Spring 2020

CSEN 1099 – Introduction to Biomedical Engineering

Biomedical Sensors

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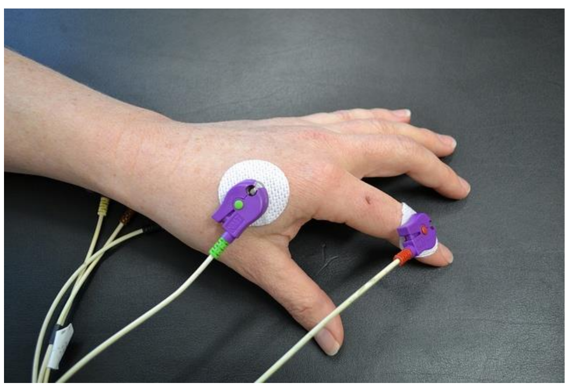
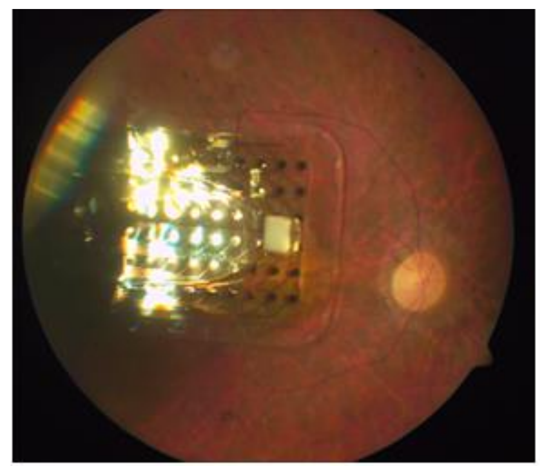
Biomedical Sensors

- Biomedical sensors are used routinely in clinical medicine and biological research for measuring many physiological variables such as heart signals, brain signals, body temperature …
- Patient self-testing and physician office screening are the two most rapidly expanding areas
- Biomedical Sensors can be classified to sensors that measure electrical, physical or chemical quantities



Muscle Activity Measurement

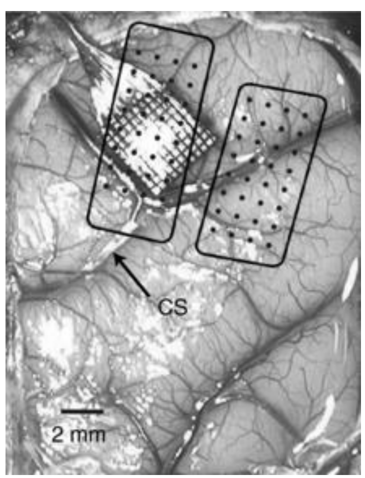
Blood Oxygenation Measurement



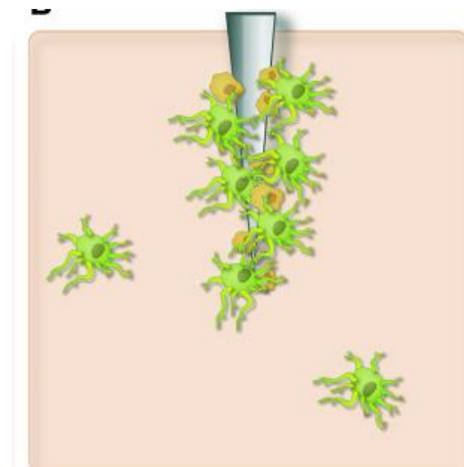
Retinal Implant

Biomedical Sensors Fabrication

- Biomedical sensors are first tested *in vitro* (not on a live subject) in terms of the accuracy, operating range, response time, sensitivity, resolution, and reproducibility
- If *in vitro* tests succeed, they are then tested *in vivo*
- Packaging of *in vivo* biomedical sensors is important as they have to be safe, biocompatible and reliable
- Whenever a sensor comes into contact with body fluids, the host itself may affect the function of the sensor or the sensor may affect the site in which it is implanted



