Sensors (Chapter 2)

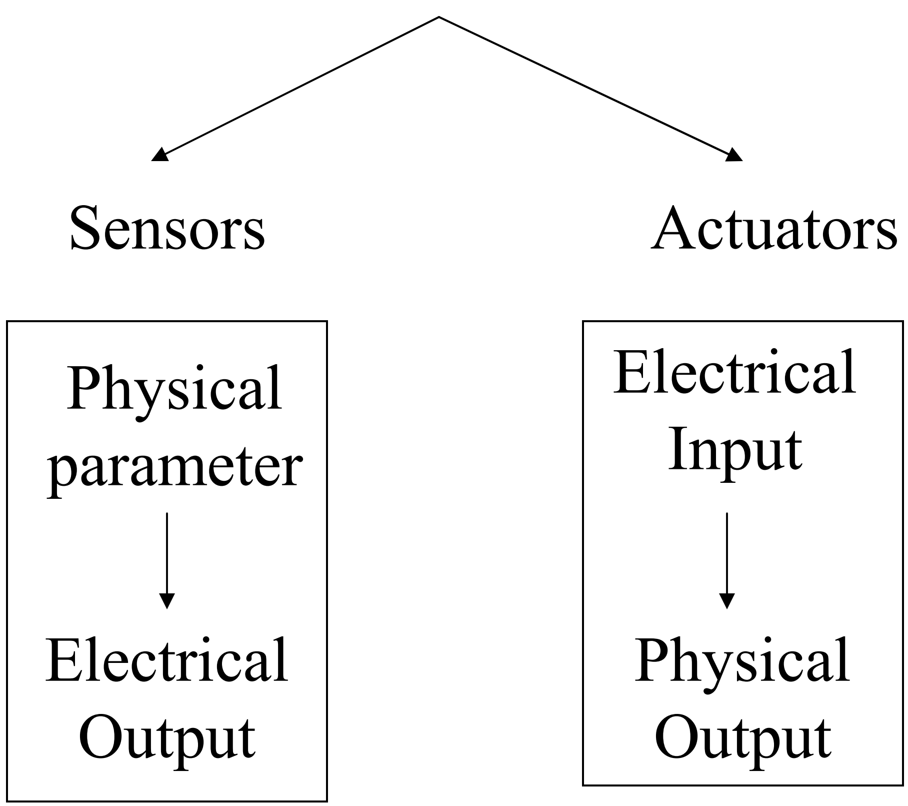
<u>Sensor characteristics</u>

<u>Physical Sensors</u>

Resistive
Capacitive
Inductive
Piezoelectric
Temperature
Optical
Chemical
Biochemical

Sensor is a Transducer: What is a transducer ?

A device which converts one form of energy to another



e.g. Piezoelectric:

Force -> voltage

Voltage-> Force

=> Ultrasound!

Sensor Performance Characteristics

Transfer Function:

The functional relationship between physical input signal and electrical output signal. Usually, this relationship is represented as a graph showing the relationship between the input and output signal, and the details of this relationship may constitute a complete description of the sensor characteristics. For expensive sensors which are individually calibrated, this might take the form of the certified calibration curve.

Sensitivity:

The sensitivity is defined in terms of the relationship between input physical signal and output electrical signal. The sensitivity is generally the ratio between a small change in electrical signal to a small change in physical signal. As such, it may be expressed as the derivative of the transfer function with respect to physical signal. Typical units : **Volts/Kelvin**. A Thermometer would have "high sensitivity" if a small temperature change resulted in a large voltage change.

Span or Dynamic Range:

The range of input physical signals which may be converted to electrical signals by the sensor. Signals outside of this range are expected to cause unacceptably large inaccuracy. This span or dynamic range is usually specified by the sensor supplier as the range over which other performance characteristics described in the data sheets are expected to apply.

Sensor Performance Characteristics

Accuracy:

Generally defined as the largest expected error between actual and ideal output signals. Typical Units : Kelvin. Sometimes this is quoted as a fraction of the full scale output. For example, a thermometer might be guaranteed accurate to within 5% of FSO (Full Scale Output)

Hysteresis:

Some sensors do not return to the same output value when the input stimulus is cycled up or down. The width of the expected error in terms of the measured quantity is defined as the hysteresis. Typical units : Kelvin or % of FSO

Nonlinearity (often called Linearity):

The maximum deviation from a linear transfer function over the specified dynamic range. There are several measures of this error. The most common compares the actual transfer function with the `best straight line', which lies midway between the two parallel lines which encompasses the entire transfer function over the specified dynamic range of the device. This choice of comparison method is popular because it makes most sensors look the best.

Sensor Performance Characteristics

Noise:

All sensors produce some output noise in addition to the output signal. The noise of the sensor limits the performance of the system based on the sensor. Noise is generally distributed across the frequency spectrum. Many common noise sources produce a white noise distribution, which is to say that the spectral noise density is the same at all frequencies. Since there is an inverse relationship between the bandwidth and measurement time, it can be said that the noise decreases with the square root of the measurement time.

Resolution:

The resolution of a sensor is defined as the minimum detectable signal fluctuation. Since fluctuations are temporal phenomena, there is some relationship between the timescale for the fluctuation and the minimum detectable amplitude. Therefore, the definition of resolution must include some information about the nature of the measurement being carried out.

Bandwidth:

All sensors have finite response times to an instantaneous change in physical signal. In addition, many sensors have decay times, which would represent the time after a step change in physical signal for the sensor output to decay to its original value. The reciprocal of these times correspond to the upper and lower cutoff frequencies, respectively. The bandwidth of a sensor is the frequency range between these two frequencies.

Physical Sensors

Flow cytometer

Physical Variables and Sensors

Physical Quantity	*Sensor*	*Variable*
Fluidic	Pressure transducer Flow meter	Pressure Flow
Force-Torque	Load cell	Applied force or torque
Geometric	Strain Gauge LVDT Ultrasonic transit time	Strain Displacement Displacement
Kinematic	Velocimeter Accelerometer	Velocity Acceleration
Thermal	Thermometer Thermal flux sensor	Temperature Heat flux

- Blood flow/blood pressure
- Impact, acceleration
- Surgical forceps to measure force applied
- Airbag
- Body temperature

PCR

Biomedical Physical Sensors

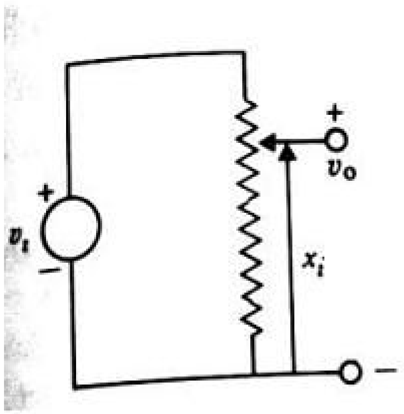
Sensor	*Application*	*Signal Range*
Liquid metal strain guage	Breathing movement	0-0.05
Magnetic displacement sensor	Breathing movement	0-10 mm
LVDT	Muscle contraction	0-20 mm
	Uterine contraction sensor	0-5 mm
Load cell	Electronic scale	0-200 kg
Accelerometer	Subject activity	0-20 m/s^2
Miniature silicon pressure sensor	Intra-arterial blood pressure	0-350 mm Hg
	Urinary bladder pressure	0-70 mm Hg
	Intrauterine pressure	0-100 mm Hg
Electromagnetic flow sensor	Cardiac o/p (with integrator)	0-500 ml/min
	Organ blood flow	0-100 ml/min

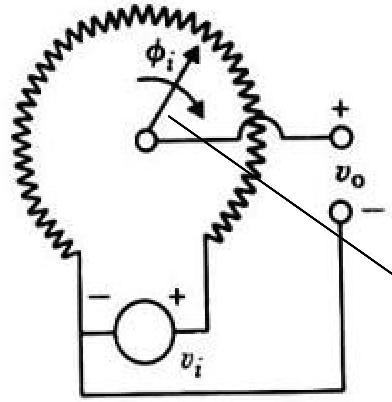
- Design circuit to use Hg strain gauge to detect chest movement/respiration

- Pacemaker
- Airbag

What application of a bladder pressure sensor can you think of?

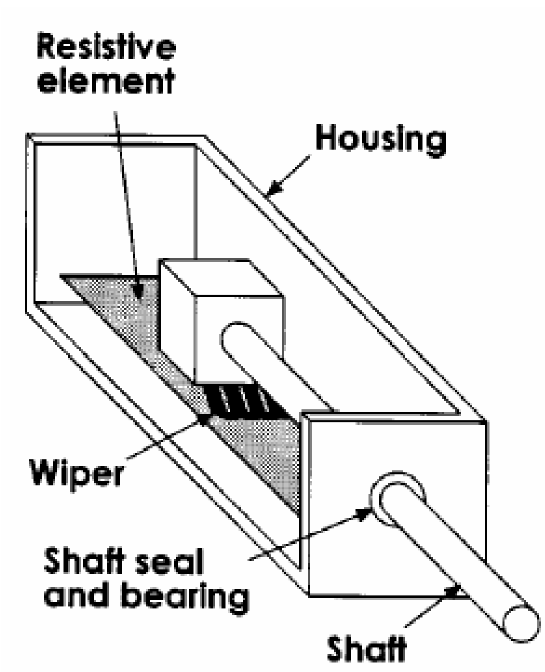
Resistive Sensors - Potentiometers

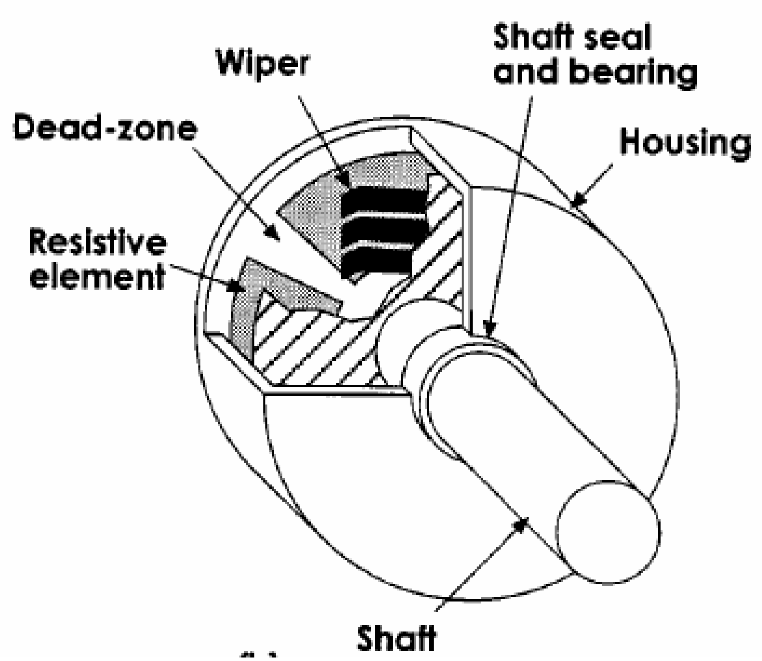




Translational and Rotational
Potentiometers

Translational or angular displacement is proportional to resistance.





