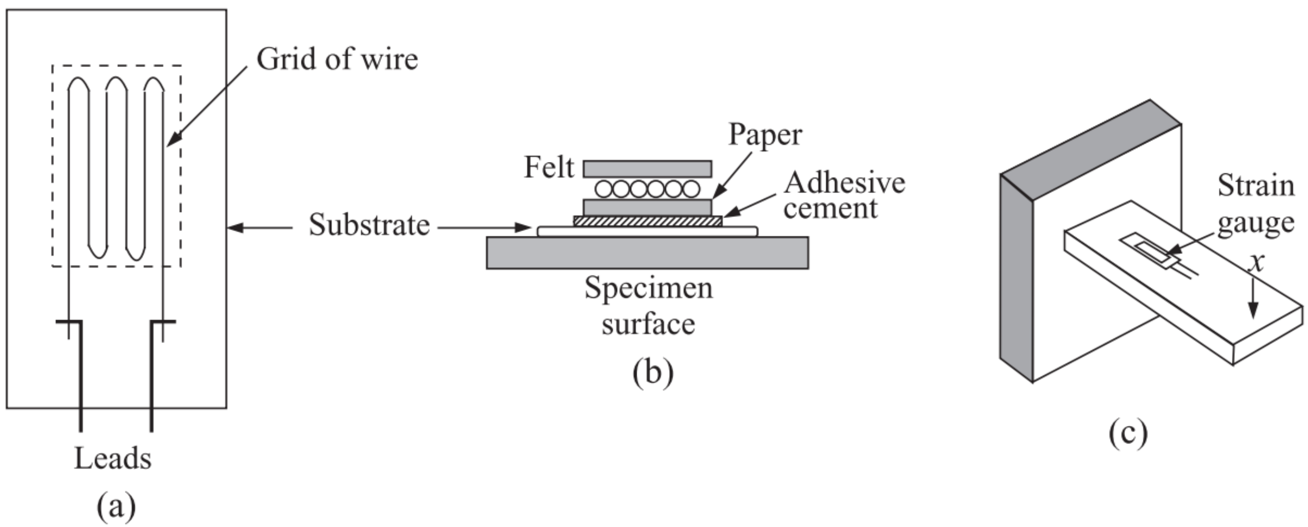


Fig. 7.3 Schematic view of a bonded strain gauge: (a) construction, (b) bonding on the surface, and (c) actual placement.

Secondary Transducers: Resistive

- ❑ **Strain gauge type**
  - ❑ **Wire wound**

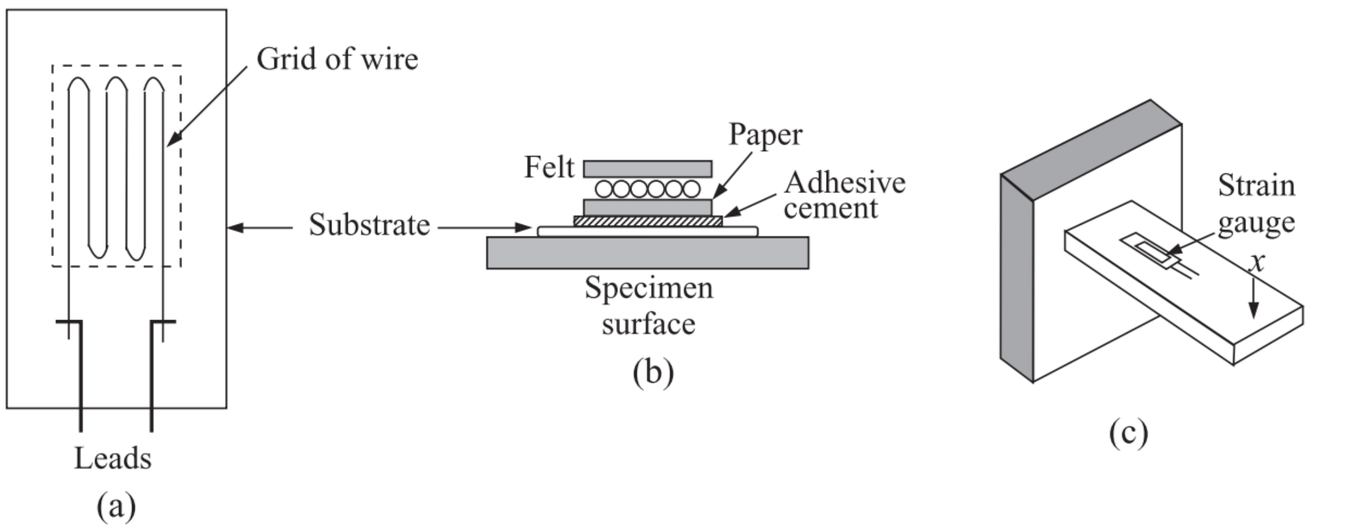


Fig. 7.3 Schematic view of a bonded strain gauge: (a) construction, (b) bonding on the surface, and (c) actual placement.

- ❑ **Issue**
  - ❑ bond between the diaphragm and the wire filament degrades with time causing changes in calibration

Secondary Transducers: Resistive

- **Strain gauge type**
  - **foil type**

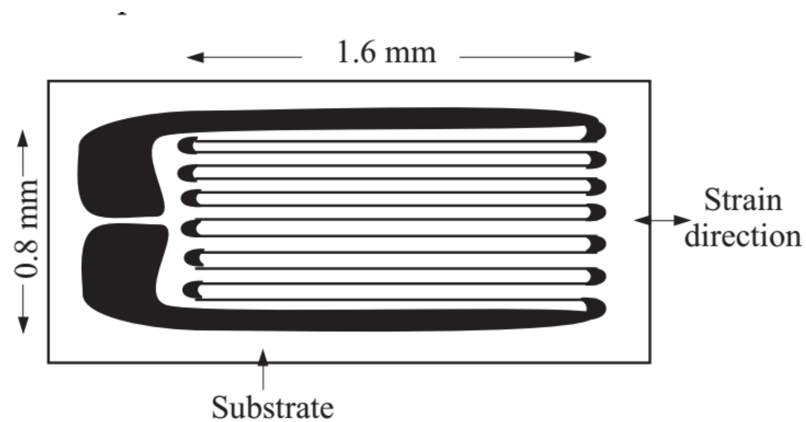


Fig. 7.5 Foil type strain gauge.

- **Issue**
  - bond between the diaphragm and the wire filament degrades with time causing changes in calibration

Secondary Transducers: Resistive

- ❑ **Strain gauge type**

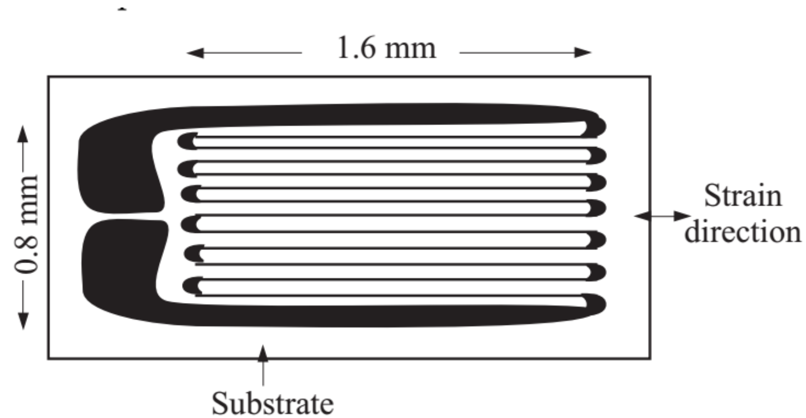
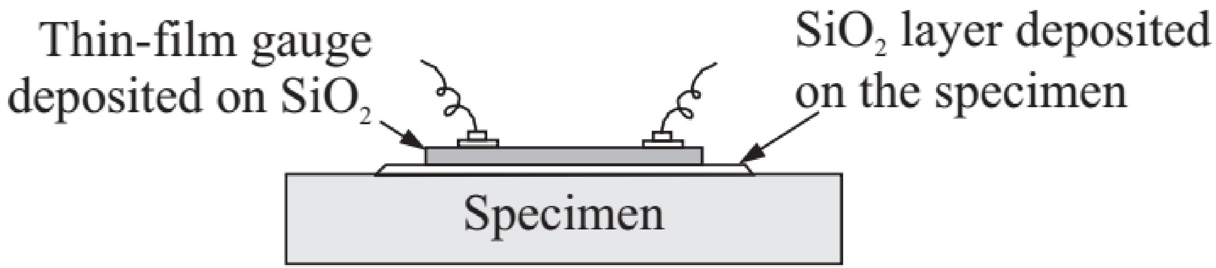


Fig. 7.5 Foil type strain gauge.

- ❑ **Bonding Issue**
  - ❑ Solution: introduction of bonded thin-film and diffused semiconductor strain gauges

Secondary Transducers: Resistive

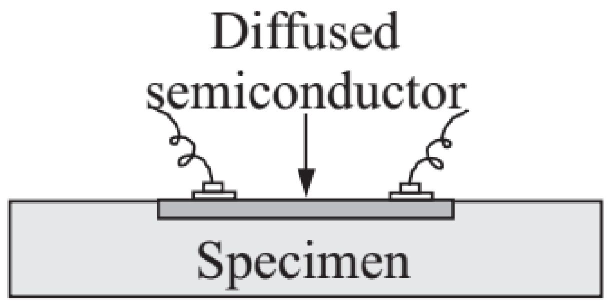
- **Semiconductor Type Gauges**



- adhesive is not required
- molecular bonding
    - much more stable
- specimen can either be a thin diaphragm or a thick beam

Secondary Transducers: Resistive

- **Semiconductor Type Gauges**



- Diffused semiconductor
  - no bonding issues
- used as sensing elements in pressure transducers

Secondary Transducers: Resistive

- Strain gauge type
- The general arrangement of using a strain gauge for measuring a differential pressure

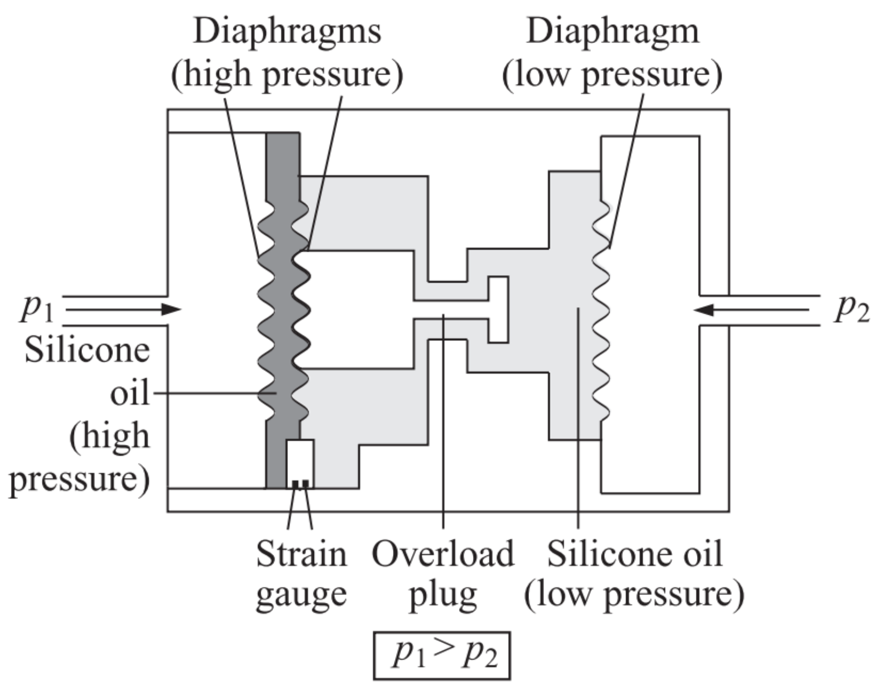


Fig. 8.14 Schematic diagram of a differential pressure gauge using a strain gauge.

Secondary Transducers: Resistive

- **Potentiometer type**
- converts the mechanically detected deflection of the force-summing device into a resistance measurement using a Wheatstone bridge circuit
- force-summing device: bellows, Bourdon tube or diaphragm

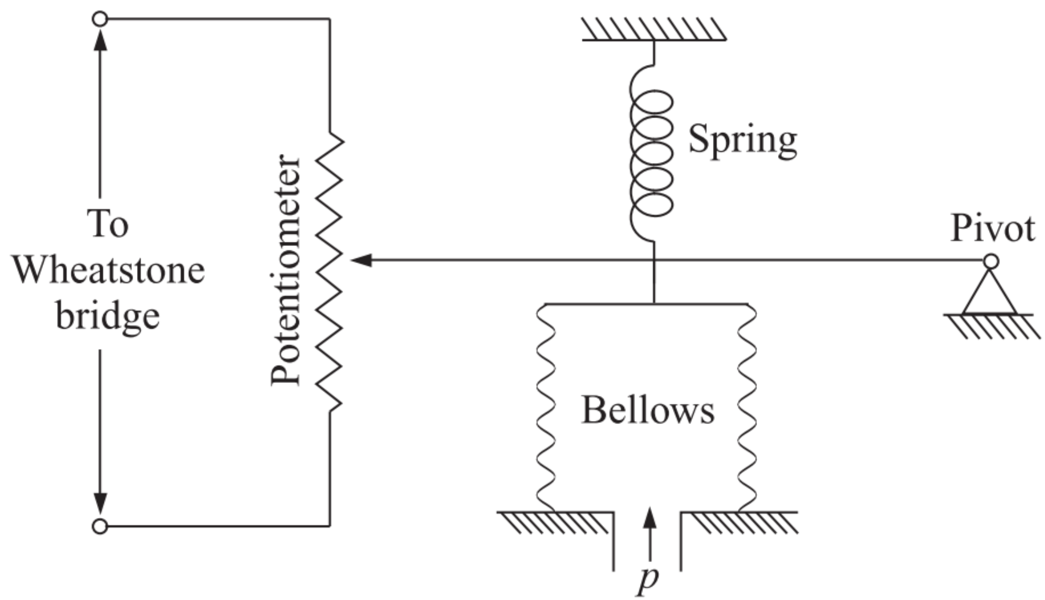


Fig. 8.15 Potentiometer type secondary transducer using a bellows force-summing device.