Implanted Microelectrode Array



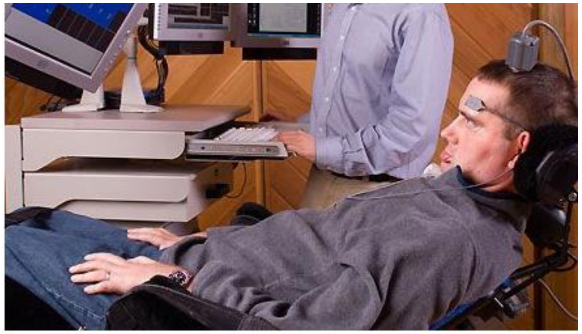
Glia Cells Surround Microelectrode Arrays

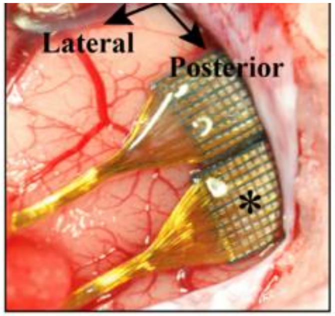
I. Biopotential Measurements

- The function of biopotential electrodes is to couple the ionic potentials generated inside the body to an electronic instrument

- Biopotential electrodes are classified either as non-invasive (skin surface) or invasive (e.g., microelectrodes or wire electrodes)

Non-invasive Brain Signals Recording

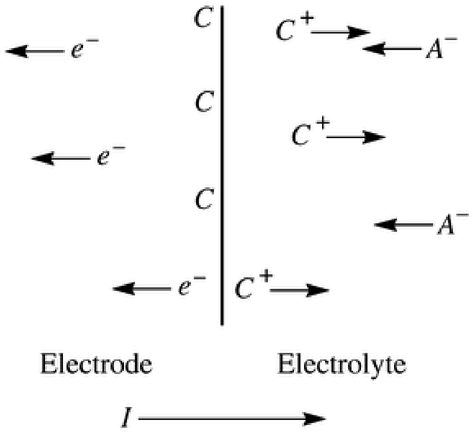




Invasive Brain Signals Recording

The Electrolyte/Metal Electrode Interface

- Skin and other body tissues act as electrolytic (ionizable) solutions
- Biopotential electrodes transduce *ionic conduction* to *electronic conduction*
- Anions in the electrolyte will flow to the interface boundary while cations in the electrolyte will flow away from the interface boundary
- To counteract this, electrons in the electrode will flow away from the interface boundary creating a current in the electrode. This process is called **oxidation of the metal**, *C*



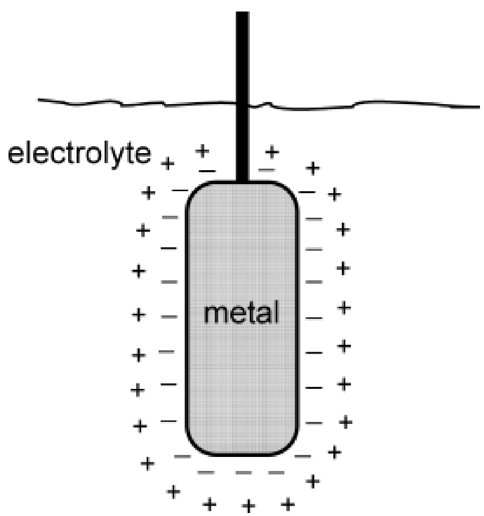
Oxidation Process

$$C \rightleftarrows C^{n+} + ne^{-}$$

The Electrolyte/Metal Electrode Interface

- When a metal is placed in an electrolyte solution, a charge distribution is created next to the metal/electrolyte interface

- This localized charge distribution causes an electric potential, called a half-cell potential, to be developed across the interface between the metal and the electrolyte solution