Taken from www.fyslab.hut.fi/kurssit/Tfy-3.441/ luennot/Luento3.pdf

Resistive Sensors - Strain Gages

Resistance is related to length and area of cross-section of the resistor and resistivity of the material as

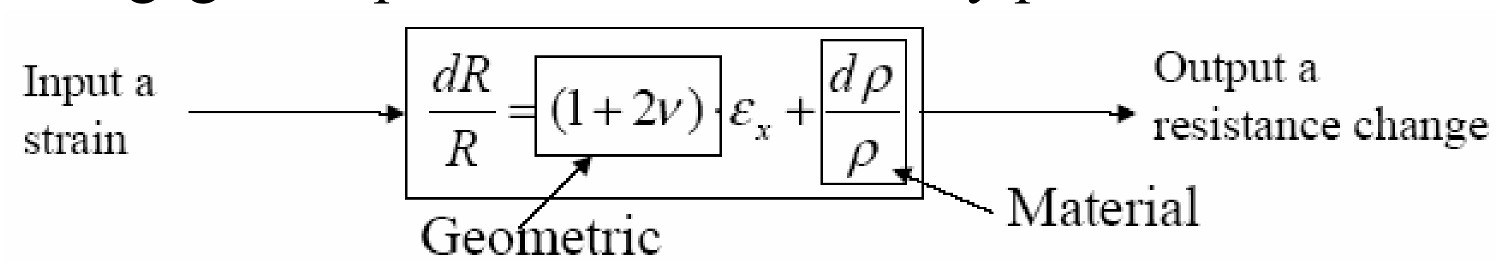
$$R \equiv \frac{\rho l}{A}$$

By taking logarithms and differentiating both sides, the equation becomes

$$\underbrace{\frac{dR}{R} = \frac{dl}{l} - \frac{dA}{A}}_{\text{Dimensional}} + \frac{d\rho}{\rho}$$

Dimensional → $\frac{dl}{l} - \frac{dA}{A}$; piezoresistance → $\frac{d\rho}{\rho}$

Strain gage component can be related by poisson's ratio as



Resistive Sensors – Strain Gage

Gage Factor of a strain gage

$$G = \frac{\text{fractional change in resistance}}{\text{fractional change in strain}}$$

$$G = \frac{1}{\varepsilon}\frac{dR}{R} = (1+2\nu) + \boxed{\frac{1}{\varepsilon}\frac{d\rho}{\rho}}$$

G is a measure of sensitivity

Think of this as a Transfer Function!

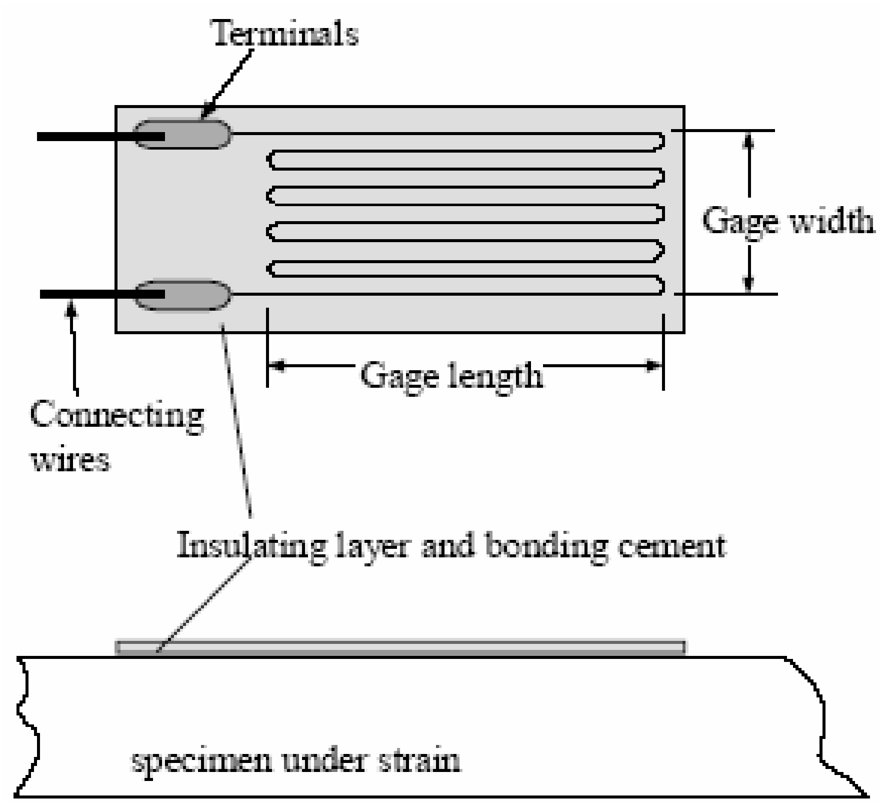
⇒Input is strain

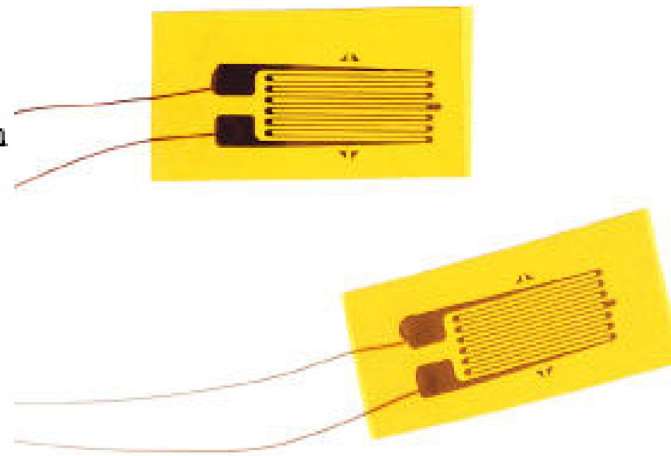
⇒ Output is dR

⇒Put mercury strain gauge around an arm or chest to measure force of muscle contraction or respiration, respectively

⇒ Used in prosthesis or neonatal apnea detection, respectively

Resistive Sensors - Strain Gages



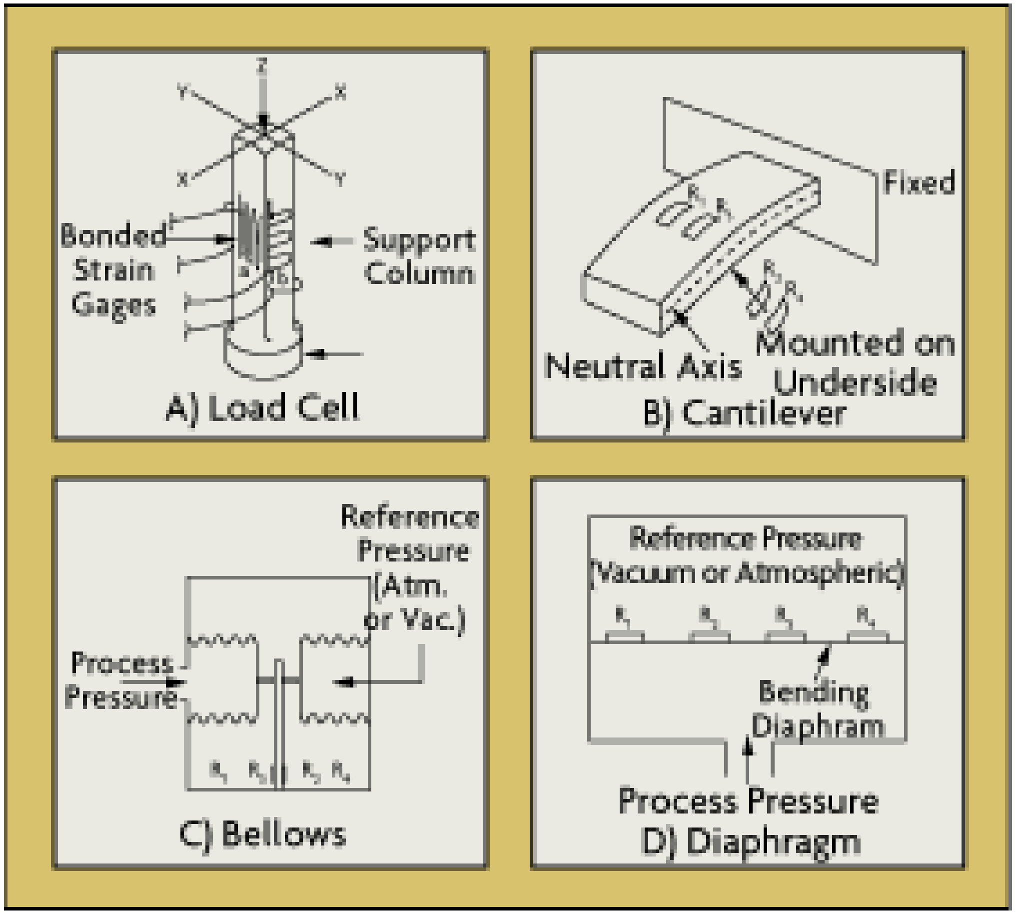


Where can you use it in the body? E.g. prosthetic, or artificial hip/knew?

Strain gages are generally mounted on cantilevers and diaphragms and measure the deflection of these.

More than one strain gage is generally used and the readout generally employs a bridge circuit.

Strain Gage Mounting



Applications!

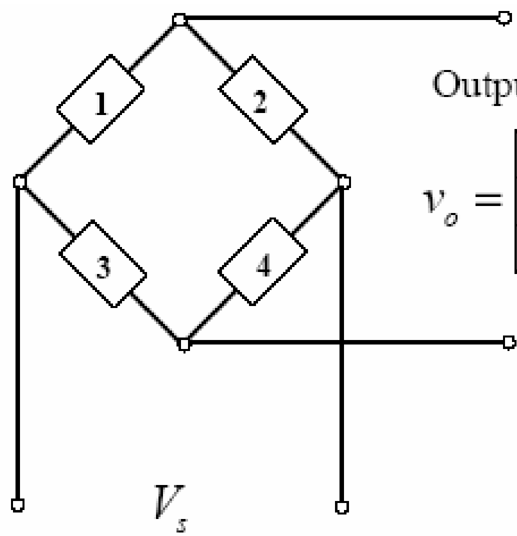
⇒ Surgical forceps

⇒ Blood pressure transducer (e.g. intracranial pressure

⇒ Atomic force microscope

Taken from http://www.omega.com/literature/transactions/volume3/strain3.html

Bridge Circuits

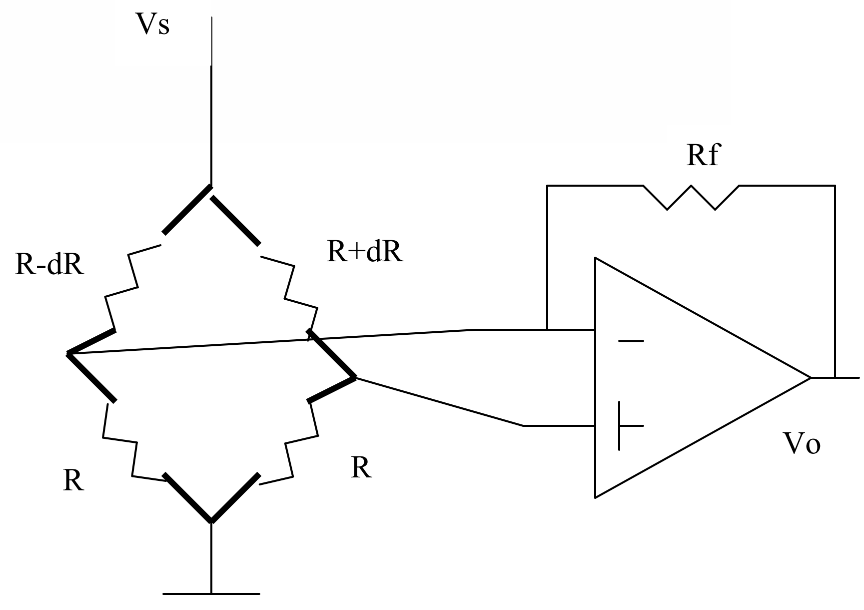


Output DC voltage

$$v_o = \left[\frac{R_1 R_4 - R_2 R_3}{(R_1 + R_2)(R_3 + R_4)} \right] \cdot V_s$$

Null condition is satisfied when: $\frac{R_1}{R_2} = \frac{R_3}{R_4}$

Wheatstone's Bridge



Real Circuit and Sensor Interface

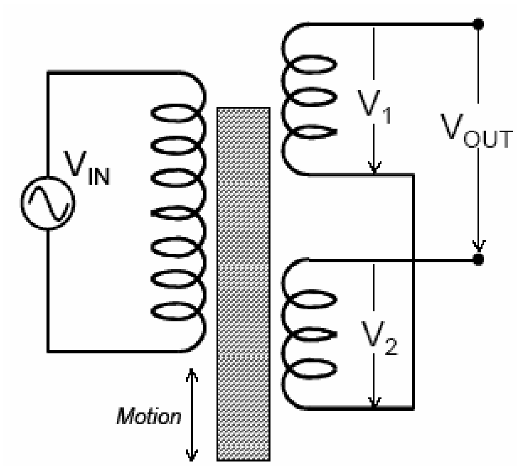
An interesting application: traffic signal

Beach comber!