Secondary Transducers: Resistive

- ❑ **Potentiometer type**

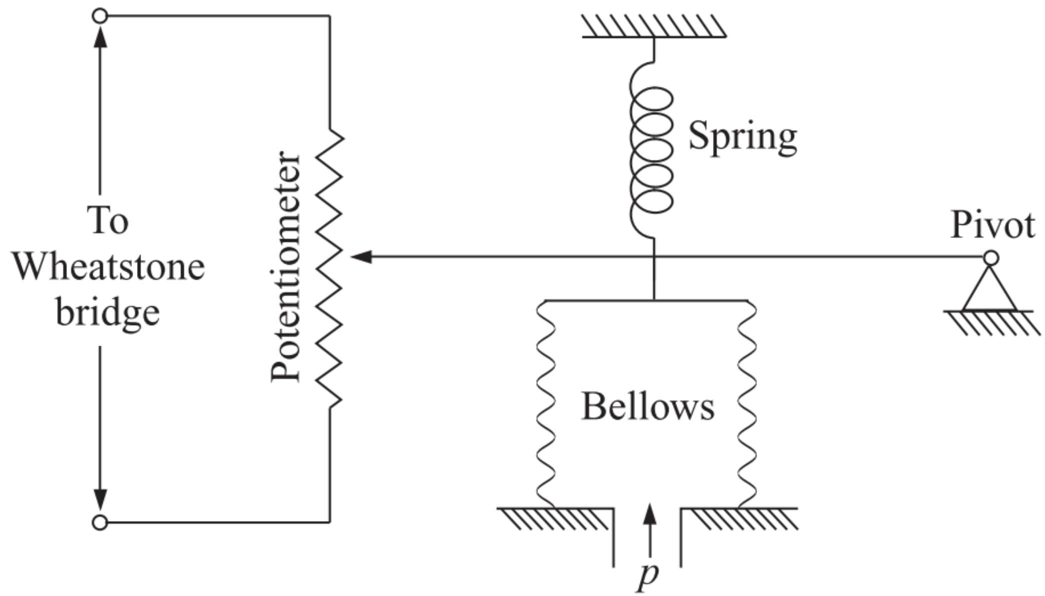


Fig. 8.15 Potentiometer type secondary transducer using a bellows force-summing device.

- ❑ **Issues**

- ❑ threshold problem: mechanical nature of the linkage between the wiper arm and the force-summing device

- ❑ temperature effects introduce errors

Secondary Transducers: Inductive

- LVDTs can be used in conjunction with bellows or Bourdon tubes to measure pressure

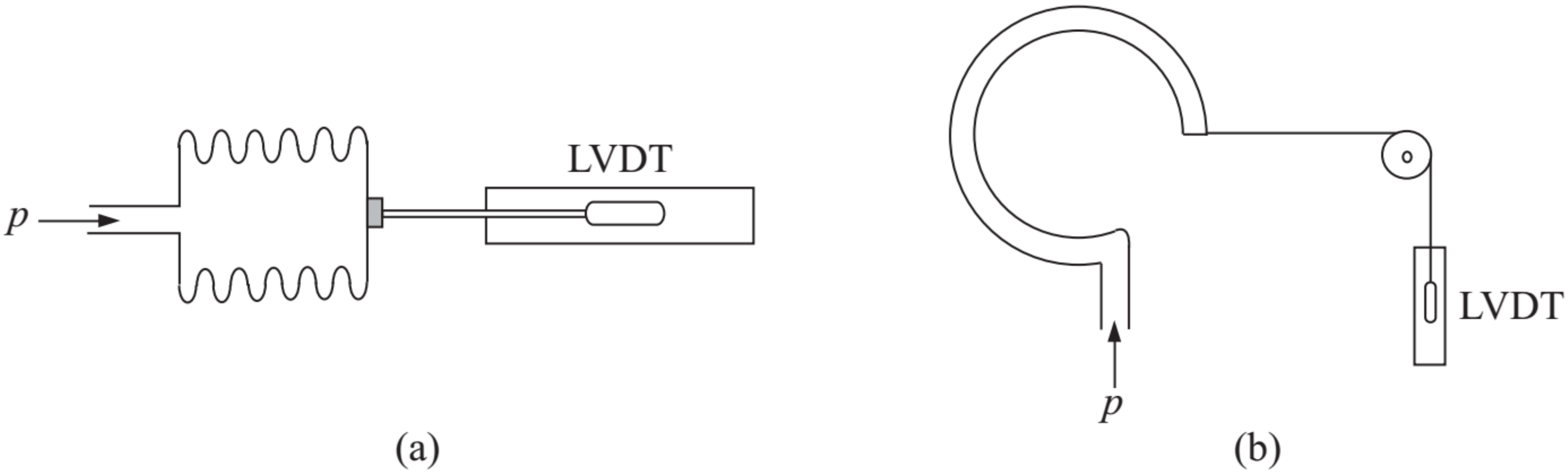
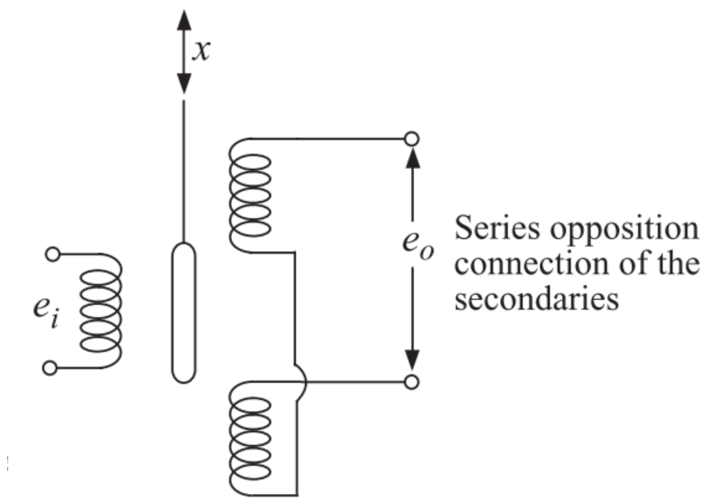


Fig. 8.16 LVDT as secondary transducer used in conjunction with (a) bellows, and (b) Bourdon tube.

Linear variable differential transformer

- ❑ Working mechanism

- ❑ Secondary windings are connected in series opposition: their voltages cancel each other to produce a null voltage



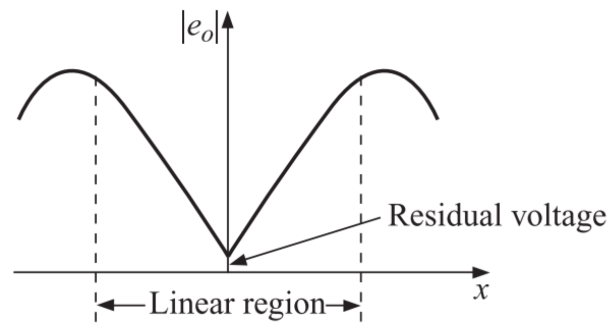


Fig. 6.12 Magnitude of output voltage for core displacement of an LVD

Secondary Transducers: Inductive

- Another arrangement: diaphragm alters the reluctance of the flux path of two coils on application of a pressure difference
- diaphragm is made of magnetic material

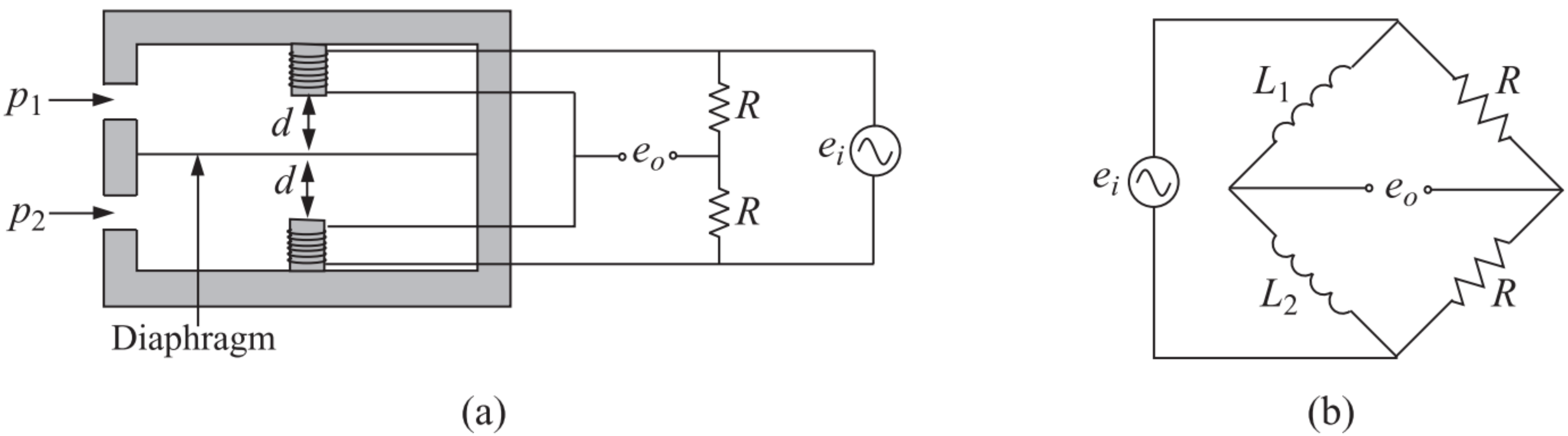
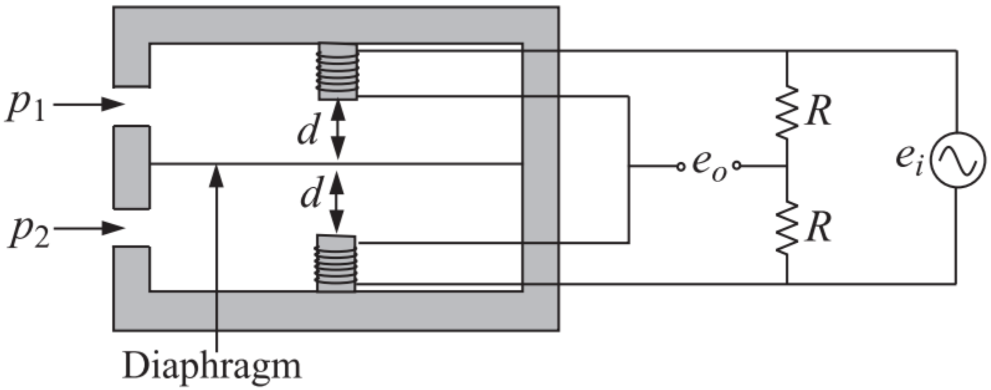
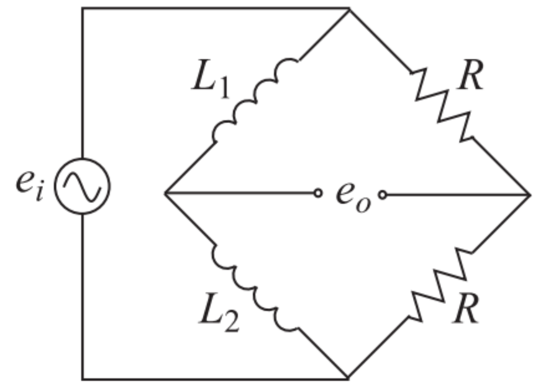


Fig. 8.17 Inductive secondary transducer for pressure measurement: (a) schematic diagram of the transducer and the circuit, and (b) the equivalent bridge.

Secondary Transducers: Inductive

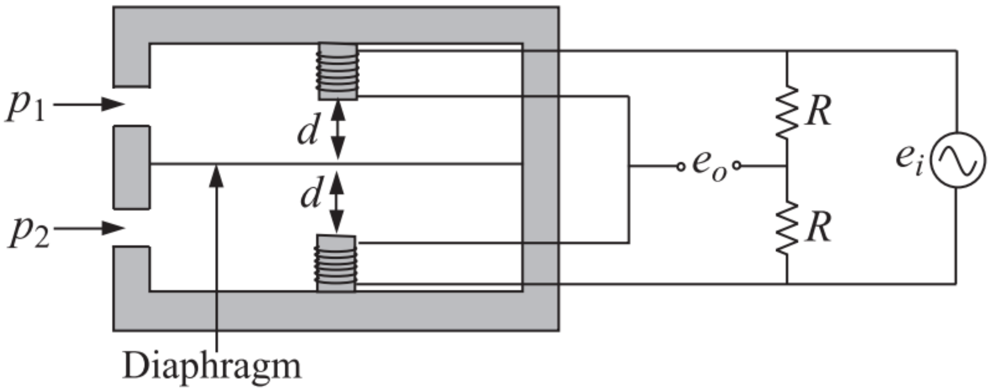
- Another arrangement: diaphragm alters the reluctance of the flux path of two coils on application of a pressure difference

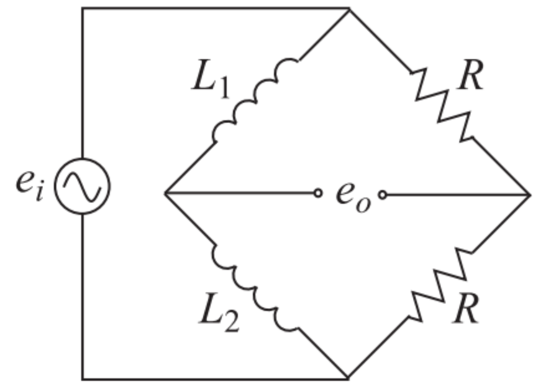




Secondary Transducers: Inductive

- Another arrangement: diaphragm alters the reluctance of the flux path of two coils on application of a pressure difference