Half-cell Potentials of Important Metals

Primary Metal and Chemical Reaction			Half-cell Potential
Al	$\longrightarrow$	$Al^{3+} + 3e^-$	−1.706
Cr	$\longrightarrow$	$Cr^{3+} + 3e^-$	−0.744
Cd	$\longrightarrow$	$Cd^{2+} + 2e^-$	−0.401
Zn	$\longrightarrow$	$Zn^{2+} + 2e^-$	−0.763
Fe	$\longrightarrow$	$Fe^{2+} + 2e^-$	−0.409
Ni	$\longrightarrow$	$Ni^{2+} + 2e^-$	−0.230
Pb	$\longrightarrow$	$Pb^{2+} + 2e^-$	−0.126
H_2	$\longrightarrow$	$2H^+ + 2e^-$	0.000 (standard by definition)
Ag	$\longrightarrow$	$Ag^+ + e^-$	+0.799
Au	$\longrightarrow$	$Au^{3+} + 3e^-$	+1.420
Cu	$\longrightarrow$	$Cu^{2+} + 2e^-$	+0.340
$Ag + Cl^-$	$\longrightarrow$	$AgCl + 2e^-$	+0.223

The Electrolyte/Metal Electrode Interface

- Example: Silver and zinc electrodes are immersed in an electrolyte solution. Calculate the potential drop between these two electrodes

  Solution:

  From the table, the half-cell potentials for the silver and zinc electrodes are 0.799 and -0.763V, respectively. Therefore, the potential drop between these two metal electrodes is equal to 0.799 + 0.763 =1.562V

- Example: Silver and aluminum electrodes are placed in an electrolyte solution. Calculate the current that will flow through the electrodes if the equivalent resistance of the solution is equal to 2 kΩ

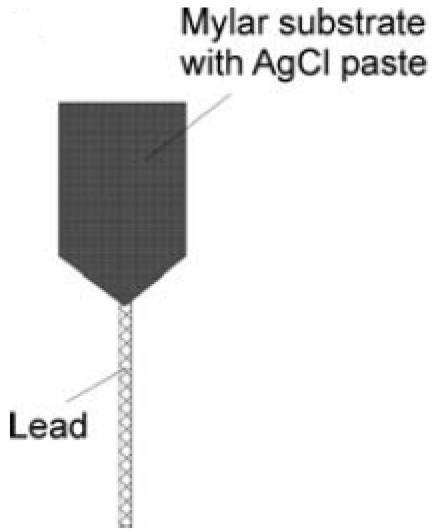
  Solution:

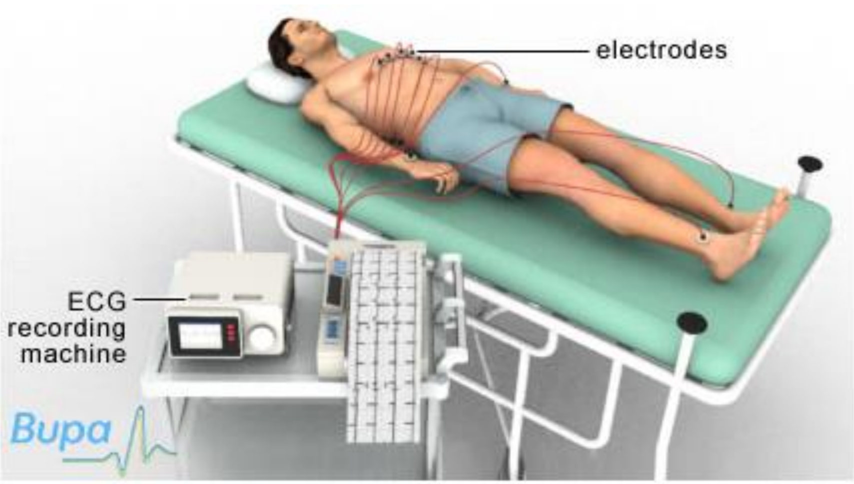
  $0.799 - (-1.706) = 2.505V$

  $2.505/2k\,\Omega = 1.252mA$

ECG Electrodes

- **Electrocardiogram** (ECG) electrodes are used to record heart signals
- A typical flexible biopotential electrode for ECG recording is composed of certain types of polymers which are made electrically conductive by the addition of a fine carbon or metal powder
- These electrodes are available with prepasted AgCl gel for quick and easy application to the skin