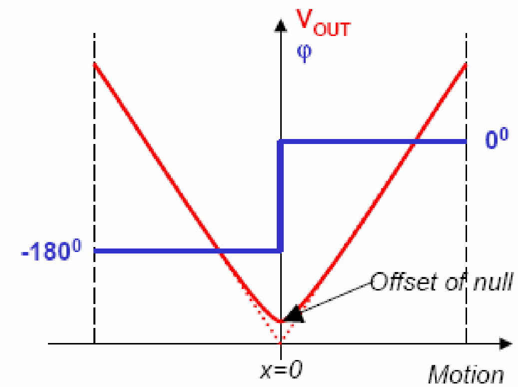
Mine sweeper

Inductive Sensors

Primary Secondary



Displacement Sensor



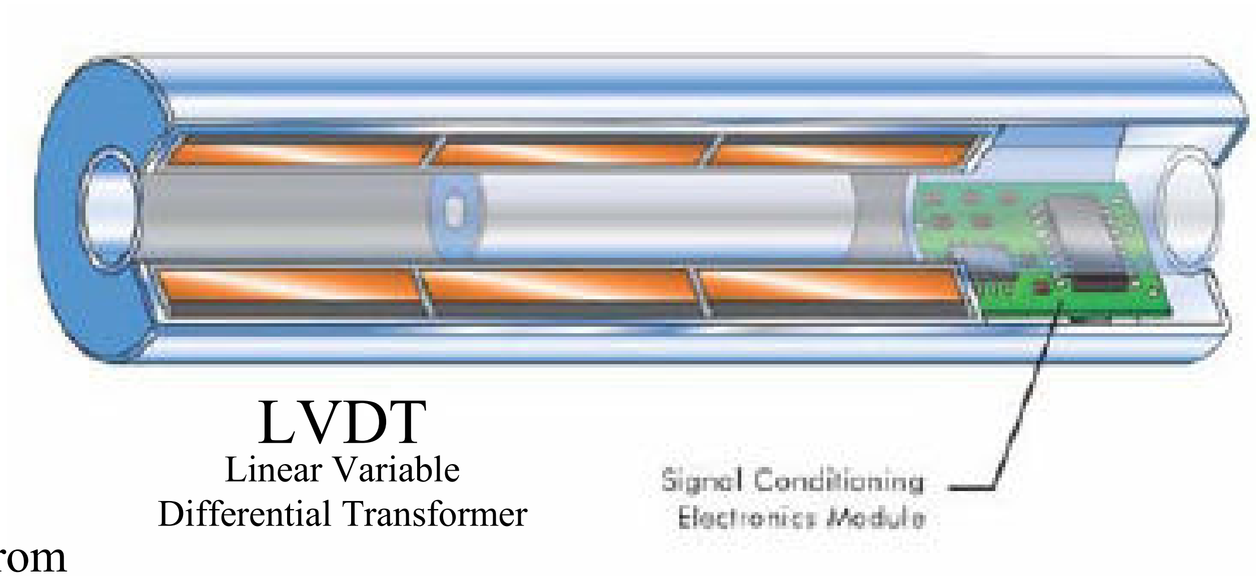
An inductor is basically a coil of wire over a “core” (usually ferrous)

It responds to electric or magnetic fields

A transformer is made of at least two coils wound over the core: one is primary and another is secondary

Inductors and tranformers work only for ac signals

Inductive Sensors - LVDT



LVDT
Linear Variable
Differential Transformer

Taken from

http://www.pages.drexel.edu/~pyo22/mem351-2004/lecture04/pp062-073lvdt.pdf

An LVDT is used as a sensitive displacement sensor: for example, in a cardiac assist device or a basic research project to study displacement produced by a contracting muscle.

Capacitive Sensors

Question: How can I detect small change in capacitance?

How does an elevator keypad or certain contact less computer keypads work?

$$C(x) = \varepsilon A / x = \varepsilon_r \varepsilon_0 A / x$$

where ε = the dielectric constant or permittivity

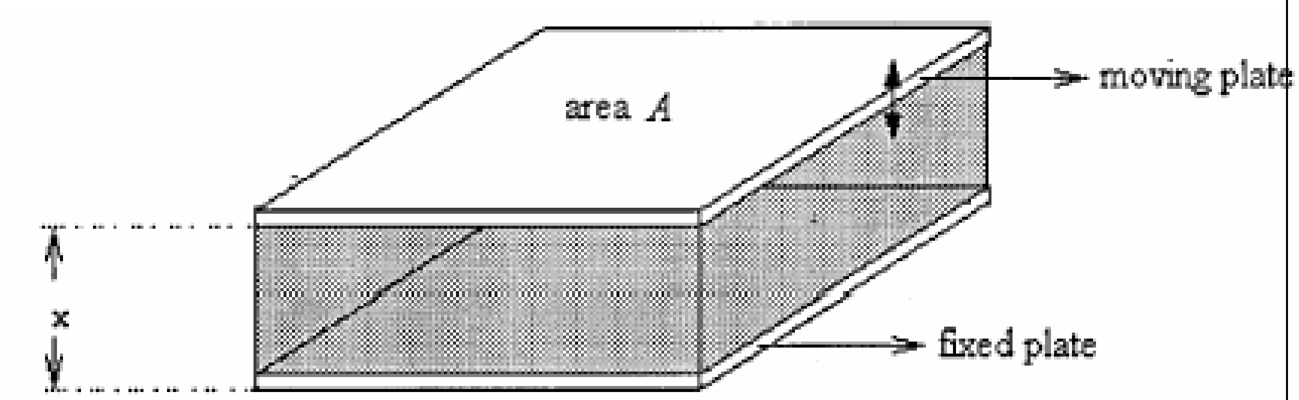
ε_r = the relative dielectric constant (in air and vacuum $\varepsilon_r \approx 1$)

ε_0 = 8.854188×10^{-12} F/m^{-1}, the dielectric constant of vacuum

x = the distance of the plates in m

A = the effective area of the plates in m^2

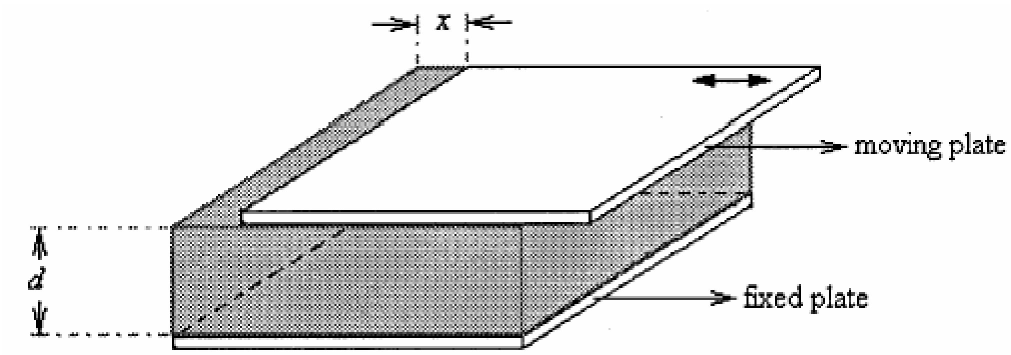
Electrolytic or ceramic capacitors are most common



e.g. An electrolytic capacitor is made of Aluminum evaporated on either side of a very thin plastic film (or electrolyte)

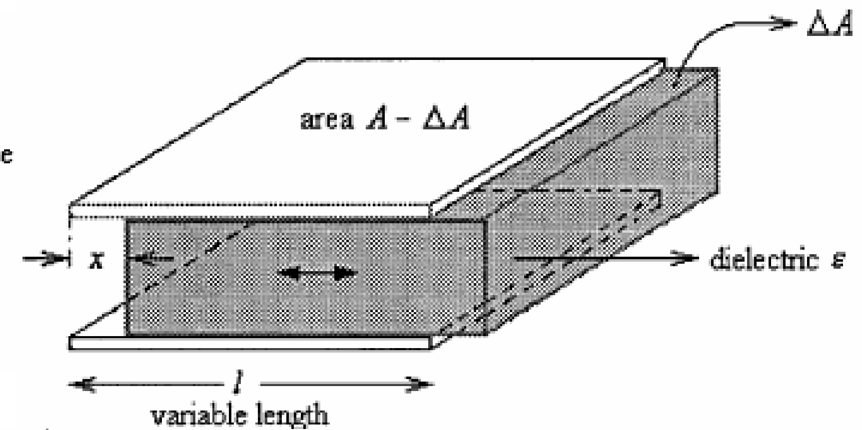
Capacitive Sensors

Other Configurations



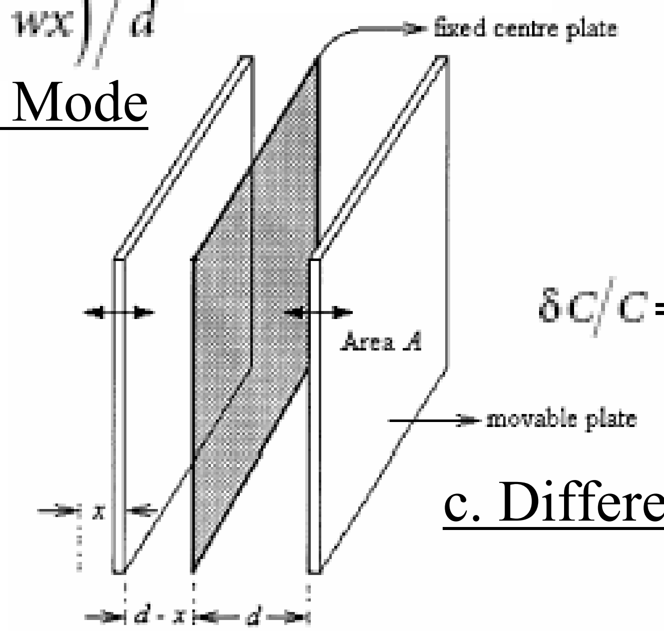
$$C = \varepsilon_r \varepsilon_0 \left(A - wx \right) / d$$

a. Variable Area Mode



$$C = \varepsilon_0 \; w \left[\varepsilon_2 l - \left(\varepsilon_2 - \varepsilon_1 \right) x \right]$$

b. Variable Dielectric Mode

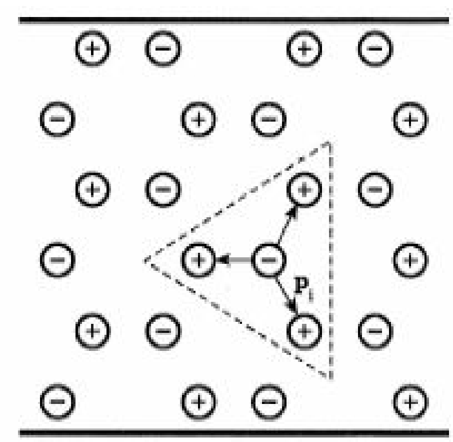


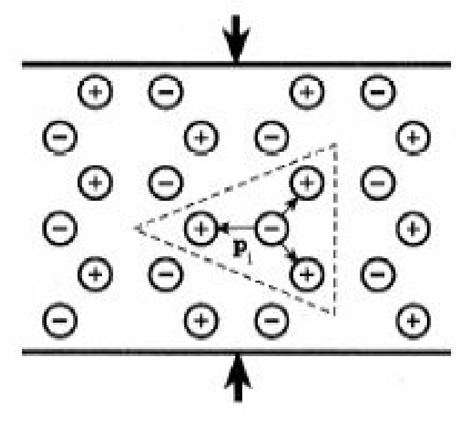
$$\delta C / C = \delta d / d$$

c. Differential Mode

Piezoelectric Sensors

What is piezoelectricity ?