- **For $p_1 = p_2$, the bridge is balanced and the output voltage $e_o = 0$**
- **But when $p_1 \neq p_2$, the bridge will generate an output voltage which varies linearly with the displacement of the diaphragm**

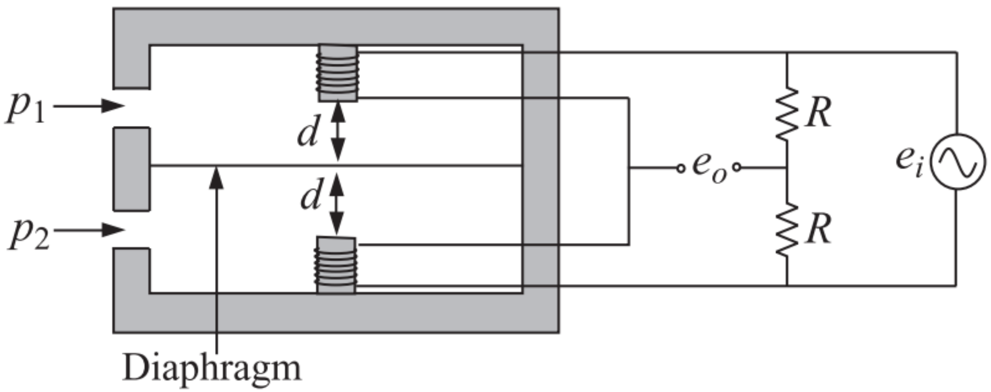
Secondary Transducers: Inductive

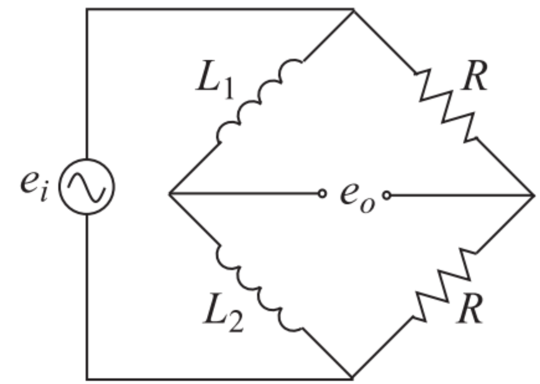
- **Self-inductance L of a coil**

$$L = \frac{N^2}{R} \quad \text{where,} \quad R = \frac{l}{\mu A}$$

N is the number of turns in the coil
R is the reluctance of the magnetic circuit
l is the length of the magnetic path
A is the area of cross-section of the magnetic path
μ is the effective permeability of the medium in and around the coil.

Secondary Transducers: Inductive



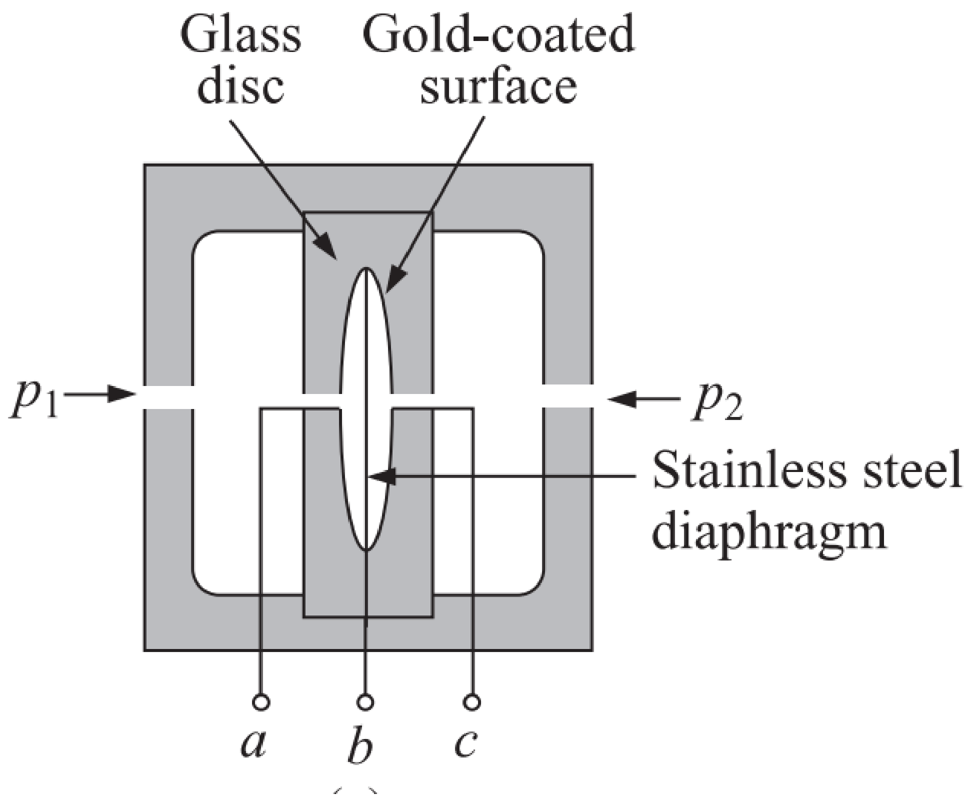


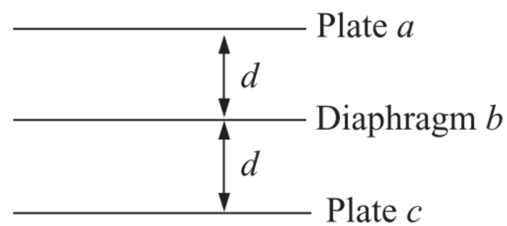
$$\text{initial self-inductance of a coil} = N^2/R_0$$

where N is its number of turns and R_0 is the reluctance of the flux path

Secondary Transducers: Capacitive

- **A differential arrangement of capacitors**





Secondary Transducers: Capacitive

- **A differential arrangement of capacitors**

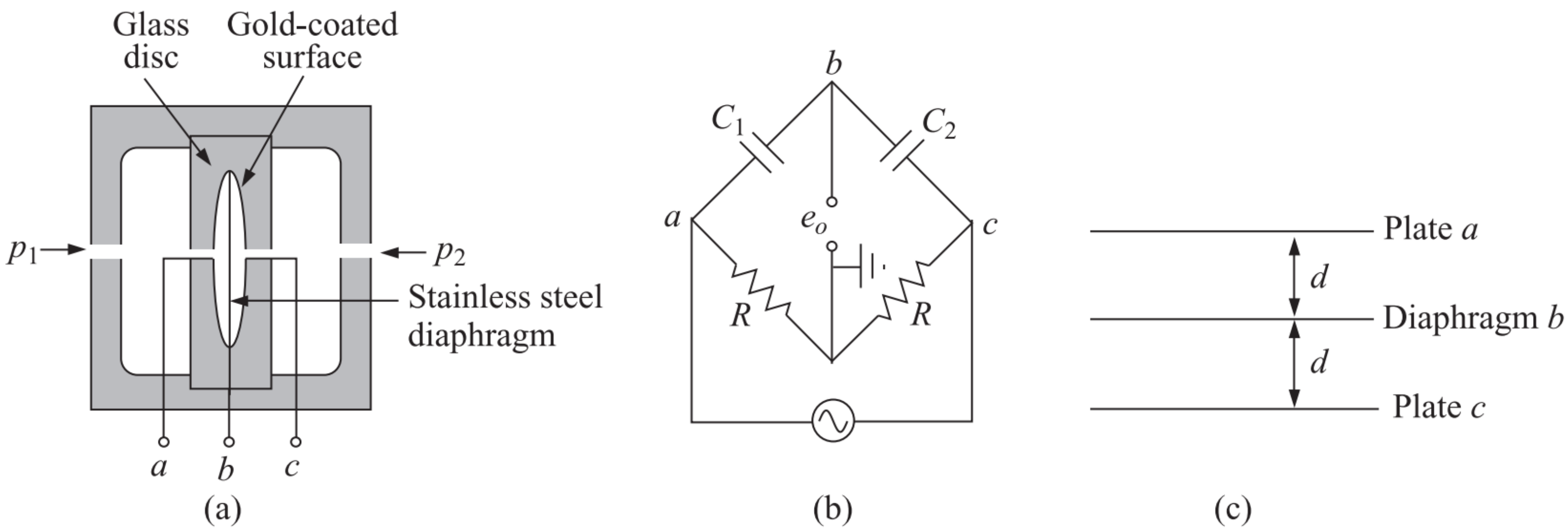


Fig. 8.18 Capacitive pressure transducer: (a) construction, (b) bridge arrangement, and (c) capacitor configuration.

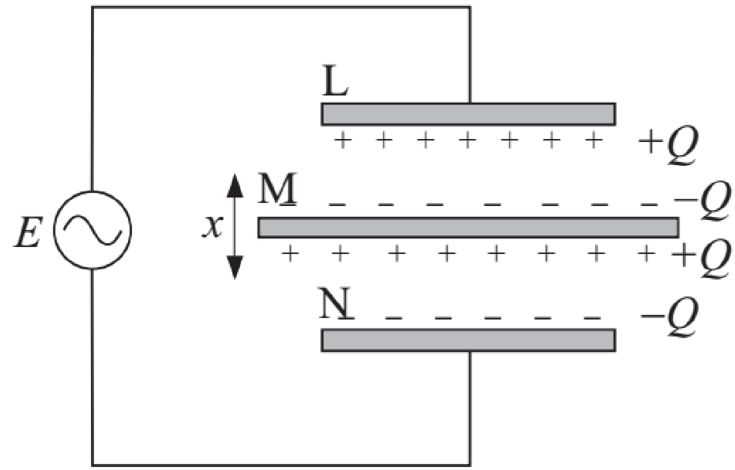
Recall
Ch. 6: Capacitive transducers

- **Differential arrangement of capacitors**

$$E_{\mathrm{LM}} = E \cdot \frac{d - x}{2d}$$

$$E_{\mathrm{MN}} = E \cdot \frac{d + x}{2d}$$

$$\Rightarrow \quad \boxed{\Delta E = E_{\mathrm{LM}} - E_{\mathrm{MN}} = \frac{E}{d} x}$$



- **ΔE has a linear relation with the displacement x of the movable plate M**

Secondary Transducers: Capacitive

- **a differential arrangement of capacitors**

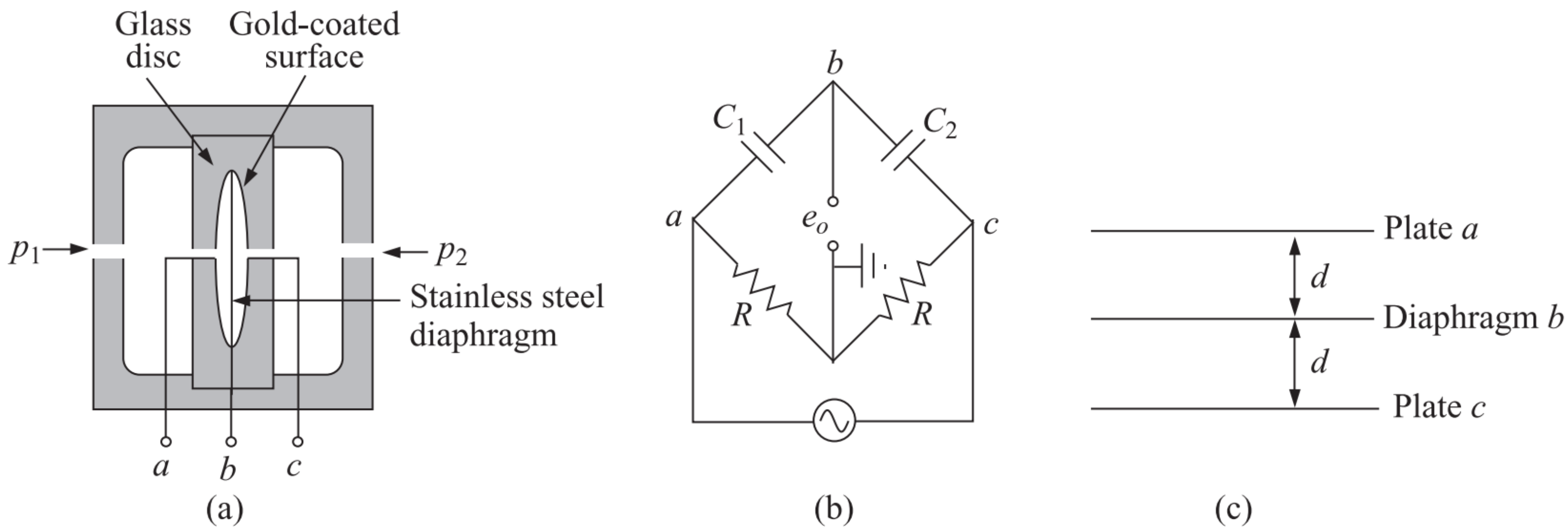


Fig. 8.18 Capacitive pressure transducer: (a) construction, (b) bridge arrangement, and (c) capacitor configuration.