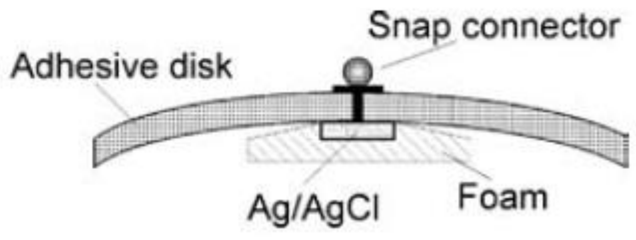


ECG Electrodes

- The most common type of ECG electrodes is the ‘‘floating’’ Ag/AgCl, which is formed by electrochemically depositing a very thin layer of silver chloride onto a silver electrode

- These electrodes are imbedded in foam that has been soaked with an electrolyte paste to provide good electrical contact with the skin

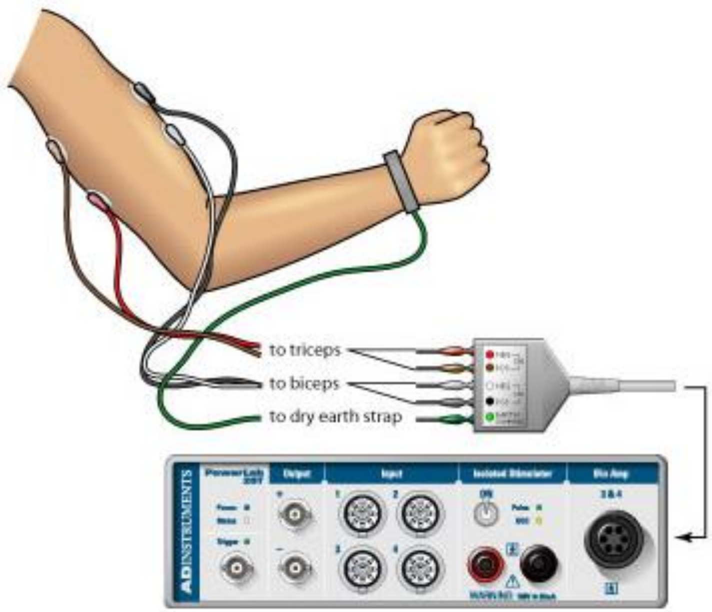
- The electrolyte saturated foam is also known to reduce motion artifacts which could be produced, when the layer of the skin moves relative to the surface of the Ag/AgCl electrode