Strain causes a redistribution of charges and results in a net electric dipole (a dipole is kind of a battery!)

A piezoelectric material produces voltage by distributing charge (under mechanical strain/stress)

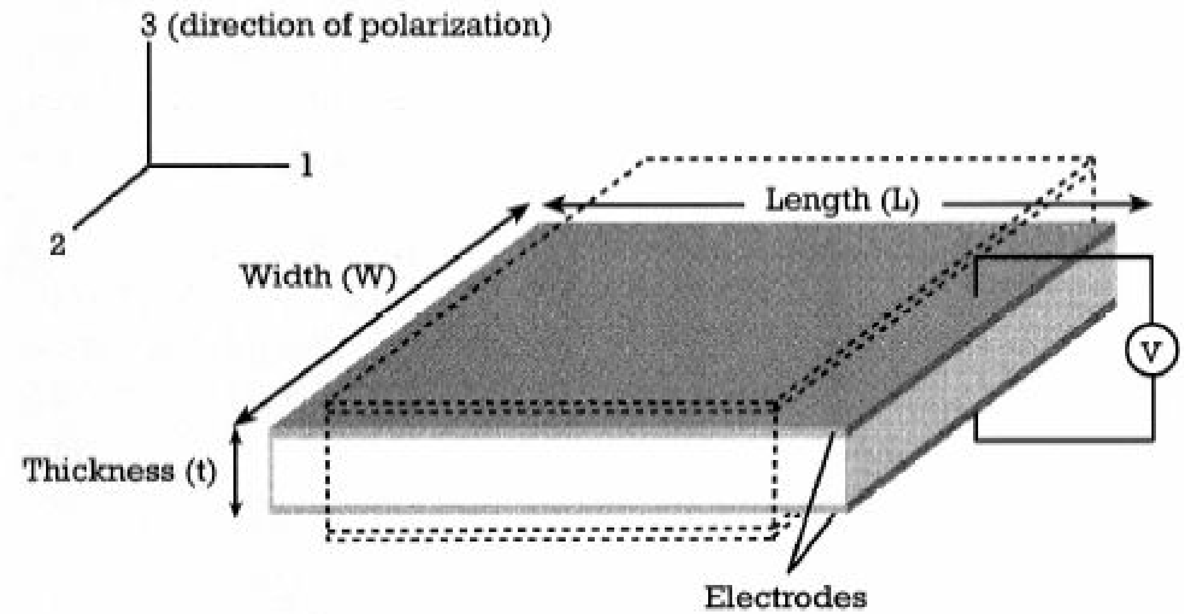
Different transducer applications:

⇒Accelerometer

⇒Microphone

Piezoelectric Sensors

31 denotes the crystal axis



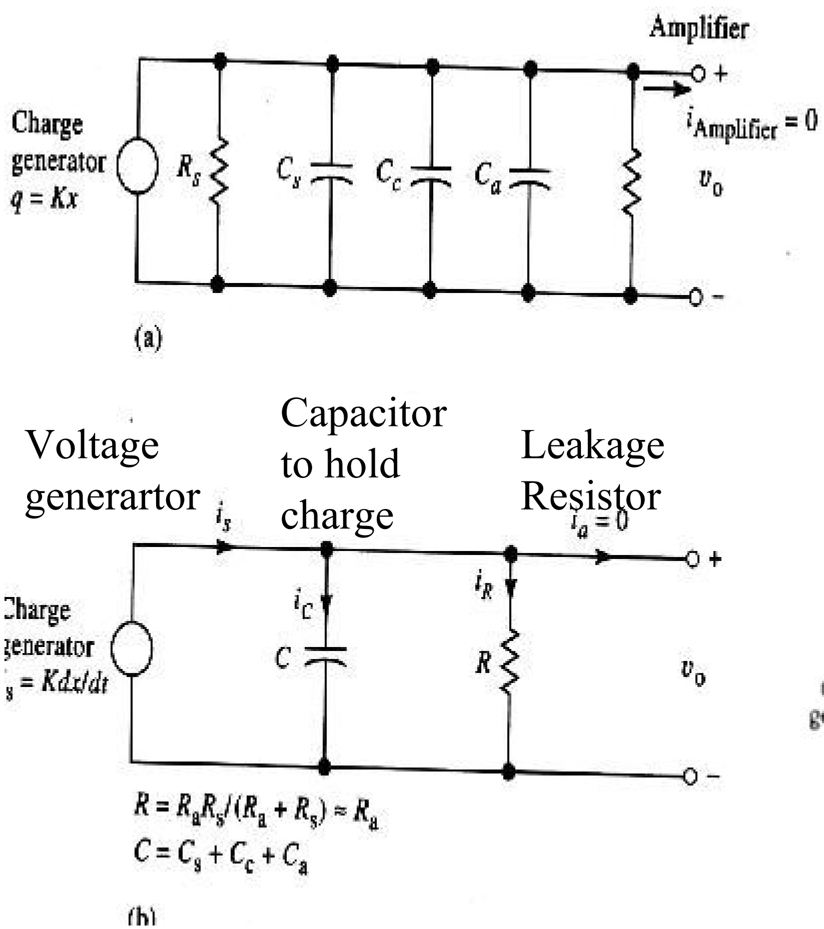
$$V_m = d_{31} \frac{F}{\varepsilon L}$$

$$V_m = d_{31} \frac{F}{\varepsilon W}$$

$$V_m = d_{33} F \frac{t}{\varepsilon L W}$$

Above equations are valid when force is applied in the L,W or t directions respectively.

Piezoelectric Sensors - Circuitry



The Equivalent Circuit

Taken from Webster, "Medical Instrumentation"

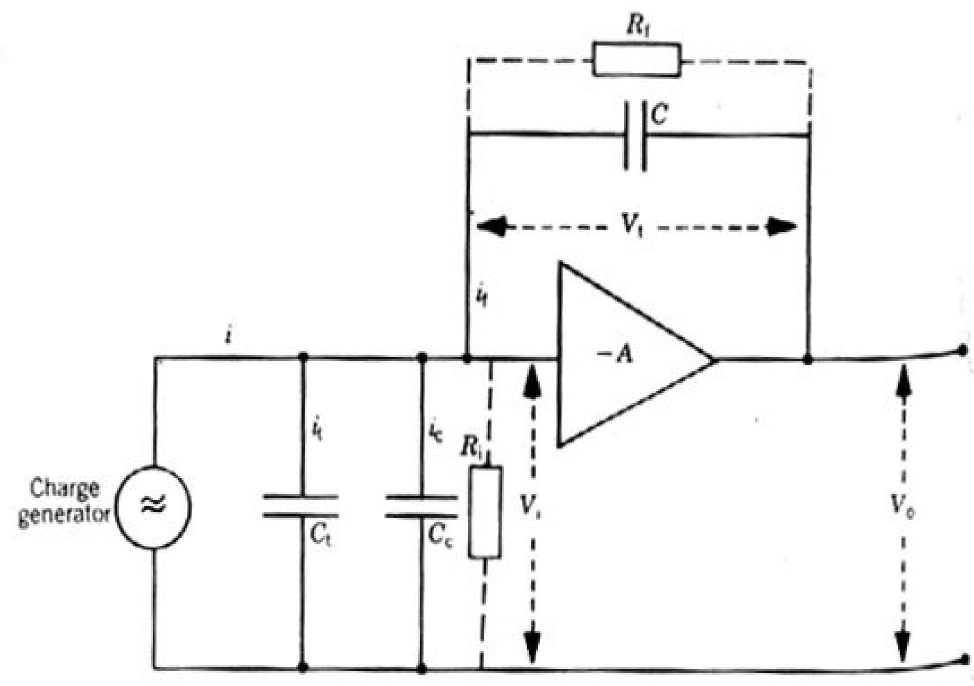


Figure 4. Schematic diagram of a charge amplifier.

Temperature Sensors

1. Resistance based
   a. Resistance Temperature Devices (RTDs)
   b. Thermistors
2. Thermoelectric – Thermocouples
3. Radiation Thermometry
4. Fiber Optic Sensor

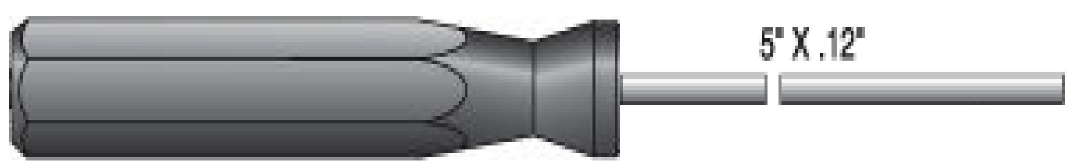
RTDs

RTDs are made of materials whose resistance changes in accordance with temperature

Metals such as platinum, nickel and copper are commonly used.

They exhibit a positive temperature coefficient.

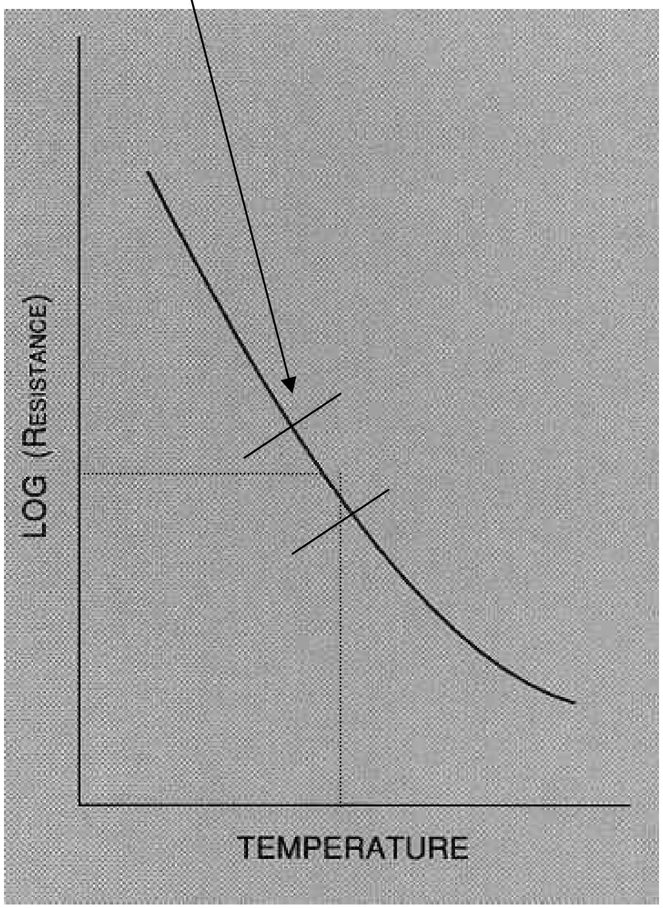
$$R_T = R_0\left[1 + \alpha_1 T + \alpha_2 T^2 + \cdots \alpha_n T^n + \right] \cong R_0\left[1 + \alpha_1 T\right]$$



A commercial ThermoWorks RTD probe

Thermistors

Over a small dynamic range a thermistor can be linearized



Thermistors are made from semiconductor material.