- the two capacitors form the two arms of the bridge
- an output voltage that is proportional to the displacement of the movable plate, diaphragm

Secondary Transducers: Capacitive

- **a differential arrangement of capacitors**

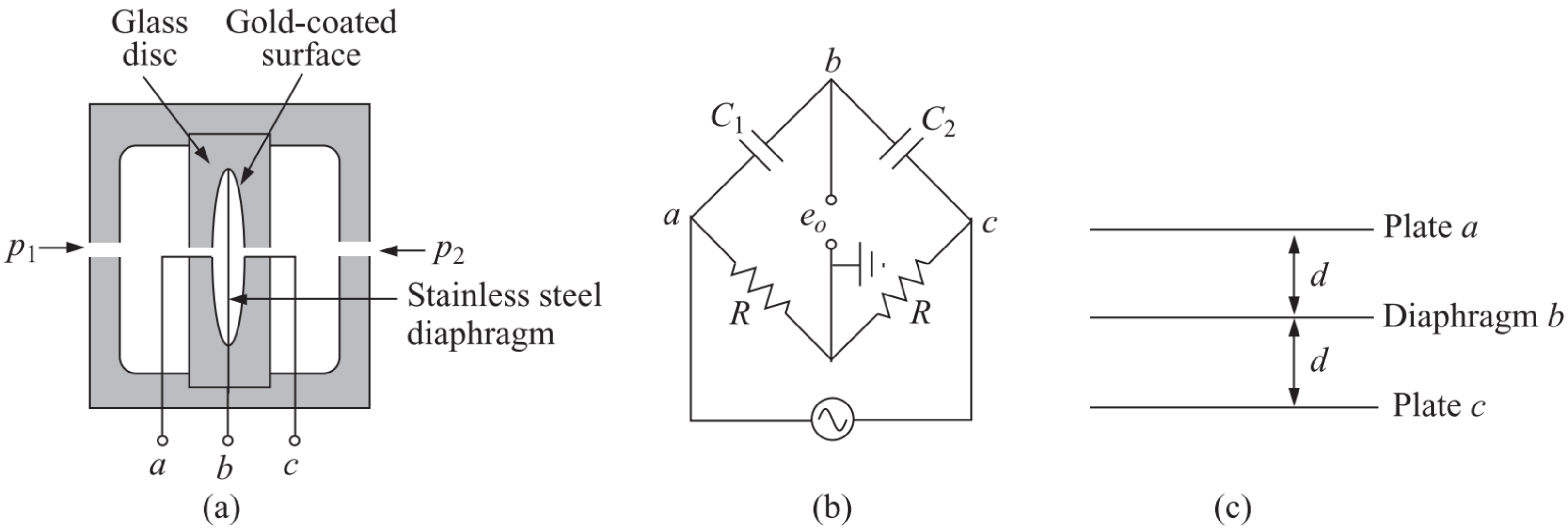


Fig. 8.18 Capacitive pressure transducer: (a) construction, (b) bridge arrangement, and (c) capacitor configuration.

- displacements between 10 $^{-8}$ mm and 10 mm can be sensed with an accuracy of 0.1%
  - very accurate pressure measurements at lower range

Secondary Transducers: Capacitive

- **a differential arrangement of capacitors**

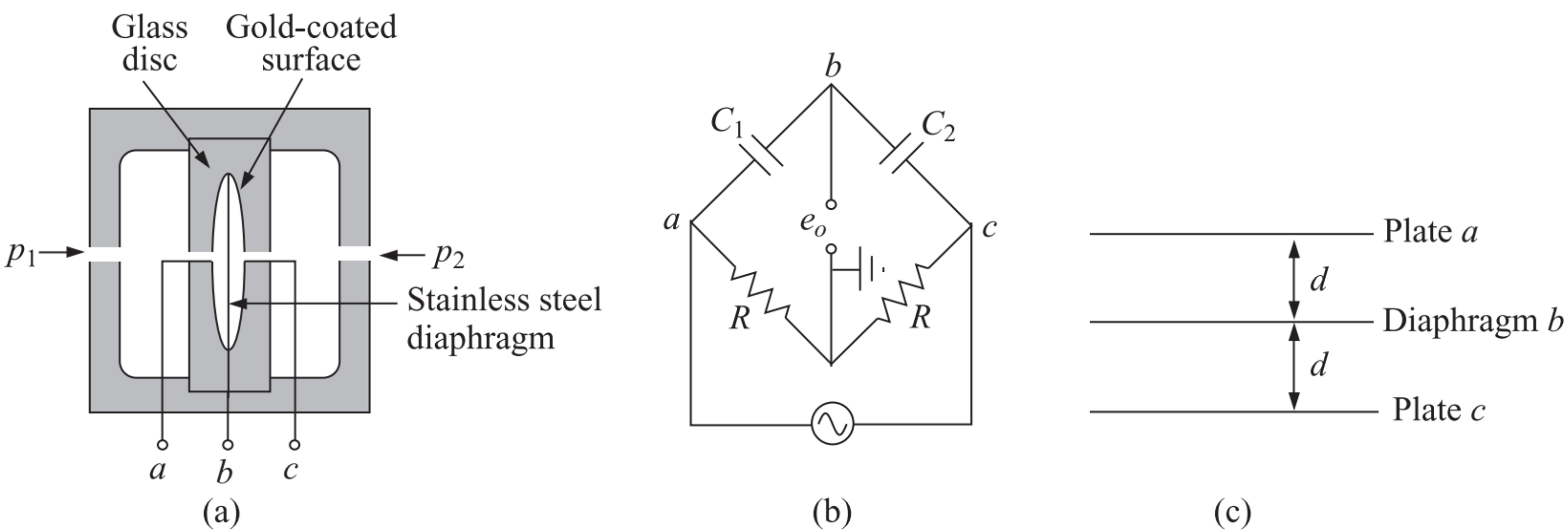


Fig. 8.18 Capacitive pressure transducer: (a) construction, (b) bridge arrangement, and (c) capacitor configuration.

Feature

- A differential pressure can be measured with this arrangement
- To measure pressure of just one gas, the other side of the diaphragm may be evacuated and sealed

Secondary Transducers: Photoelectric

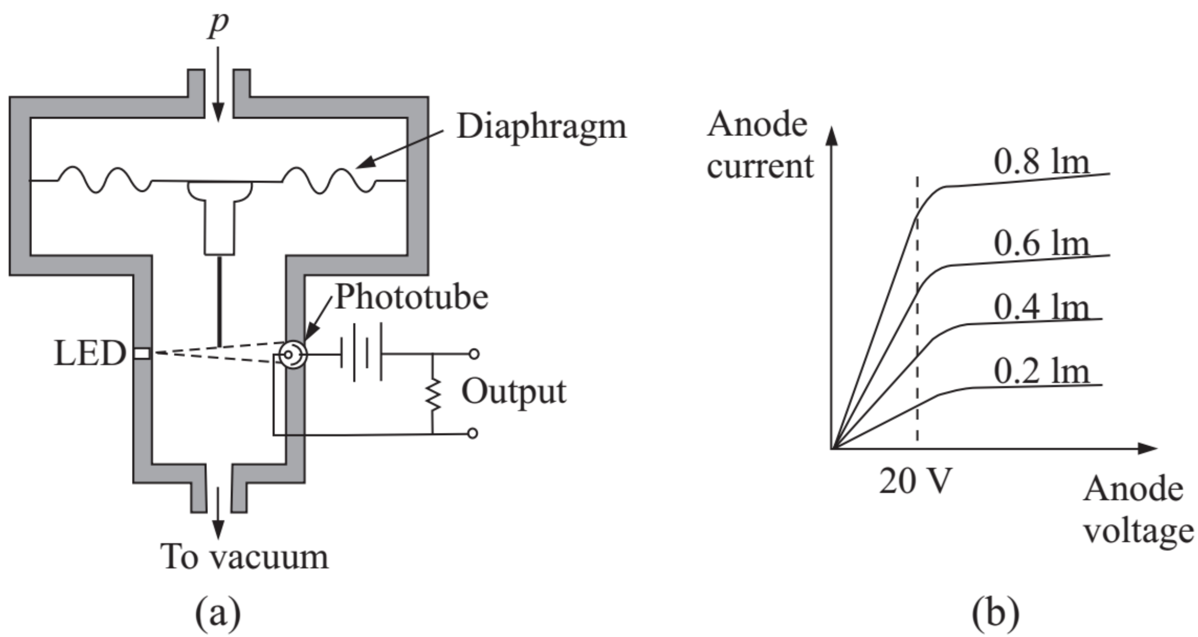


Fig. 8.19 (a) Photoelectric secondary transducer, and (b) phototube characteristics.

Secondary Transducers: Photoelectric

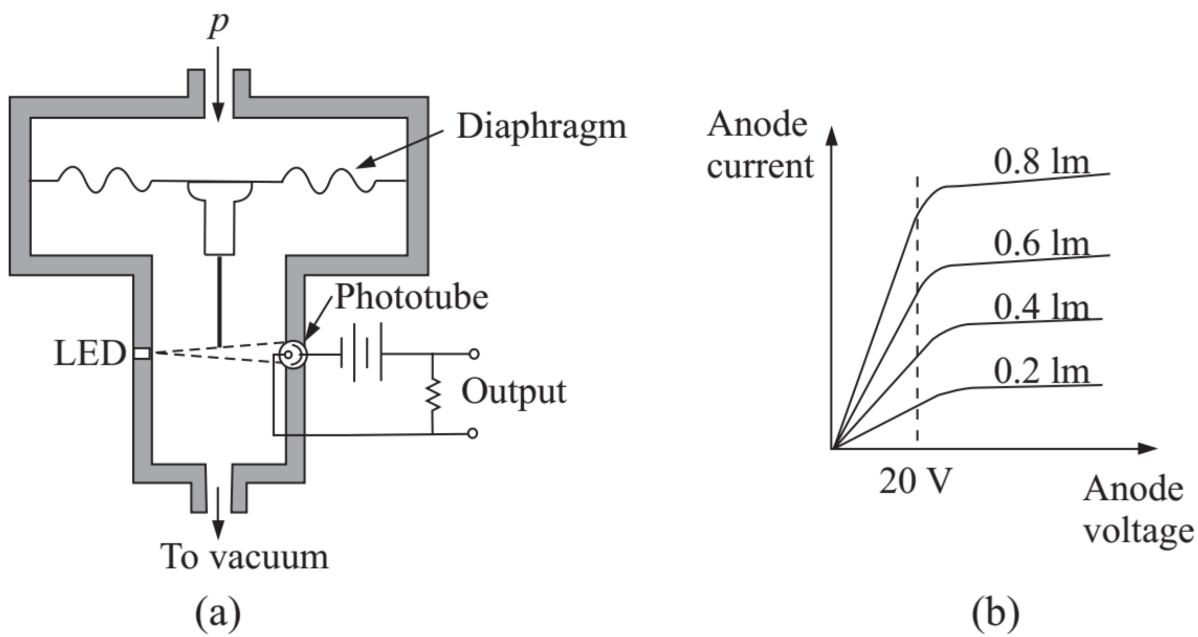


Fig. 8.19 (a) Photoelectric secondary transducer, and (b) phototube characteristics.

Working mechanism

- ❑ With the application of pressure, the diaphragm is depressed thereby reducing the in the width of the aperture, thus reducing the intensity of light falling on the photon detector
- ❑ This causes a variation in the output voltage owing to the variation of current in the circuit

Secondary Transducers: Photoelectric

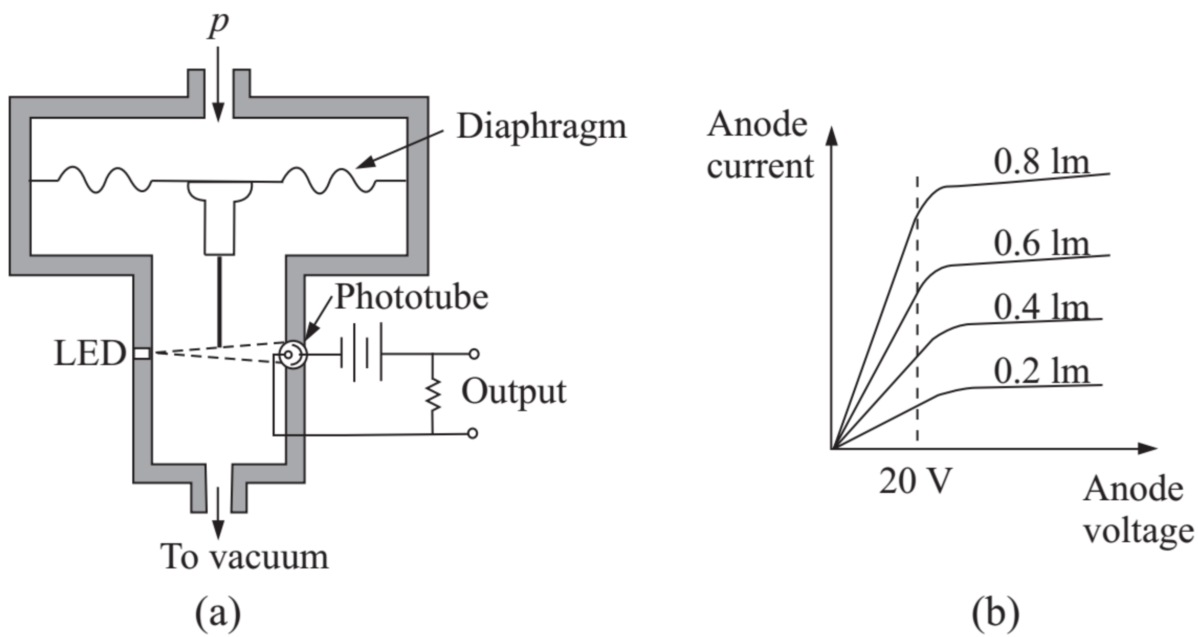


Fig. 8.19 (a) Photoelectric secondary transducer, and (b) phototube characteristics.