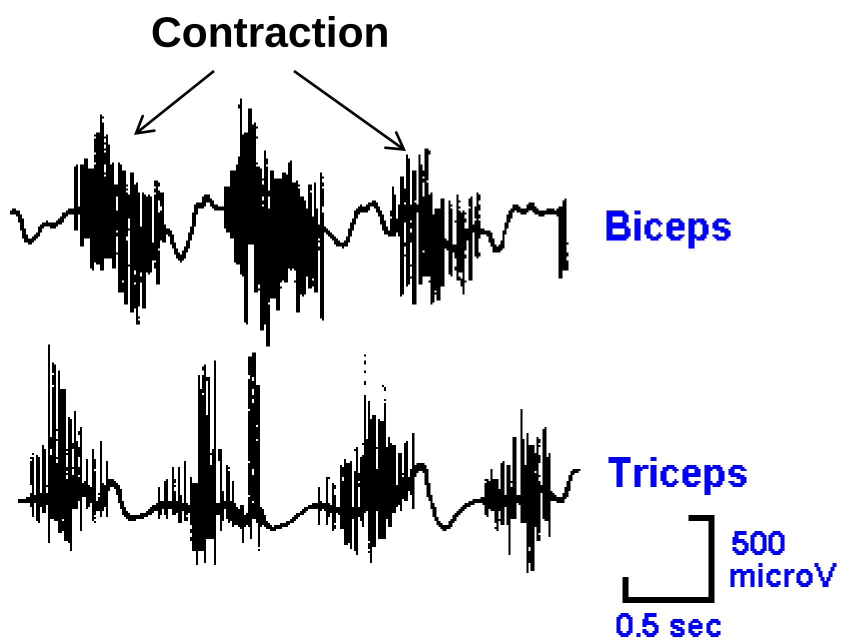


EMG Electrodes

- **Electromyogram** (EMG) electrodes are used to record muscle activity

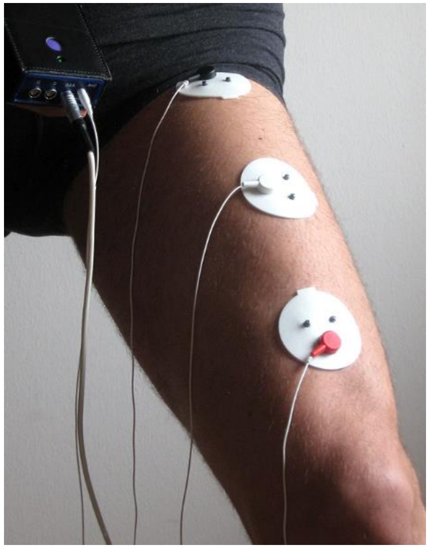
- EMG signals can be analyzed to detect medical abnormalities, activation level, recruitment order or to analyze the biomechanics of human or animal movement



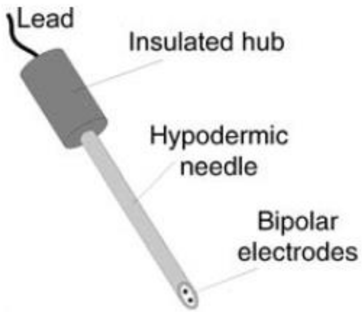


EMG Electrodes

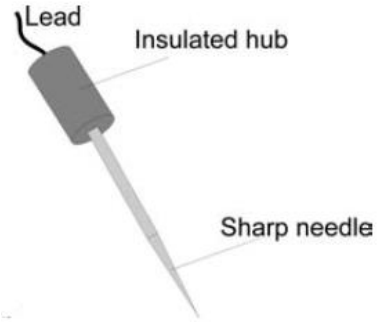
- The most common electrodes used for surface EMG recording are circular discs, about 1 cm in diameter, that are made of silver or platinum



- For direct recording of electrical signals from muscle fibers, a variety of needle electrodes are available



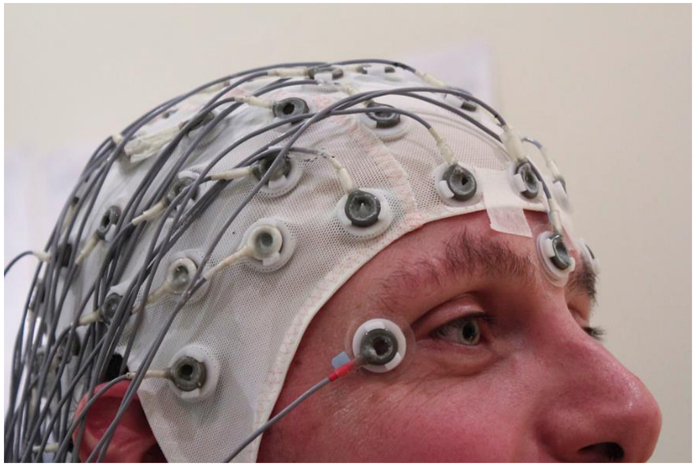
Bipolar electrodes (one for recording the other is reference)



Unipolar electrode for recording (Requires another wire as reference)

EEG Electrodes

- **Electroencephalography** (EEG) electrodes are used to record brain activity from the scalp
- Cup electrodes are usually used that are made of platinum or tin and are approximately 5–10mm in diameter
- These cup electrodes are filled with a conducting electrolyte gel and can be attached to the scalp with an adhesive tape



EEG Recording Cap

Injecting conductive gel into the electrodes

EEG Electrodes

- The inconvenience of traditional EEG systems motivated the production of more user-friendly systems

- Such systems do not require conductive gel injection and have wireless interfaces