Generally, they have a negative temperature coefficient (NTC), that is NTC thermistors are most commonly used.

$$R_T = R_0 \exp\left[B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

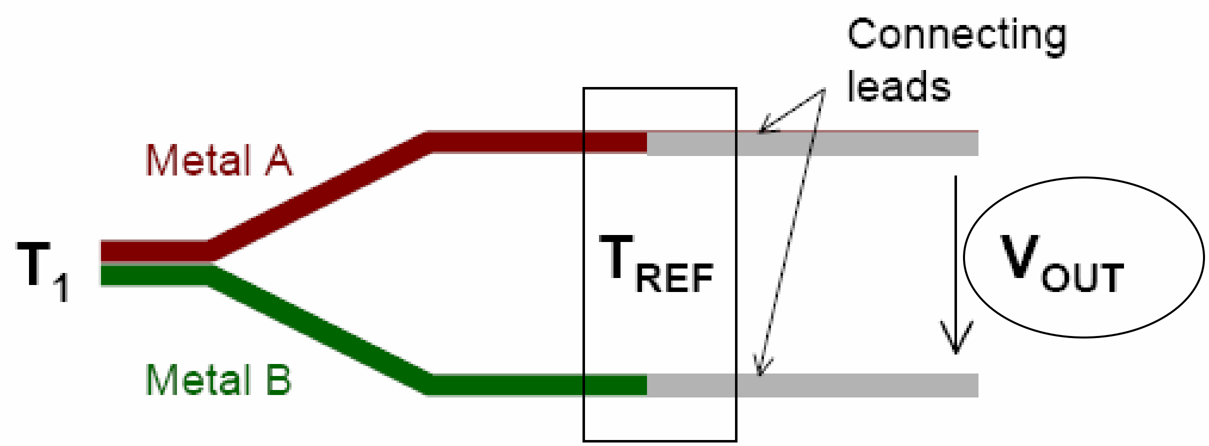
Ro is the resistance at a reference point (in the limit, absolute 0).

Thermocouples

Seebeck Effect

When a pair of dissimilar metals are joined at one end, and there is a temperature difference between the joined ends and the open ends, thermal emf is generated, which can be measured in the open ends.

This forms the basis of thermocouples.



In a bimetallic strip, each metal has a different thermal coefficient…this results in electromagnetic force/emf or bending of the metals.

Thermocouples

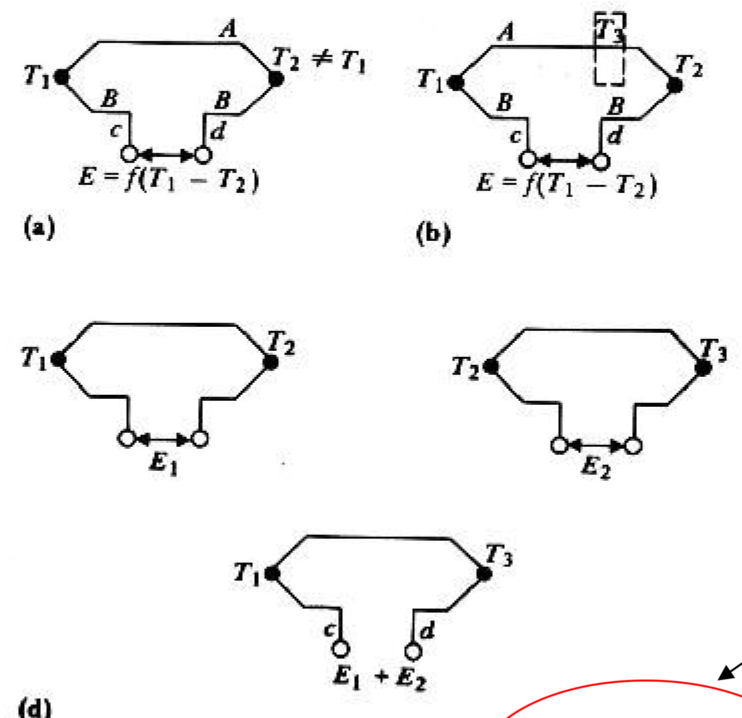


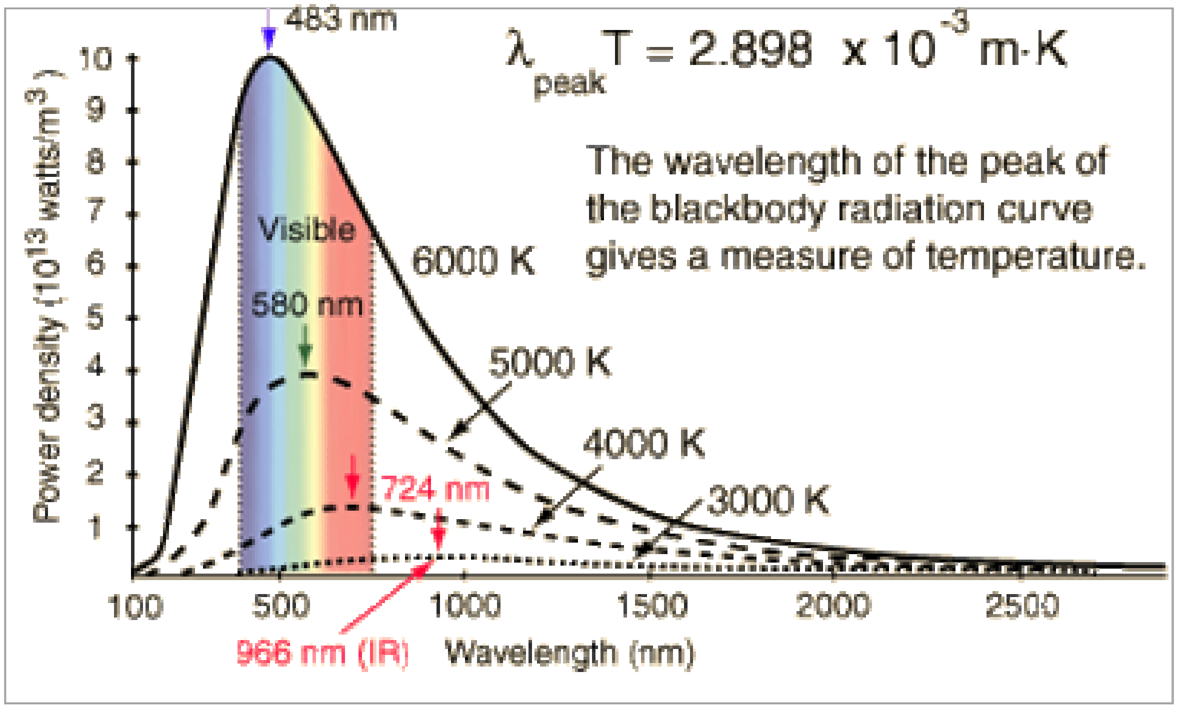
Figure 2.12 Thermocouple circuits (a) Peltier emf. (b) Law of homogeneous circuits. (c) Law of intermediate metals. (d) Law of intermediate temperatures.

Cooling electronics, camera chips

Taken from Webster, “Medical Instrumentation”

Radiation Thermometry

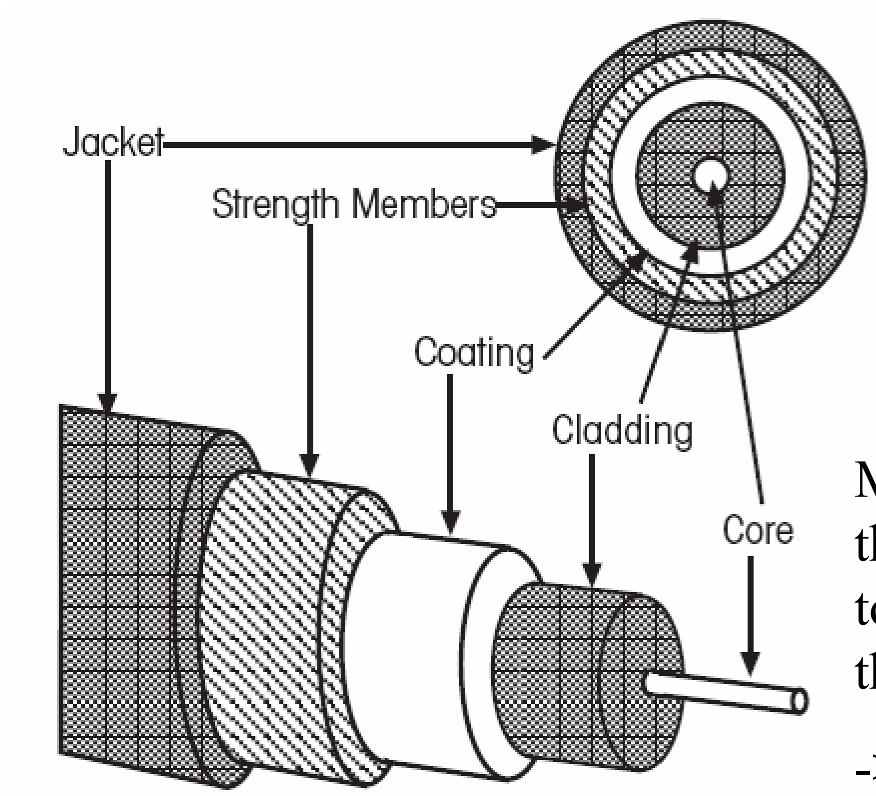
Governed by Wien's Displacement Law which says that at the peak of the emitted radiant flux per unit area per unit wavelength occurs when $\lambda_{max}T=2.898 \times 10^{-3}\ m^{o}K$



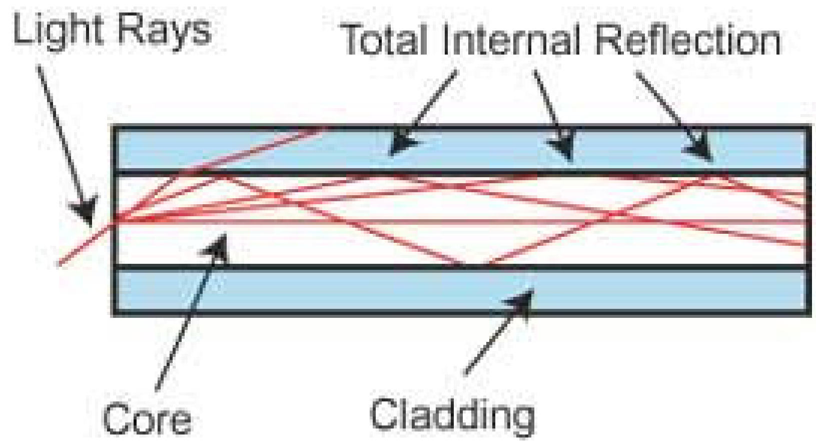
Infrared or thermal cameras

Taken from http://hyperphysics.phy-astr.gsu.edu/hbase/wien.html#c2

Fiber Optics



A fiber optic cable



Most of the light is trapped in the core, but if the cladding is temperature sensitive (e.g. due to expansion), it might allow some light to leak through.

-> hence the amount of light transmitted would be proportional to temperature

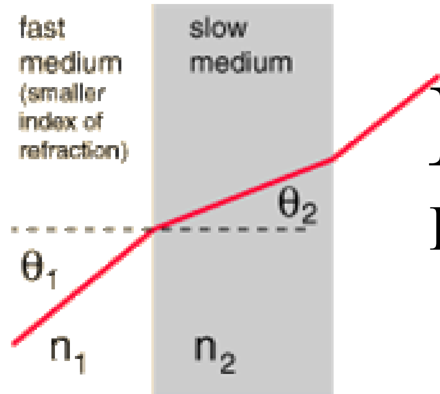
-> since you are measuring small changes in light level, this sensor is exquisitely sensitive.