- Phototube characteristics
- if the anode voltage is higher than 20 V, the anode current is linearly proportional to the intensity of illumination

Secondary Transducers: Photoelectric

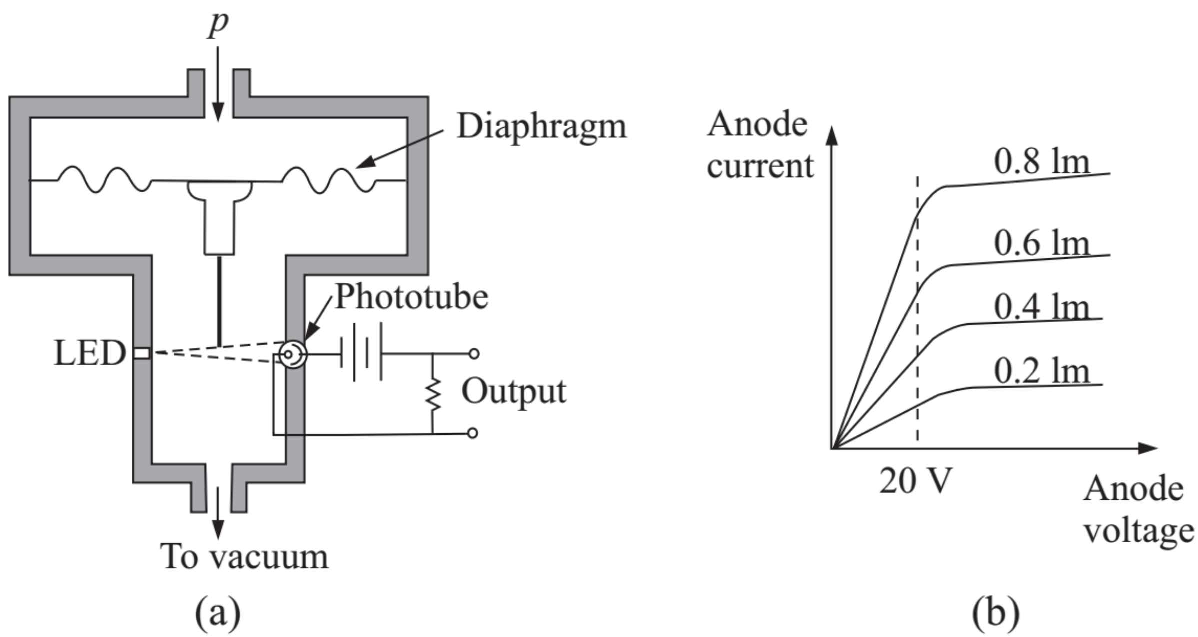
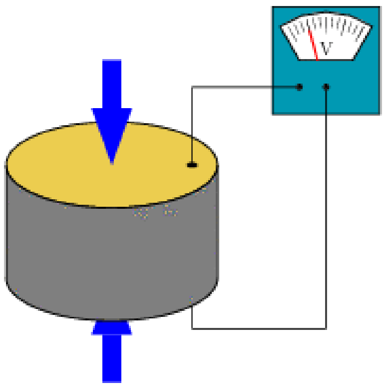


Fig. 8.19 (a) Photoelectric secondary transducer, and (b) phototube characteristics.

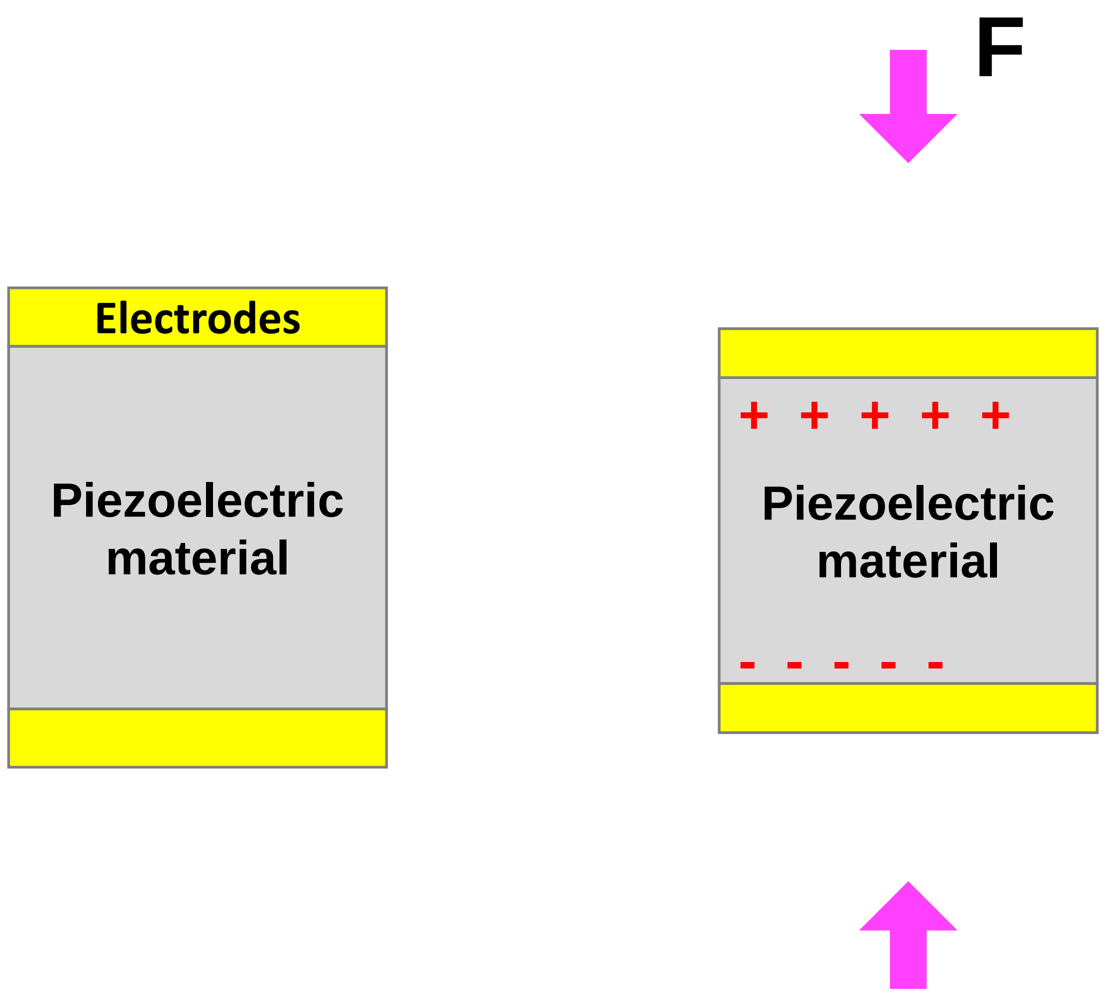
Issues

- ❑ needs a highly stabilised power supply to the lamp
- ❑ due to low photocurrent (μA), a stable amplifier is necessary for the signal
- ❑ appreciable displacement of the diaphragm is necessary to produce a detectable current

Secondary Transducers: Piezoelectric

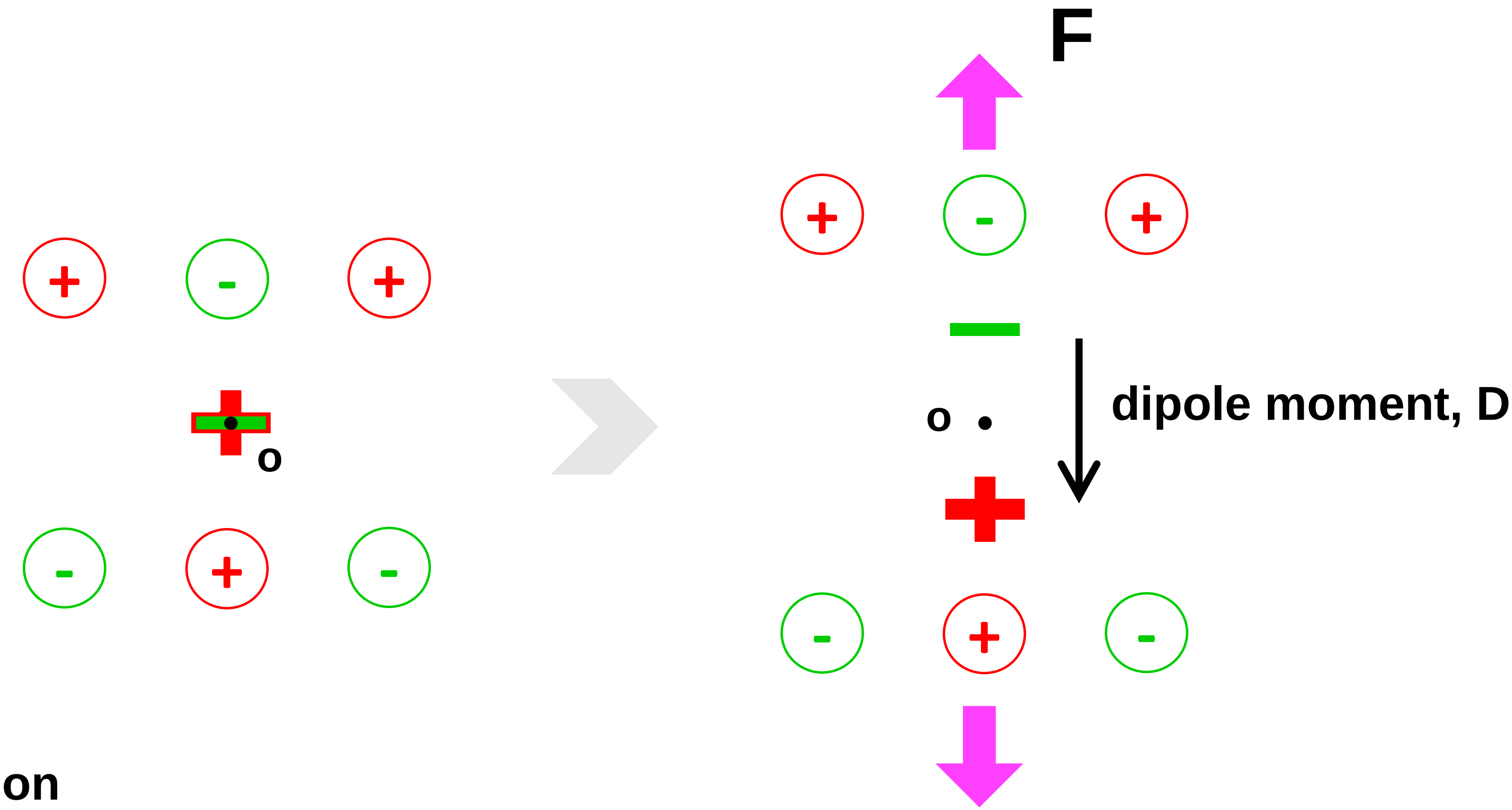


Piezoelectric devices



Origin of Piezoelectricity

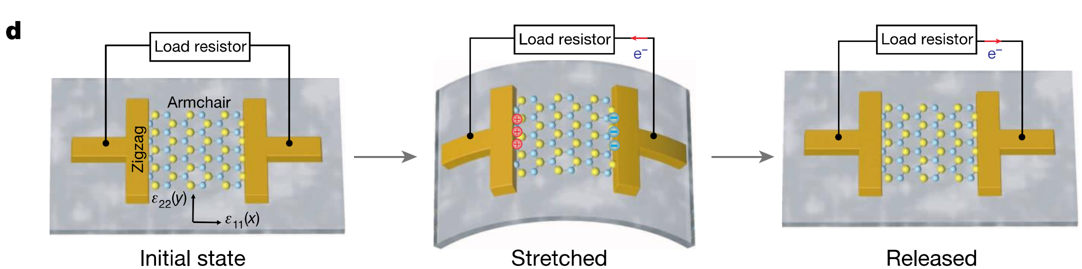
- a force F applied to the fictitious non centrosymmetric unit cell

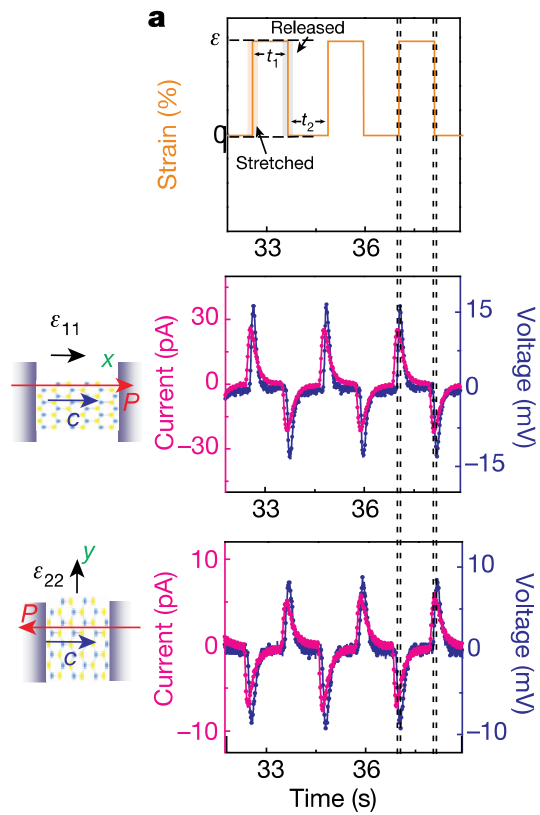


- **Conclusion**
  - **When the unit cell is non symmetrical around the center (i.e., non centrosymmetric), the material is piezoelectric**

Piezoelectric Transducers

- ❑ **Measurement of piezoelectric voltage**
  - ❑ Input impedance of the instrument must be very high
    - ❑ The measuring instrument (load resistance) provides a path for the induced charge to leak away





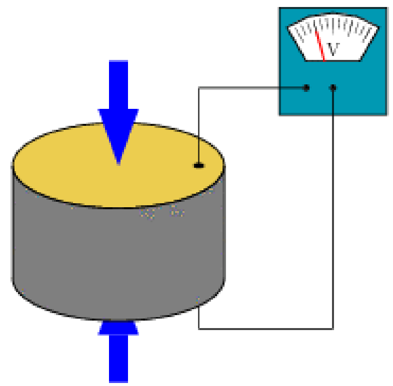
✓ **1GΩ load resistor**

Piezoelectric: Monolayer molybdenum disulfide

Z. L. Wang et al., NATURE, VOL 514, 2014.

Secondary Transducers: Piezoelectric

- **(Electrostatic) piezoelectric transducer**
  - charge developed across a piezoelectric crystal is proportional to the applied force
  - therefore, it can be used to measure pressure which is the force per unit area