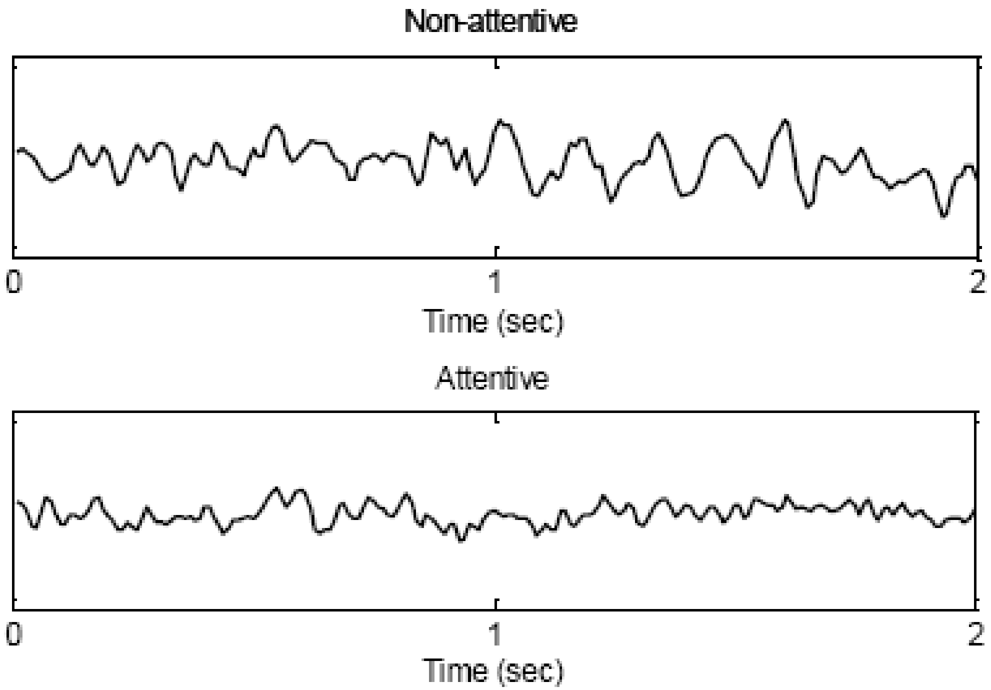
EEG traditional System

New EEG Dry Sensor Headsets

EEG Electrodes

- Example of EEG Recording:

  Alpha waves of frequencies 3-7 Hz are present in EEG recording from parietal areas when the subject is non attentive while such waves disappear when the subject becomes attentive

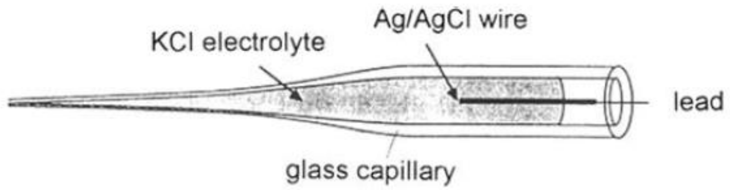


Microelectrodes

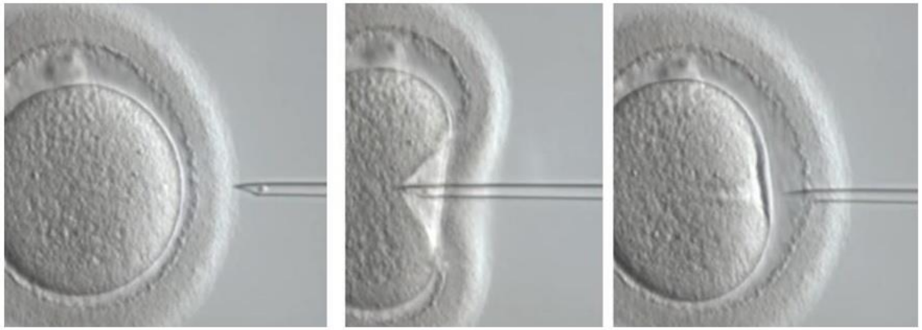
- **Microelectrodes** are biopotential electrodes with an ultra-fine tapered tip that can be inserted into individual biological cells

- The tip of these electrodes must be small with respect to the dimensions of the biological cell to avoid cell damage and at the same time sufficiently strong to penetrate the cell wall

- Glass Micropipette: A short piece of Ag/AgCl wire is inserted through the stem of a capillary tube to provide an electrical contact with the electrolyte solution and the inside of the cell