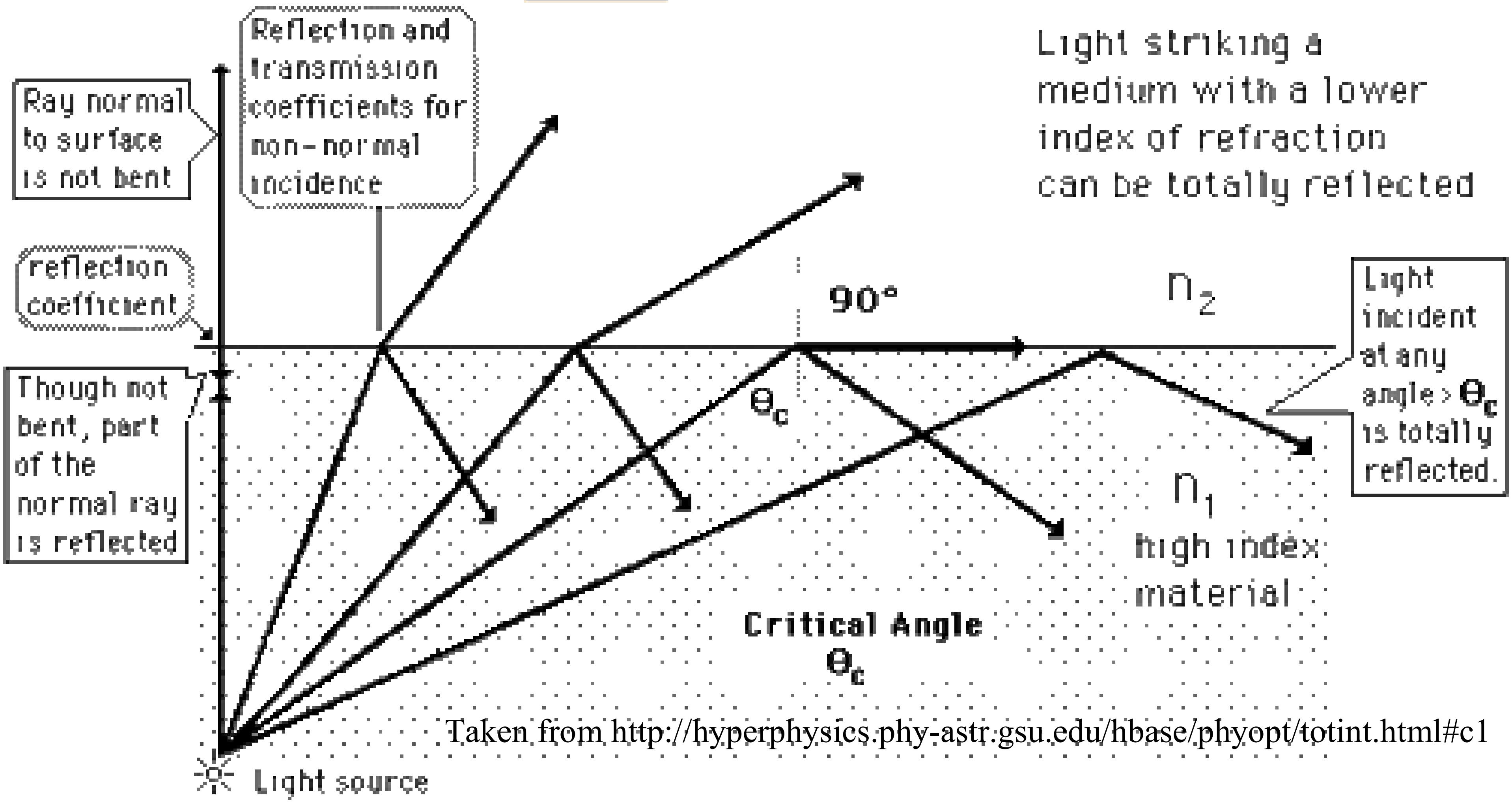
Fiber Optics

Based on **Total Internal Reflection**

Snell's Law

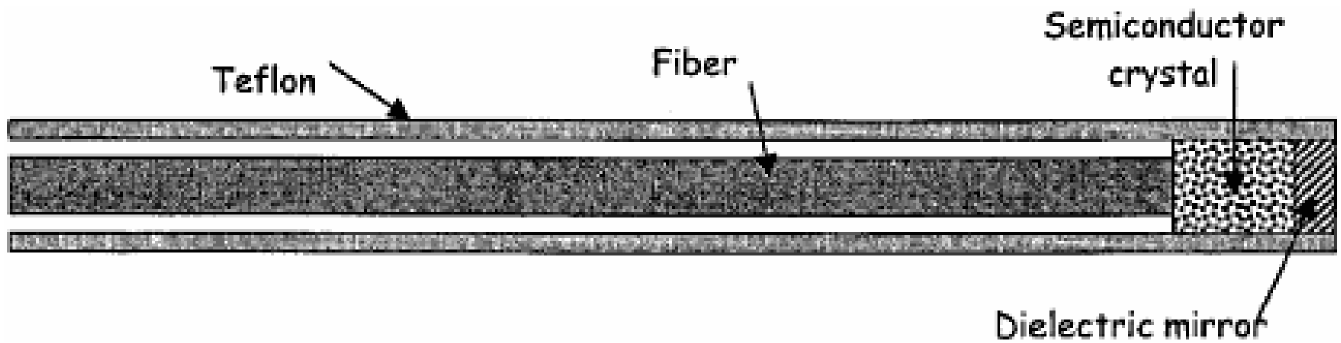
$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$





Taken from http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/totint.html#c1

Fiber Optic Temperature Sensors



Nortech's fiber-optic temperature sensor probe consists of a gallium arsenide crystal and a dielectric mirror on one end of an optical fiber and a stainless steel connector at the other end.

Taken from http://www.sensorsmag.com/articles/0501/57/main.shtml

Other Physical Sensors

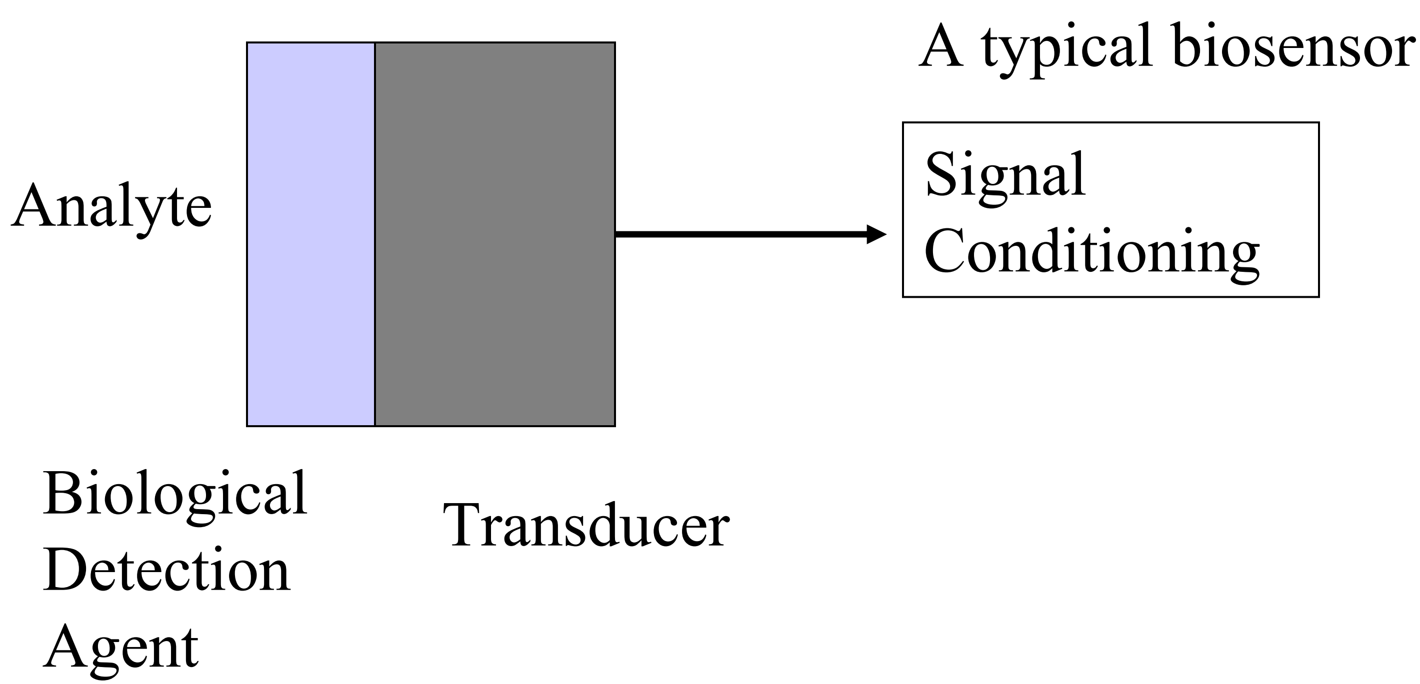
Photoemissive sensors

Photoconductive sensors (LDRs)

Photovoltaic sensors

Chemical Sensors (Biosensors)

Biosensors produce an output (electrical) which is proportional to the concentration of biological analytes.



Biosensing Principles

Chemical Sensing

- Electrochemical => Neurochemical sensor for Dopamine, Nitric Oxide, etc.
  - Potentiometric
  - Amperometric
  - FET based
  - Conductometric

  Direct electrochemical transduction

- Optical => Pulse oximeter

  Absorption, fiber optic transmission

- Piezoelectric => Accelerometer, microphone

  Chemical binding changes the resonance property such as frequency

- Thermal => Implanted rectal probe, pacemaker

  Thermal/temperature response to chemical reaction

Biosensing Principles

Analyte	Method of assay
Glucose	Amperometric biosensor
Urea	Potentiometric biosensor
Lactate	Amperometric biosensor
Hepatitis B	Chemiluminescent immunoassay
Candida albicans	Piezo-electric immunoassay
Cholesterol	Amperometric biosensor
Penicillins	Potentiometric biosensor
Sodium	Glass ion-selective electrode
Potassium	Ion-exchange-selective electrode
Calcium	Ionophore ion-selective electrode
Oxygen	Fluorescent quenching sensor
pH	Glass ion-selective electrode

Holly Grail…da Vinci Code of sensing…Glucose sensor

-> Know every thing there is to know…research “

Electrochemical Sensors

Potentiometric : These involve the measurement of the emf (potential) of a cell at zero current. The emf is proportional to the logarithm of the concentration of the substance being determined.

Amperometric : An increasing (decreasing) potential is applied to the cell until oxidation (reduction) of the substance to be analyzed occurs and there is a sharp rise (fall) in the current to give a peak current. The height of the peak current is directly proportional to the concentration of the electroactive material. If the appropriate oxidation (reduction) potential is known, one may step the potential directly to that value and observe the current.

Conductometric. Most reactions involve a change in the composition of the solution. This will normally result in a change in the electrical conductivity of the solution, which can be measured electrically.

Blood Gas Measurement

Fast and accurate measurements of the blood levels of the partial pressures of oxygen (pO_2), carbon dioxide (pCO_2) as well as the concentration of hydrogen ions (pH) are vital in diagnosis.

Oxygen is measured indirectly as a percentage of Haemoglobin which is combined with oxygen (sO_2)

$$sO_2 = \frac{[HbO_2]}{[Hb]} \times 100$$

pO_2 can also provide the above value using the oxyhaemoglobin dissociation curve but is a poor estimate.

pH electrode

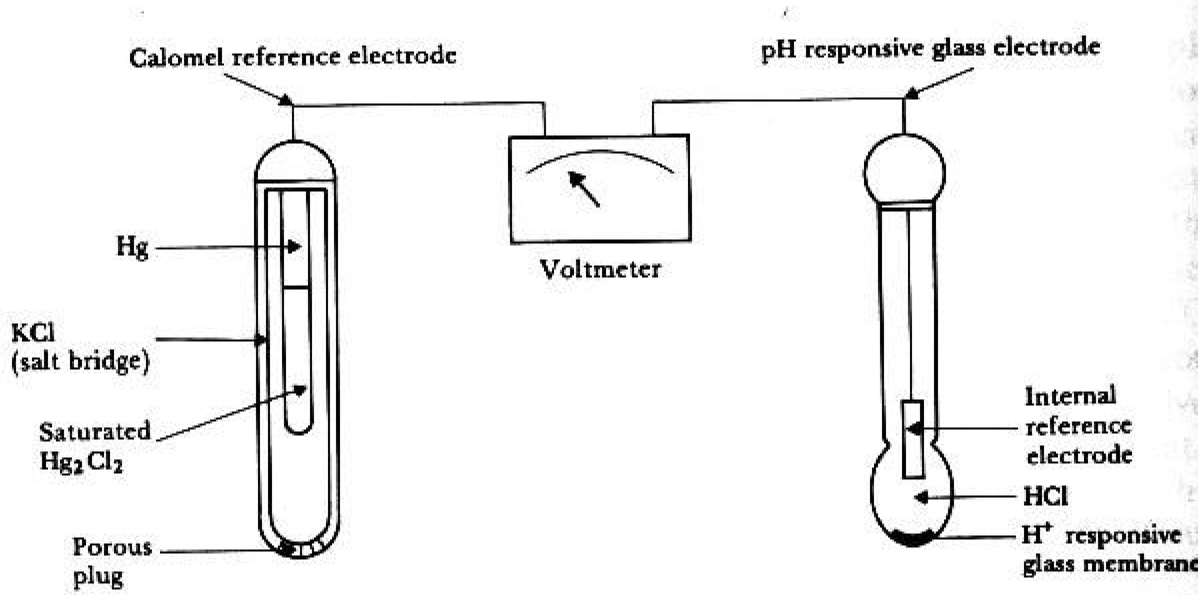


Figure 10.2 pH electrode (From R. Hicks, J. R. Schenken, and M. A. Steinrauf, *Laboratory Instrumentation.* Hagerstown, MD: Harper & Row, 1974. Used with permission of C. A. McWhorter.)