- **Features**
- Practically, the electric signal generated by the piezoelectric crystal decays rapidly
  - piezoelectric sensors are not suitable for measurement of static pressures
  - they can be used for dynamic pressure measurement

Secondary Transducers: Piezoelectric

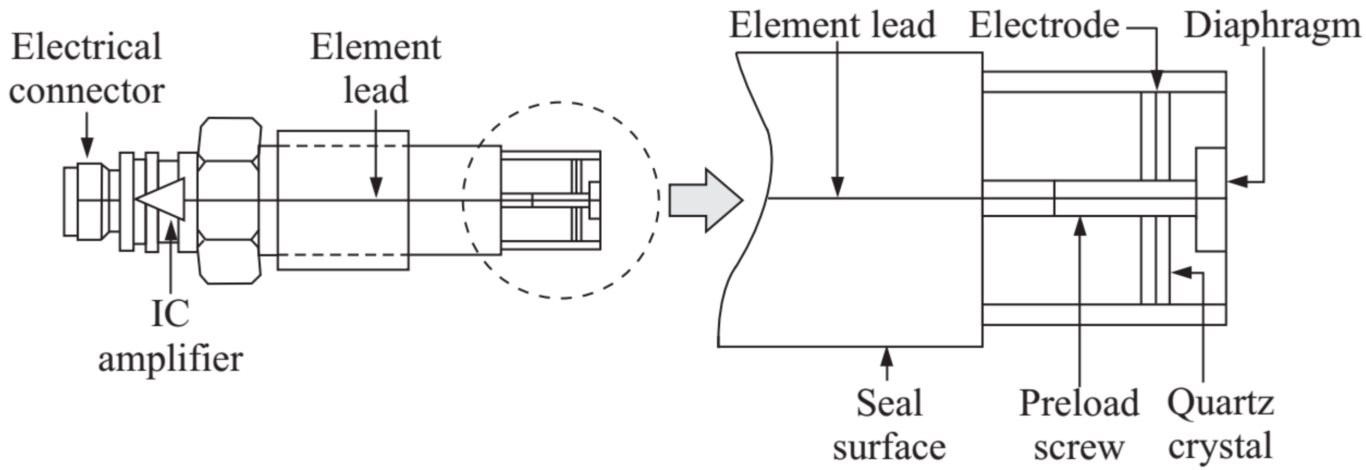
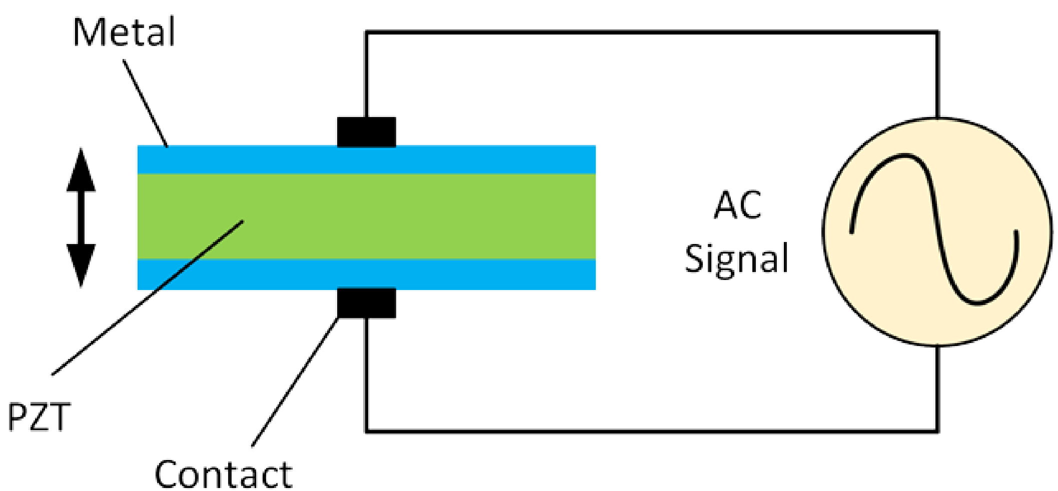


Fig. 8.20 Electrostatic piezoelectric pressure sensor.

- ❑ **Features**
- ❑ high speed response: 30 kHz to 100 kHz
  - ❑ suitable for measuring transient phenomena like rapidly changing pressures from blasts, explosions or other sources of shock and vibration

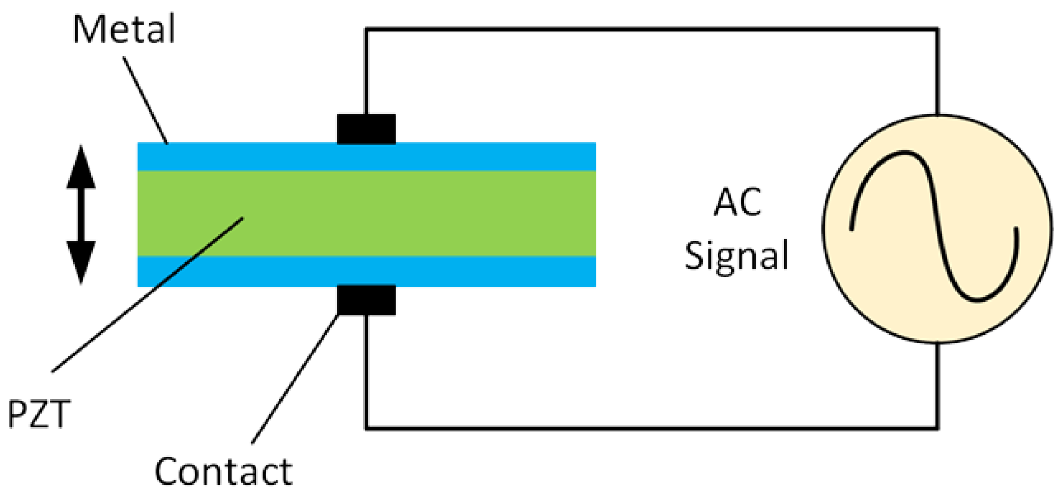
Secondary Transducers: Piezoelectric

- Resonant piezoelectric pressure transducers/sensors
  - variation of the resonant frequency of piezoelectric transducer crystals when a force is applied to them
  - The sensor is oscillating through the inverse piezoelectric effect by applying an oscillating electric field
    - The sensor can be in the form of a suspended beam



Secondary Transducers: Piezoelectric

- **Resonant piezoelectric pressure transducers/sensors**



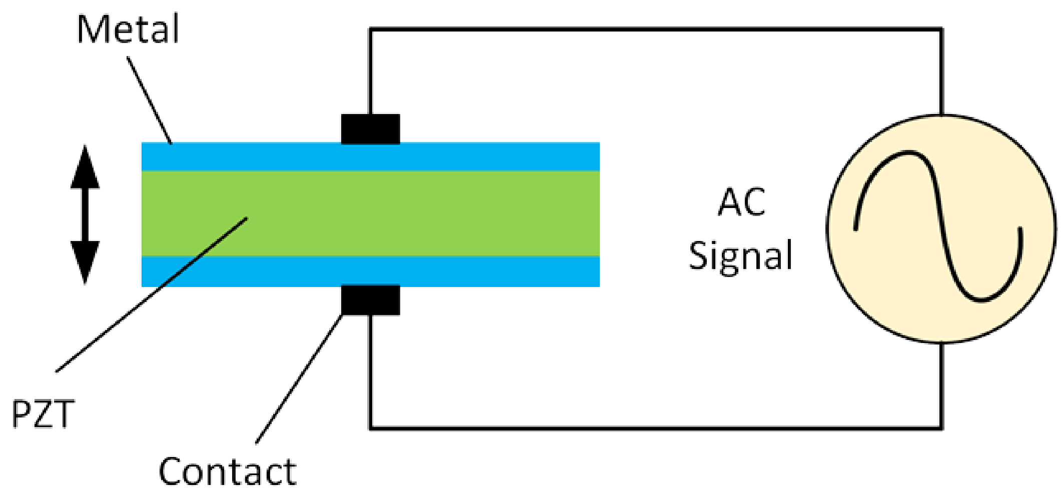
- **Pressure and resonant frequency relation**

$$p = A\left(1 - \frac{\nu_p}{\nu_0}\right) - B\left(1 - \frac{\nu_p^2}{\nu_0}\right) \tag{8.12}$$

where A, B are constants and ν_p, ν_0 are resonant frequencies corresponding to applied pressure p and zero pressure respectively.

Secondary Transducers: Piezoelectric

- **Resonant piezoelectric pressure transducers/sensors**



- **Features**
  - Can measure static pressures
  - Range: 0 and 6 MPa

Piezoresistivity

- **Origin of piezoresistivity**
  - Change in resistivity of the semiconductor when strained
    - When strained, the interatomic spacings within the material change
    - The change in the interatomic spacings eventually changes the bandgaps in each atom

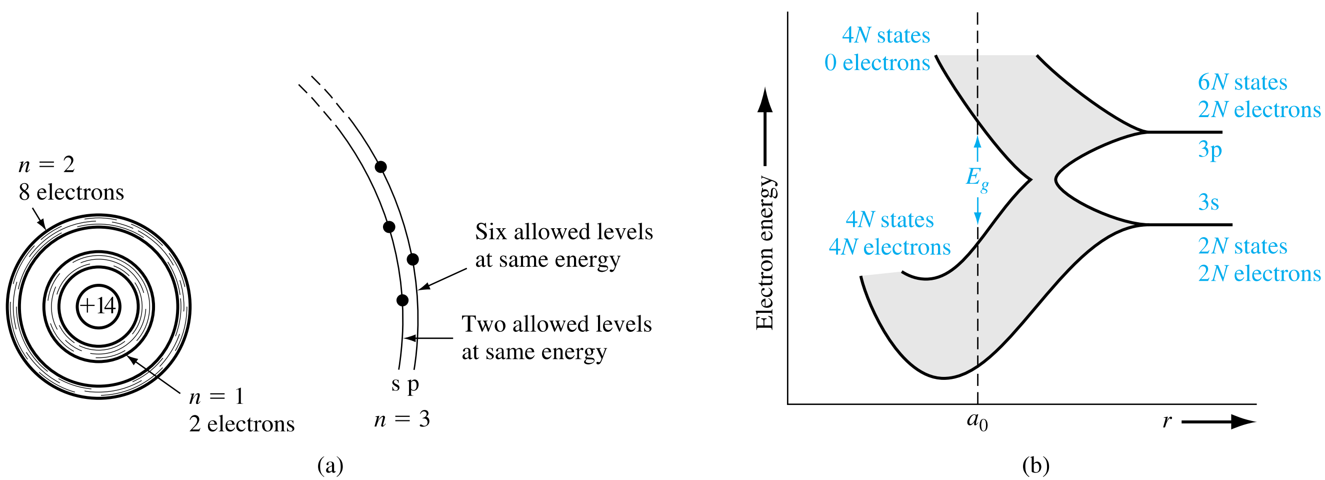
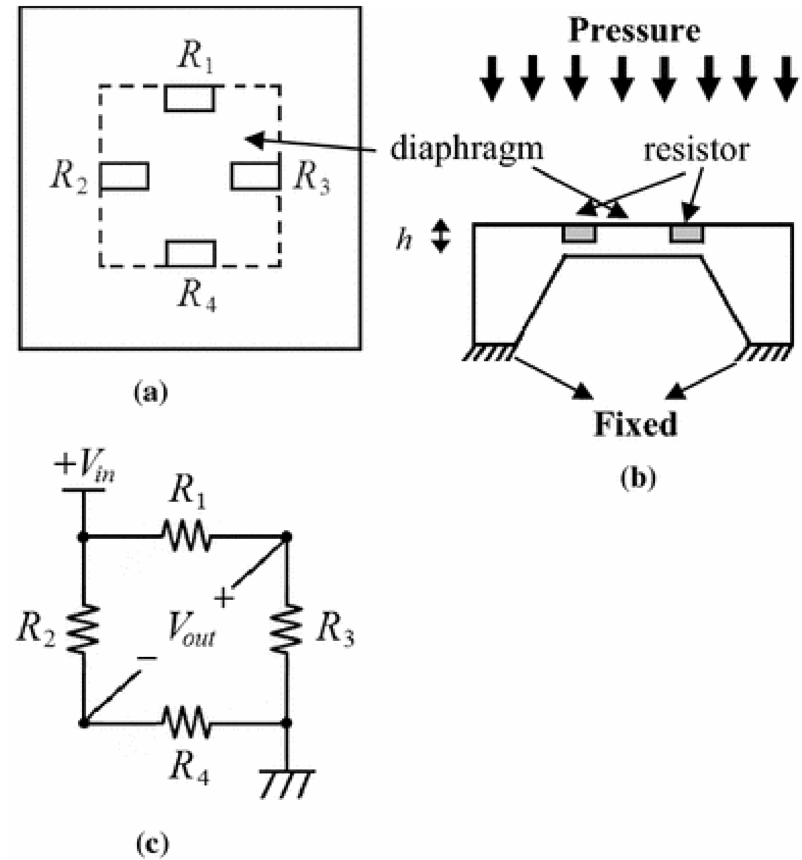


Figure 3.4 | (a) Schematic of an isolated silicon atom. (b) The splitting of the 3s and 3p states of silicon into the allowed and forbidden energy bands.
(From Shockley [6].)