Governing equation is the Nernst Equation

$$E_H = \frac{RT}{nF}\ln\left(\frac{[H]_0}{[H]_i}\right)$$

pCO_2 Electrode

The measurement of pCO_2 is based on its linear relationship with pH over the range of 10 to 90 mm Hg.

$$H_2O + CO_2 \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^-$$

The dissociation constant is given by

$$k = \frac{[H^+][HCO_3^-]}{a \cdot pCO_2}$$

Taking logarithms

$$pH = \log[HCO_3^-] - \log k - \log a - \log pCO_2$$

pO_2 electrode

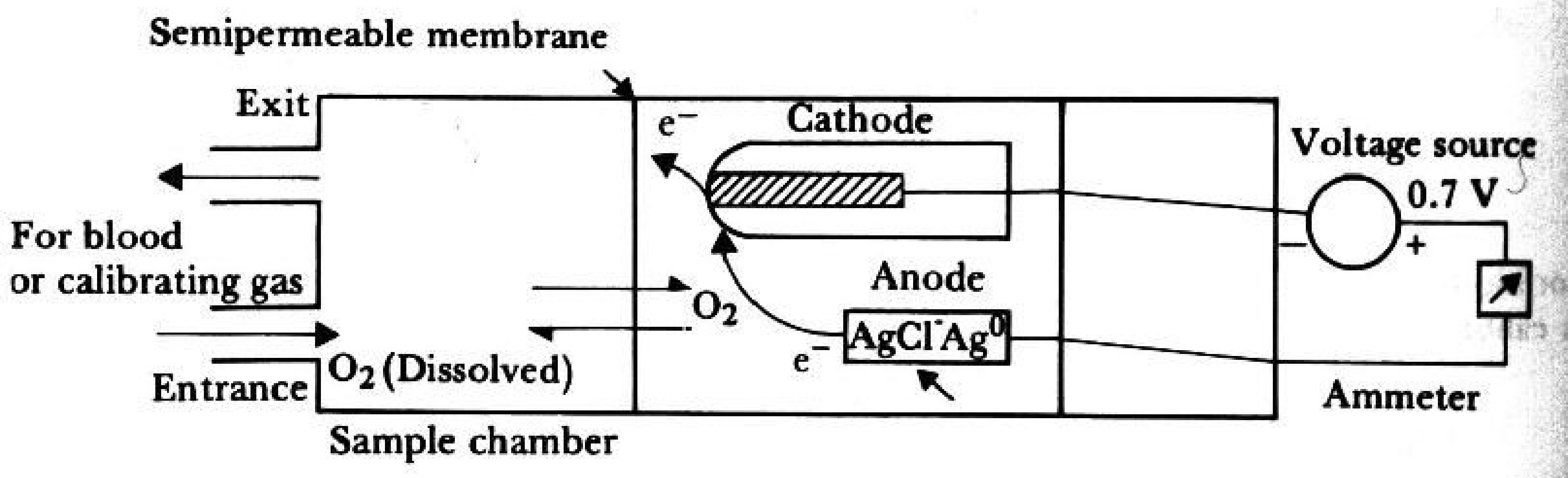
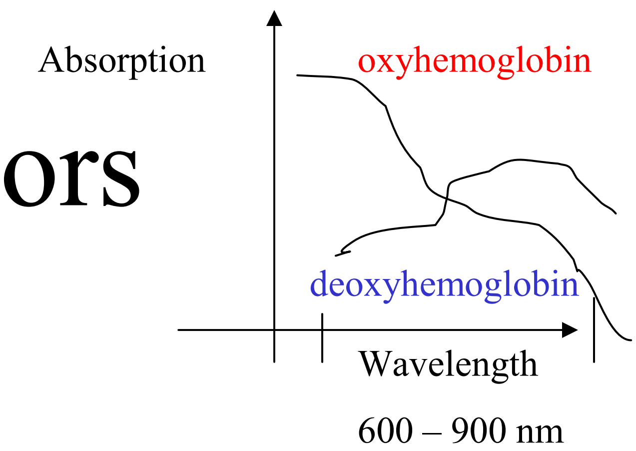


Figure 10.4 ***P_{O_2}* electrode** (From R. Hicks, J. R., Schenken, and M. Steinrauf, *Laboratory Instrumentation.* Hagerstown, MD: Harper & R[o]
1974. Used with permission of C. A. McWhorter.)

The pO_2 electrode consists of a platinum cathode and a Ag/AgCl reference electrode.

Optical Biosensors

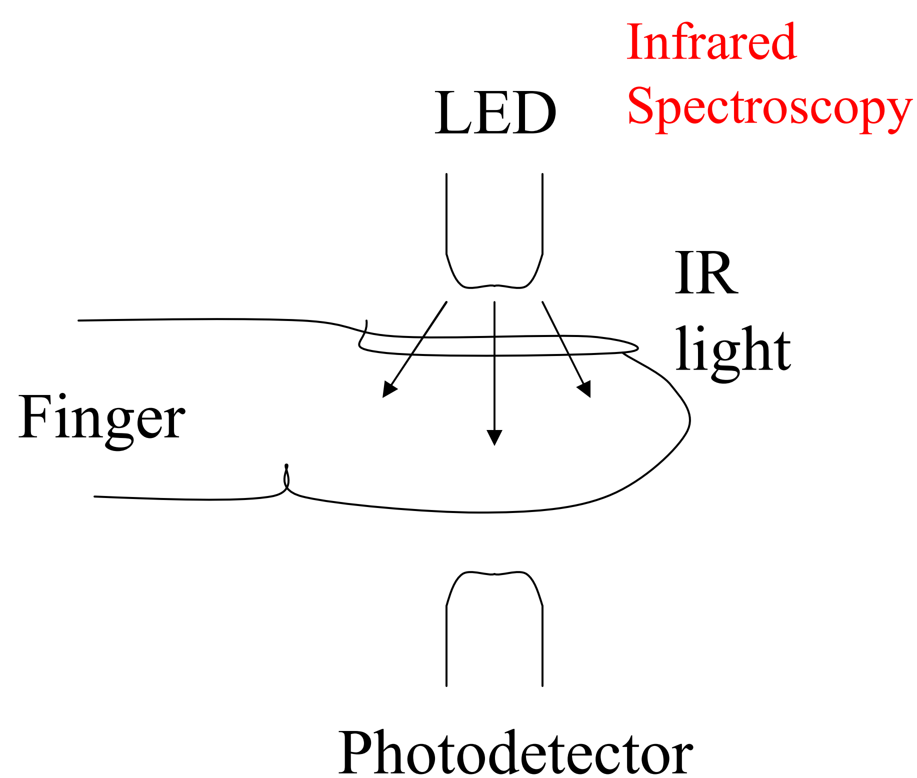


Sensing Principle

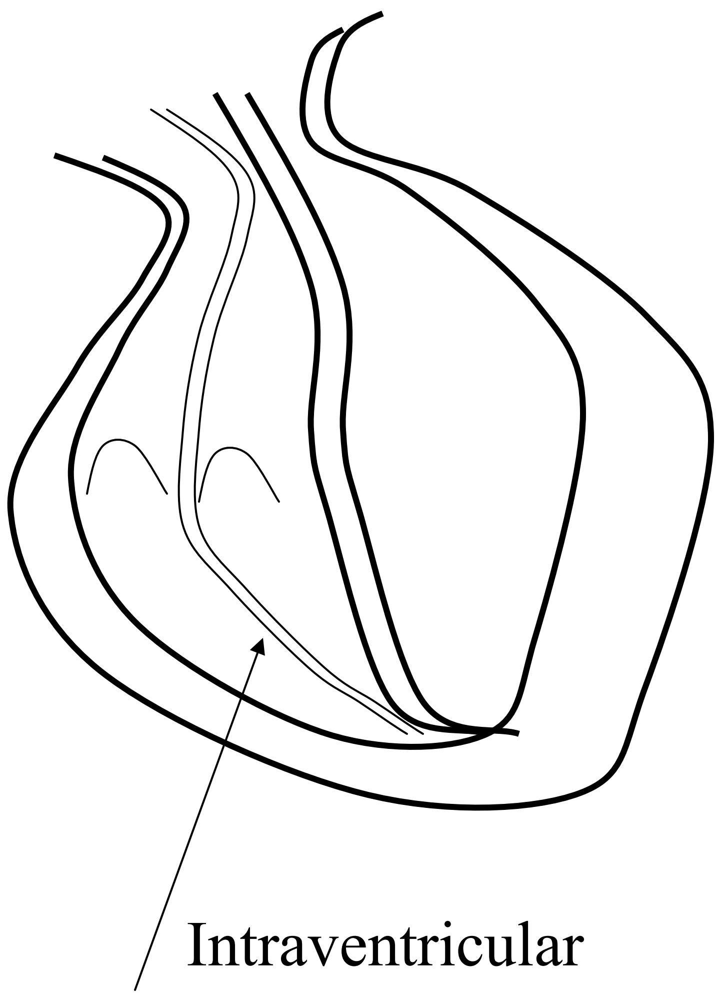
They link changes in light intensity to changes in mass or concentration, hence, fluorescent or colorimetric molecules must be present.

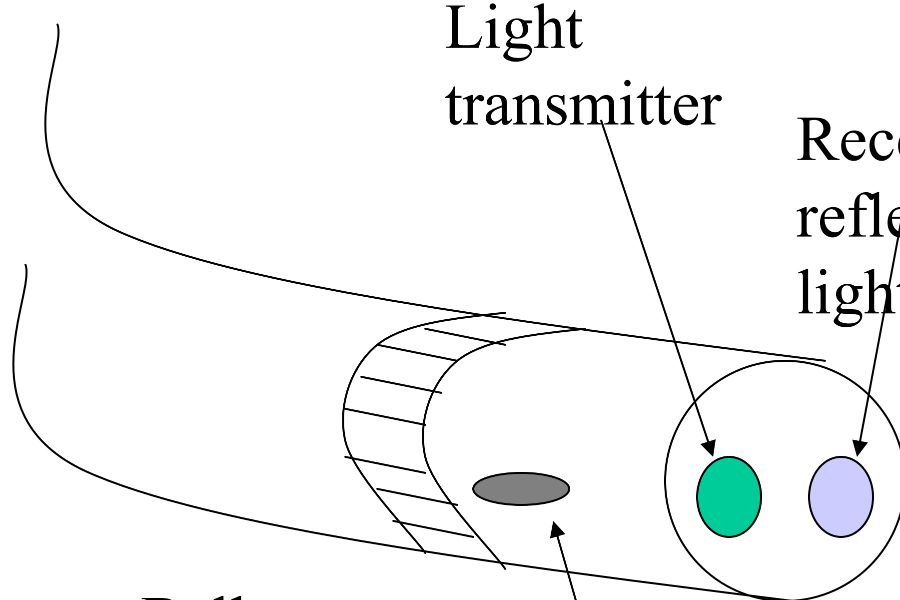
Various principles and methods are used :

Optical fibres, surface plasmon resonance,Absorbance, Luminescence



Fiber Optic Biosensor





Absorption/Fluorescence

Different dyes show peaks of different values at different concentrations when the absorbance or excitation is plotted against wavelength.

Phenol Red is a pH sensitive reversible dye whose relative absorbance (indicated by ratio of green and red light transmitted) is used to measure pH.

HPTS is an irreversible fluorescent dye used to measure pH.

Similarly, there are fluorescent dyes which can be used to measure O_2 and CO_2 levels.

Pulse Oximetry

The pulse oximeter is a spectrophotometric device that detects and calculates the differential absorption of light by oxygenated and reduced hemoglobin to get sO_2. A light source and a photodetector are contained within an ear or finger probe for easy application.

Two wavelengths of monochromatic light -- red (660 nm) and infrared (940 nm) -- are used to gauge the presence of oxygenated and reduced hemoglobin in blood. With each pulse beat the device interprets the ratio of the pulse-added red absorbance to the pulse-added infrared absorbance. The calculation requires previously determined calibration curves that relate transcutaneous light absorption to sO_2.

Glucose Sensors

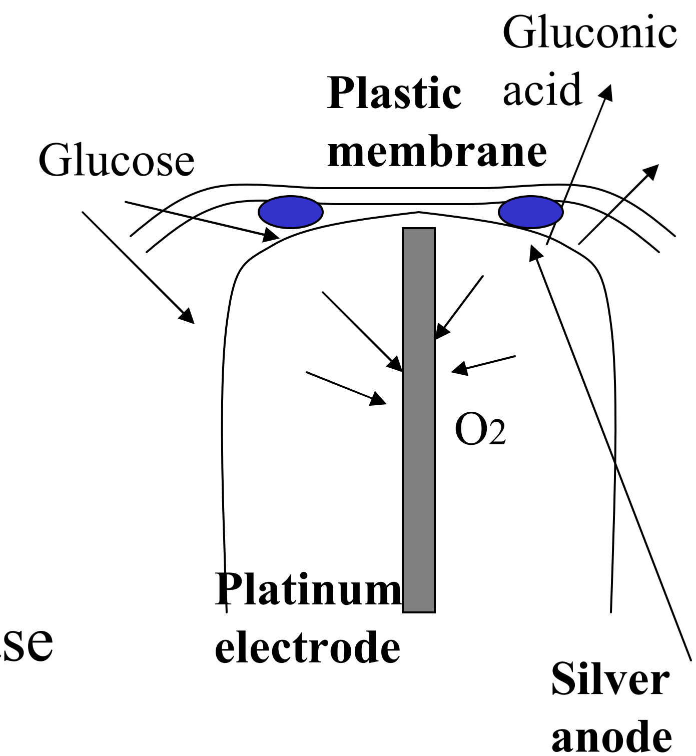
Enzymatic Approach

$$Glucose + O_2 \xrightarrow{Glucose Oxidase} Gluconic Acid + H_2O_2$$

Makes use of catalytic (enzymatic) oxidation of glucose

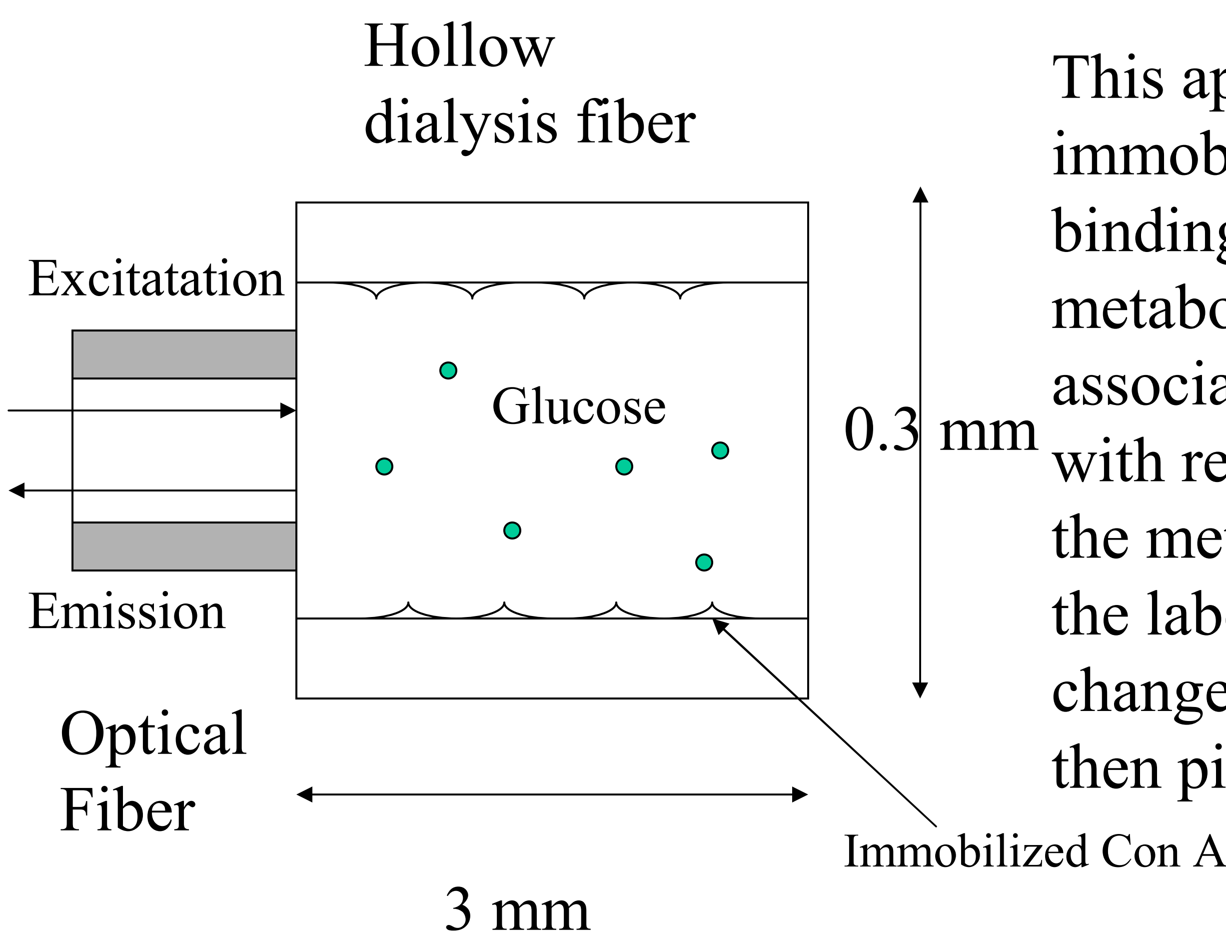
The setup contains an enzyme electrode and an oxygen electrode and the difference in the readings indicates the glucose level.

The enzyme electrode has glucose oxidase immobilized on a membrane or a gel matrix.



Glucose Sensor

Affinity Approach



This approach is based on the immobilized competitive binding of a particular metabolite (glucose) and its associated fluorescent label with receptor sites specific to the metabolite (glucose) and the labeled ligand. This change in light intensity is then picked up.

Problems (1)

(a) Describe a sensor or a measurement system in which *accuracy* is important. In contrast, describe a sensor or a measurement in which *precision* is important.

(b) A temperature sensor, such as a thermistor can be described by a first order system. Write down the general equation for a first order system (you can write a differential equation *or* a transfer function).

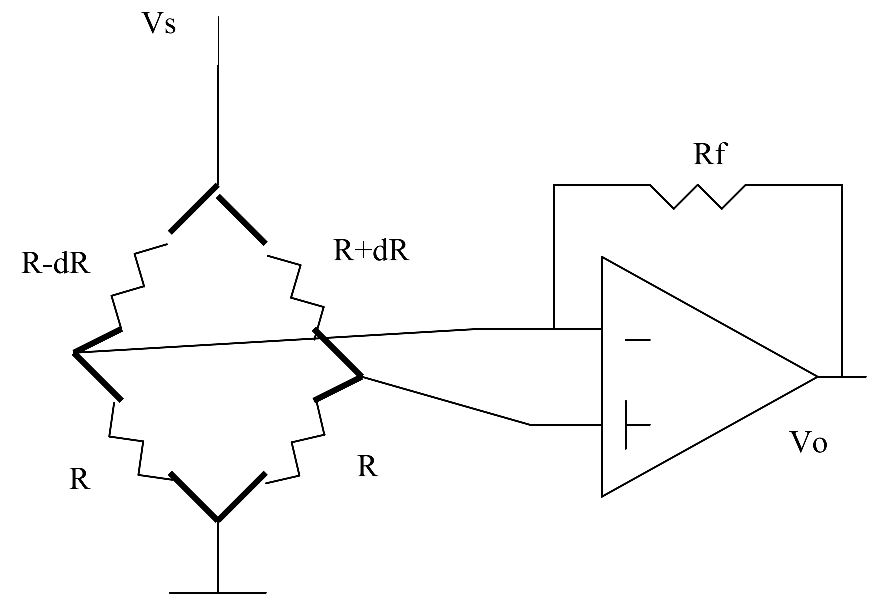
Plot the output of the first order system in response to a step change in temperature.

A blood pressure sensor is described by a second order system. Write down the general equation for a second order system (you can write a differential equation or a transfer function).

Plot the output of the second order *underdamped* pressure system in response to a blood pressure signal.

Problem (2)

We would like to measure small temperature changes using a thermistor. Thermistor is a resistor which changes its resistance in proportion to temperature. (i) First, suggest a suitable biomedical application of the thermistor. (ii) A useful design is to put the thermistor in a bridge circuit design. Calculate the output of the following circuit for a very small dR changes with respect to the R values of the bridge elements (there are two sensors, one's resistance goes up while the other goes down). Hint: The output should be a relationship between Vs, R, dR, Rf and Vo.



Problem (3)

We would like to develop a novel temperature sensor for measuring central body temperature very accurately. Two applications are proposed:

(i) noninvasively measure the temperature of an infant, and

(ii) measure the temperature change in a rate responsive implantable pacemaker (so that exercise dependent changes in the temperature can be used to alter the pacing rate).

Please suggest suitable sensors, and describe *very briefly,* the benefits and problems of your design solution. Specifically, why did you selected that particular sensor, what should be its performance/specification, and what are its benefits and disadvantages.

An optical system is used in a “smart cane” to detect and warn of an obstacle. Draw the CIRCUIT of a light source and a photodetector for this project.

Problems (4)

You are asked to record magnetic field from the brain. Now, brain's magnetic field is 10e-15 Tesla as opposed to earth's field which is 10e-7 Tesla. What kind of sensor would you use to record brain's magnetic field (now, I realize that this is a long shot – but just may be, you could figure this out)? What precautions would you take to record this very small magnetic field from the brain in presence of other interference?

What instrument is used to measure the magnetic field from the brain? B) What are the possible advantages and disadvantages of the magnetic versus electrical measurement? C) To your knowledge, what breakthroughs in the scientific world that have are occurred (or ought to occur?) that would make magnetic field measurement more feasible and affordable? D) If you had a cheap magnetic field sensor (with a relatively lower sensitivity) available what other biomedical application would you think of (other than biopotential measurements).

Problems (5)

Describe one “innovative” sensor and matching instrumentation for recording breathing or respiration. The applications might be respirometry/spirometry, atheltes knowing what their heart rate is, paralyzed individuals who have difficulty breathing needing a respiratory sensor to stimulate and control phrenic nerve. You may select one of these or other applications, and then identify a suitable sensor. The design (develop suitable circuit) for interfacing to the sensor to get respiratory signal.

Design and draw a small circuit to detect the heart beat pulse (do not draw or design ECG amplifier) and pulse based oxygenation. Come up with a suitable sensor and interface electronics. Give only the pulse detection circuit. Now, search and review a) commercial pulse and oximeter design concepts, b) locate some patents, and c) publications in the past few year on the subject.

Problem (6)

- What are the different ways you can measure temperature? i.e. give different sensor elements…R, diode/transistor… what else?
- How would you measure temperature in infants, core body, noninvasively, without contact, through clothes or chemical weapon protective clothes?