Ref: Semiconductor Physics and Devices: Basic Principles by Donald A. Neamen

Secondary Transducers: Piezoresistive

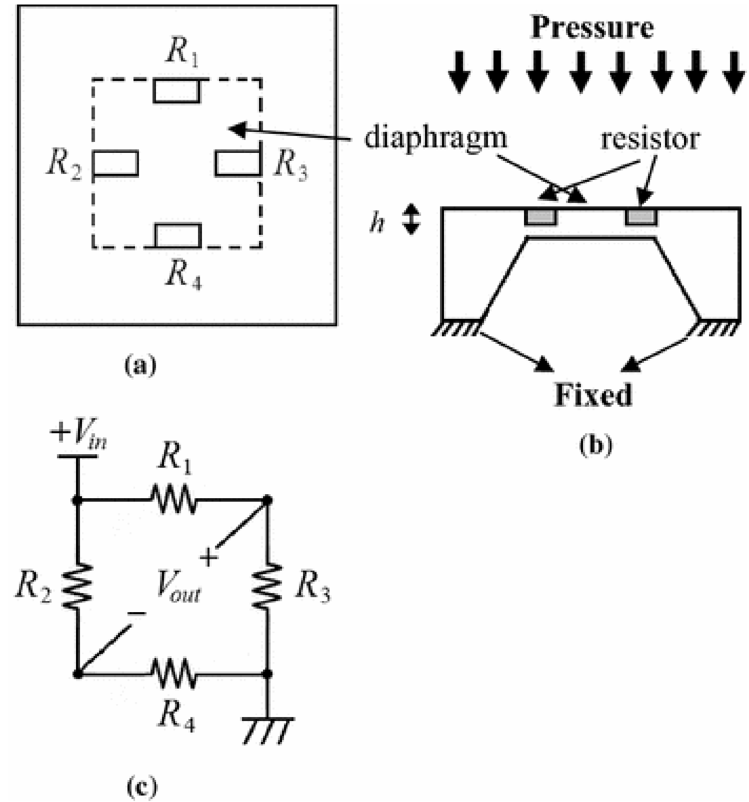
- Piezoresistivity: the resistivity of semiconductors depends on the force applied on them



- Piezoresistive pressure sensor
  - the diaphragm itself is a semiconductor (typically silicon) wafer
  - four sensing resistors are diffused into it during the growth of the wafer

Secondary Transducers: Piezoresistive

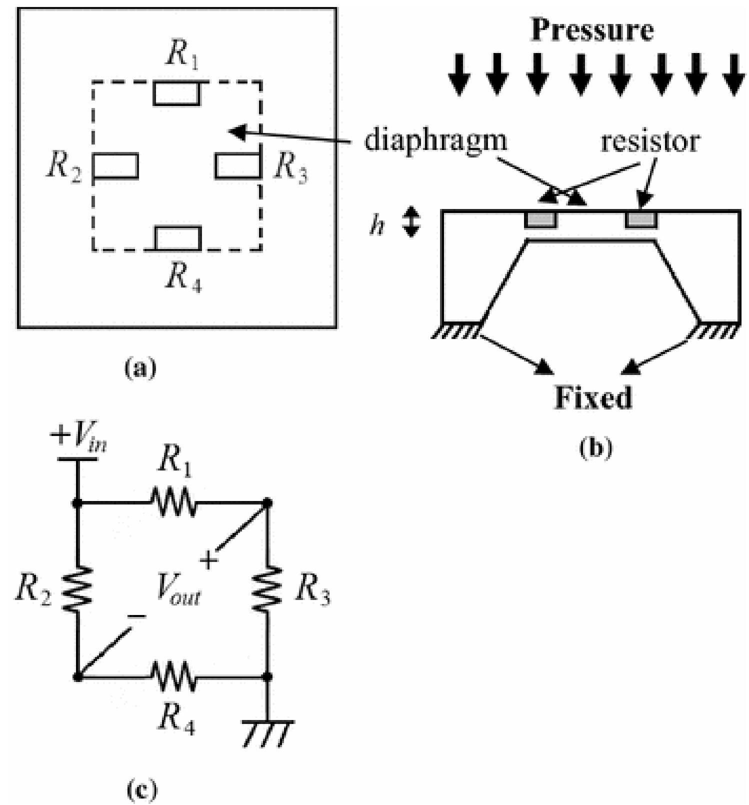
- ❑ **Piezoresistive pressure sensors**



- ❑ **Features**
  - ❑ for absolute pressure measurement, the fabrication process is carried out in vacuum and the cavity behind the diaphragm is kept evacuated
  - ❑ for a relative pressure measurement, the cavity behind is either ported to a reference pressure or to the atmosphere

Secondary Transducers: Piezoresistive

- ❑ **Piezoresistive pressure sensors**



- ❑ **Features**
  - ❑ Piezoresistivity does not decay with time, they can measure static pressures with the help these sensors
  - ❑ Measure: 21 kPa and 100 Mpa

Secondary Transducers: Hall-effect

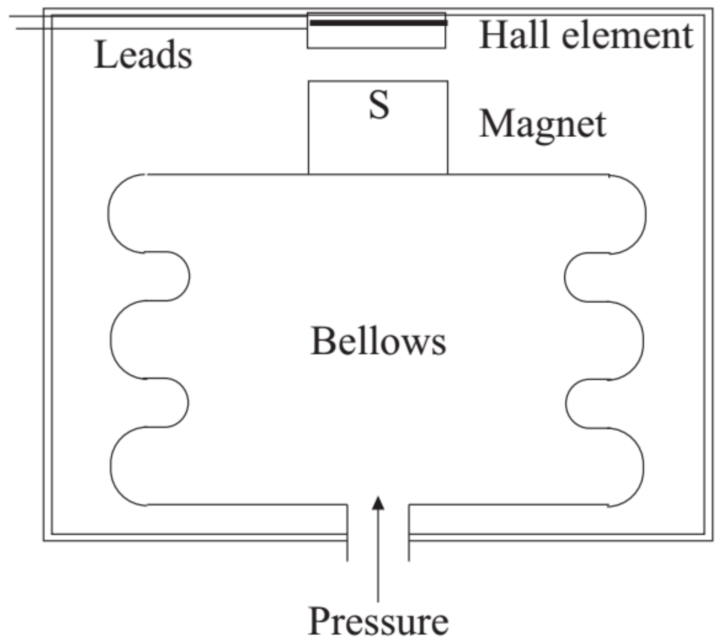


Fig. 8.21 Use of Hall effect transducer in pressure sensing.

Secondary Transducers: Hall-effect

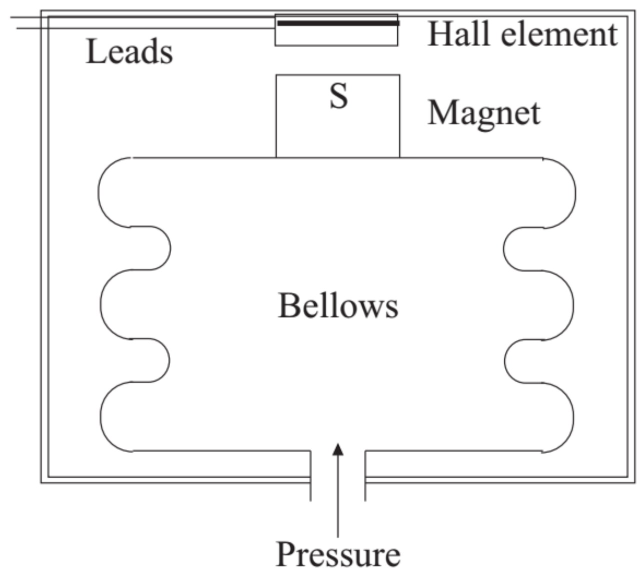
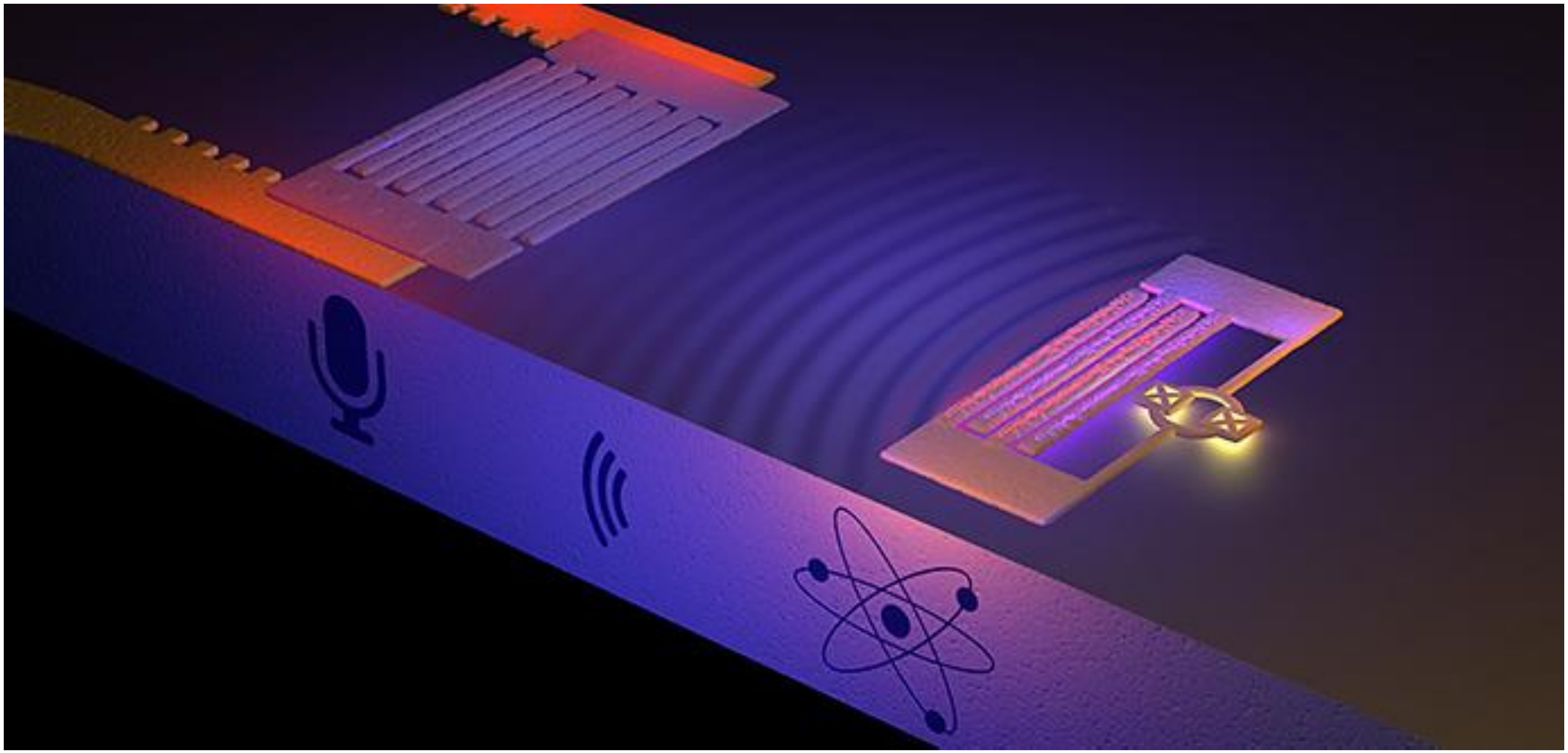


Fig. 8.21 Use of Hall effect transducer in pressure sensing.

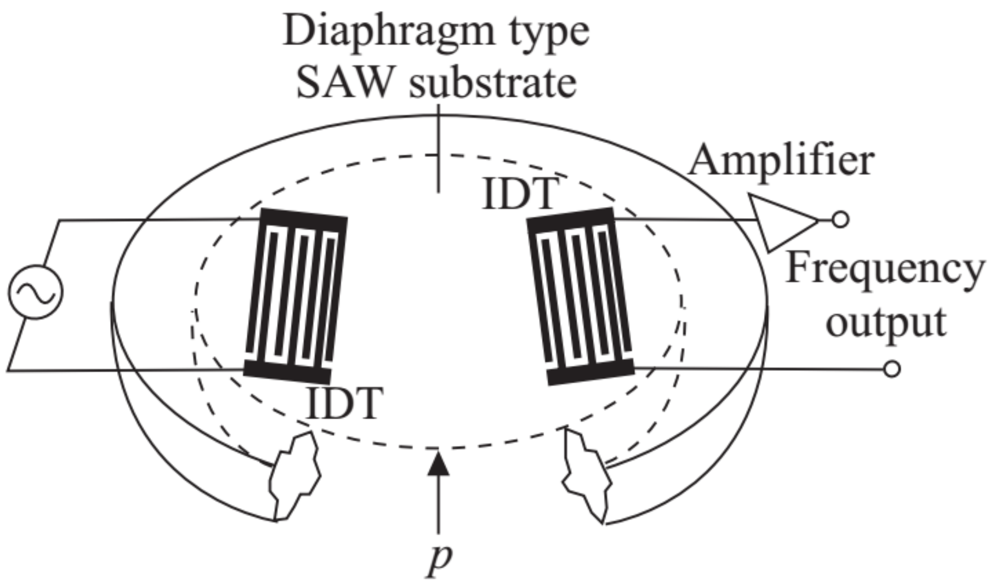
- **Working and sensor design**
- The Hall effect devices can be used as a secondary transducer to measure pressure by coupling it with a force-summing device like bellows
- an output voltage proportional to pressure input to the force summing device

Surface Acoustic Waves (SAW)

- Mechanical waves that once created on the surface of a piezoelectric material travel along it's surface

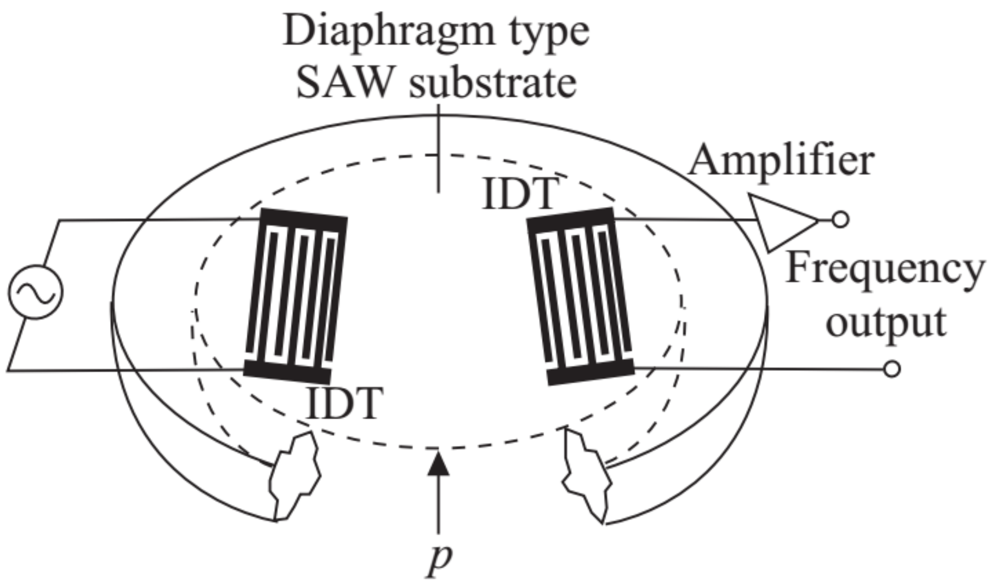


Secondary Transducers: Surface Acoustic Wave



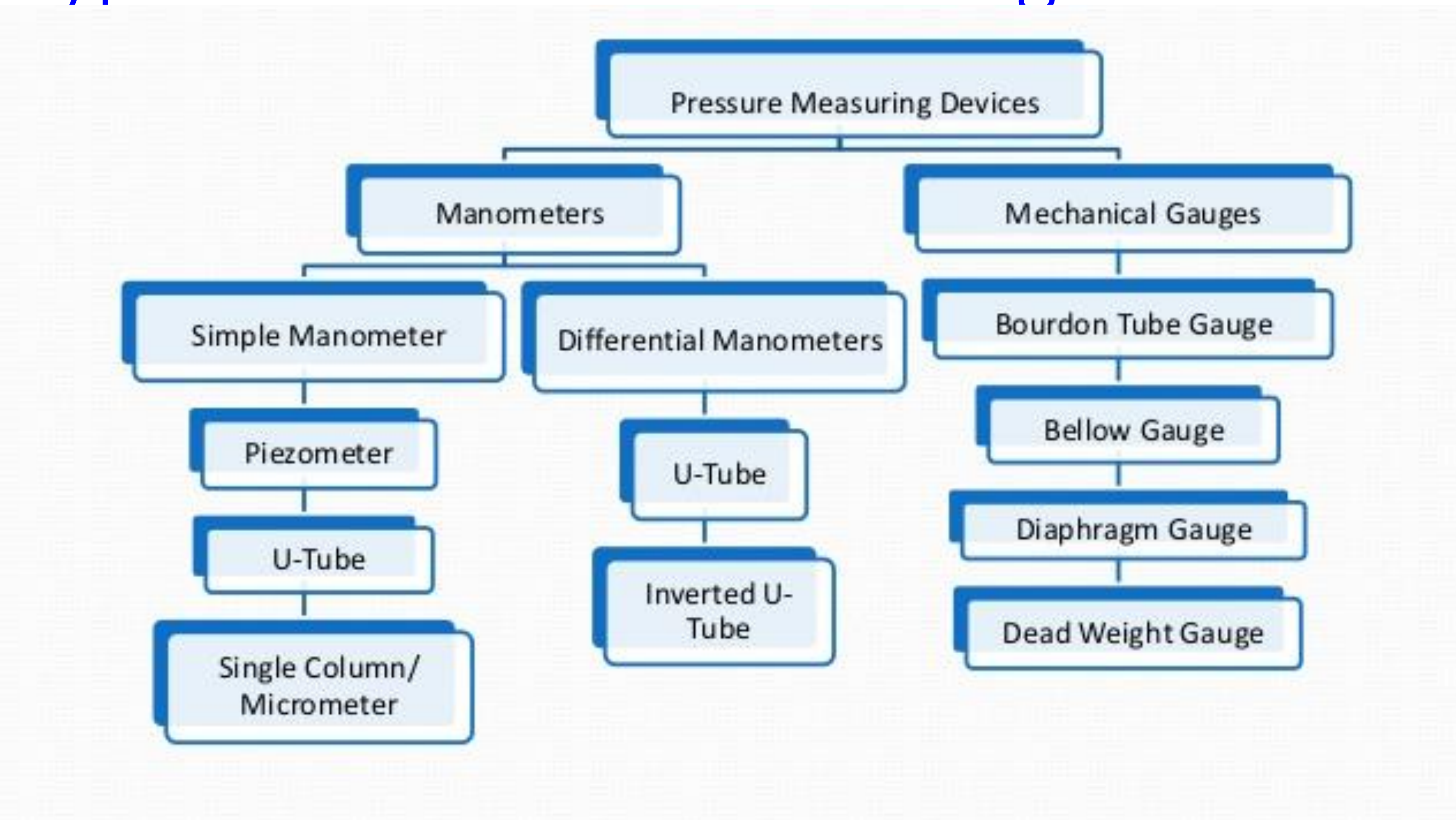
- Sensor design and working
  - A SAW pressure sensor: a SAW device fabricated onto a diaphragm
  - Surface acoustic wave velocities are strongly affected by stresses applied to the piezoelectric substrate on which the wave is propagating

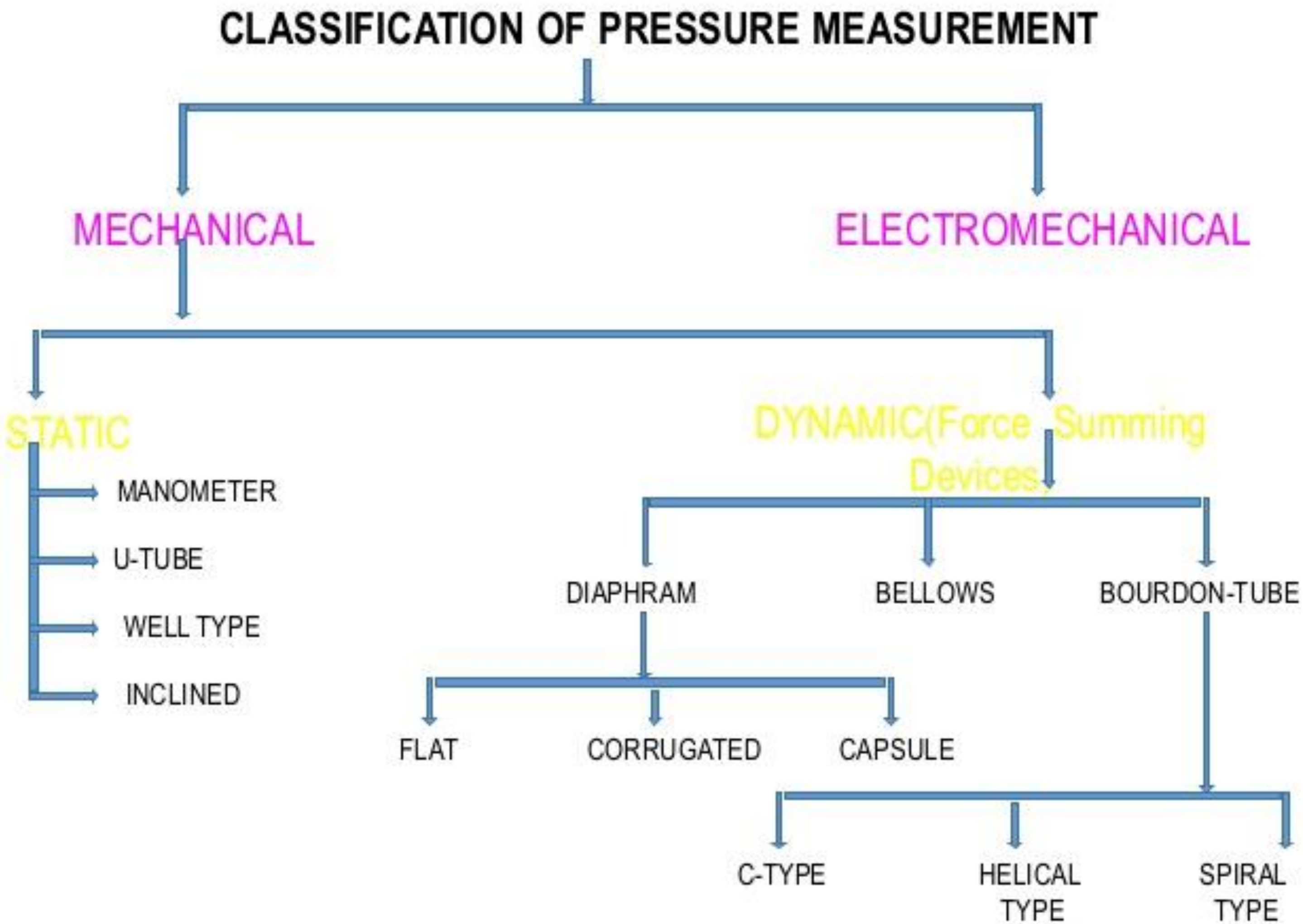
Secondary Transducers: Surface Acoustic Wave



- Issues: Temperature effects and compensation
  - Affected by temperature
  - Compensation: a reference SAW device close to the measuring SAW on the same substrate

Summary
Types of Pressure Measuring Devices




CLASSIFICATION OF PRESSURE MEASUREMENT
MECHANICAL
ELECTROMECHANICAL
STATIC
MANOMETER
U-TUBE
WELL TYPE
INCLINED
DYNAMIC(Force Summing Devices)
DIAPHRAM
BELLOWS
BOURDON-TUBE
FLAT
CORRUGATED
CAPSULE
C-TYPE
HELICAL TYPE
SPIRAL TYPE

Classification of Pressure Measuring Instrument Based on Pressure-Levels

High Vacuum Measuring Instruments

- Mcleod gage
- Thermal conductivity gauge
  - Thermocouple gage
  - Pirani Gage
- Ionization gauge

Low Pressure Measuring Instruments

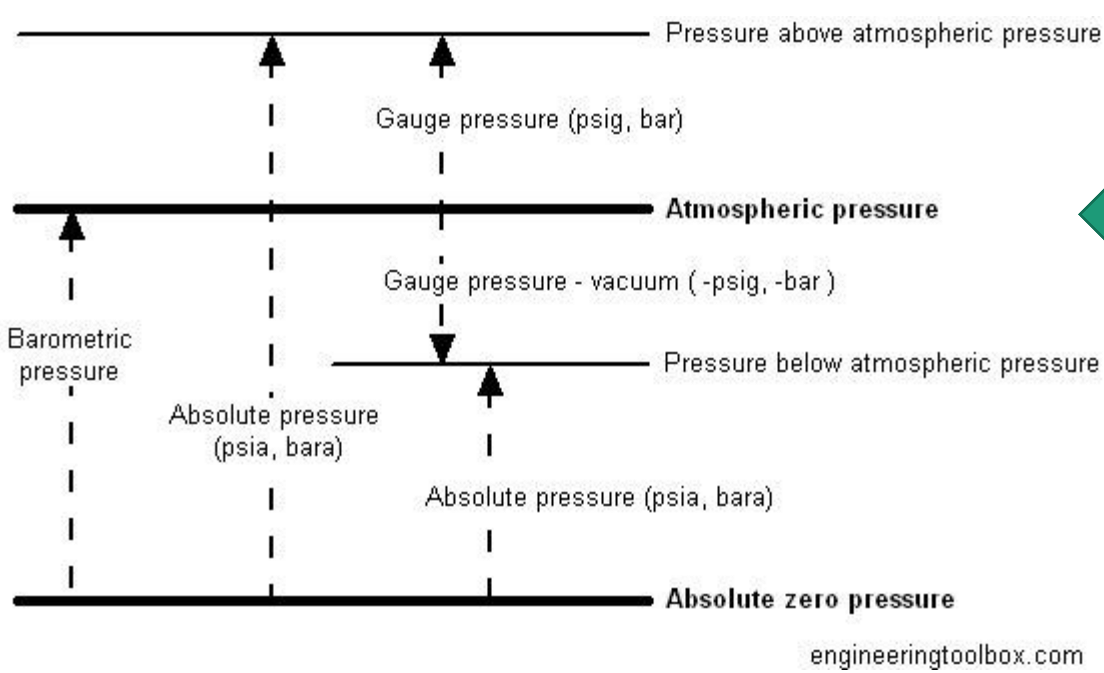
- Manometer

Moderate pressure measuring instrument

- Elastic pressure transducer
  - Bourdon tube pressure gage
  - Diaphragm type gage
  - Bellows gage

Recall….

Perfect Vacuum	0 Torr (theoretically impossible)
Outer Space	about 10^{-9} to 10^{-17} Torr
Extreme High Vacuum	about 10^{-13} Torr
Ultra High Vacuum (UHV)	about 10^{-10} to 10^{-11} Torr
High or Hard Vacuum (HV)	about 10^{-5} to 10^{-8} Torr
Medium or Intermediate Vacuum	about 10^{-3} to 10^{-5} Torr
Low, Soft or Rough Vacuum	about 10^{-3} Torr
Atmospheric Pressure	760 Torr



Classification of Pressure Measuring Instrument Based on Pressure-Levels

Type of pressure to be measured	Pressure Measuring instrument to be used
Low pressure	Manometer
High and medium pressure	Bourdon tube pressure gauge. Diaphragm gauge. Bellows Gauges.
Low vacuum and ultra high vacuum	Mcleod vacuum gauge thermal conductivity gauges. Ionisation gauges.
Very high pressure	Bourdon tube pressure gauge. Diphragm gauge. Bulk modulus pressure gauge.

- Low pr (Below 1 mm of Hg)- manometer and low pr gauges
- Medium and low (between 1mm of Hg 1000 atm)- Bourdon gauge and Diaphragm gauges
- Low vacuum and ultra high vacuum(760 torr to 10 raise to -9 torr and beyond)- McLeod, thermal conductivity and ionisation gauge
- Very high pr (1000 atm and above)- Bourdon gauge,Diaphragm and electrical pr gauges

Queries

Thanks!