Micropipette

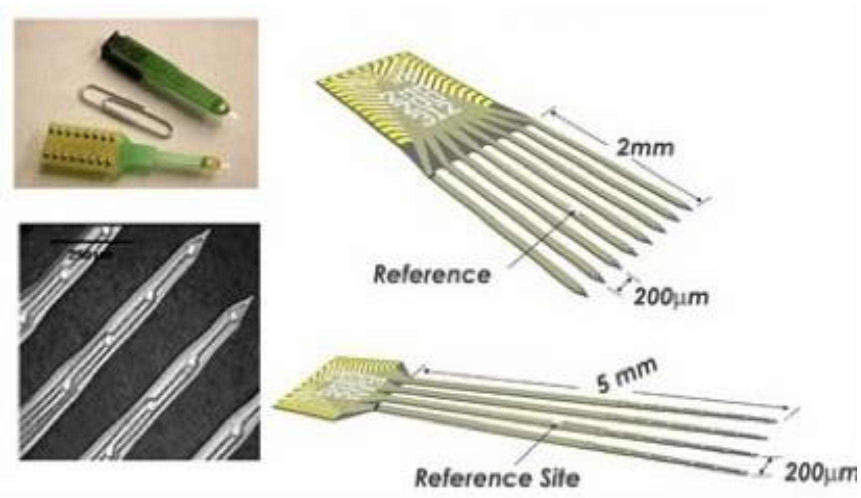


Micropipette penetrating a cell

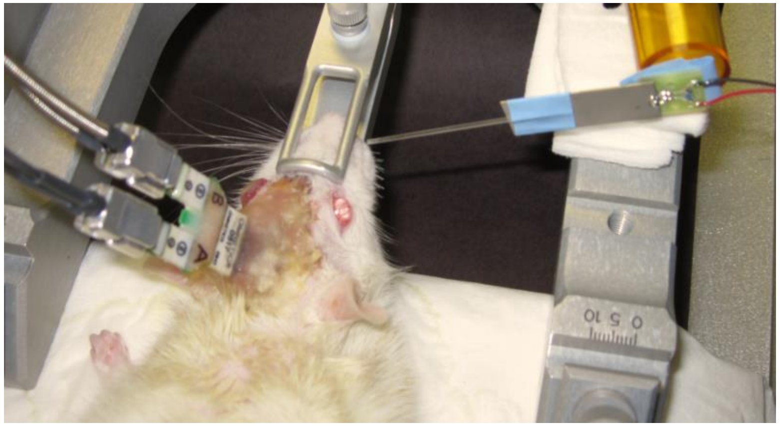
Microelectrodes

- Solid-state microfabrication techniques commonly used in the production of integrated circuits can be used to produce **multichannel electrodes** of biopotentials of neurons in the brain

- These electrodes are normally used to record activity of multiple neurons simultaneously



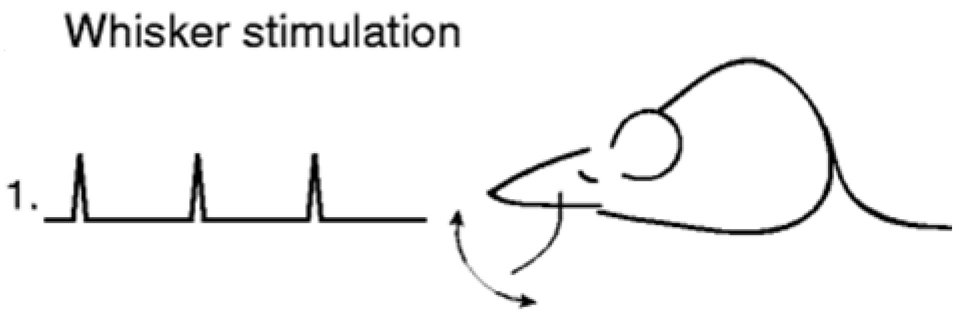
Multielectrode Arrays Design



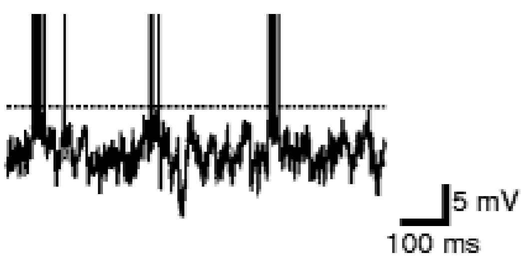
Multielectrode Array Implanted in a Rat

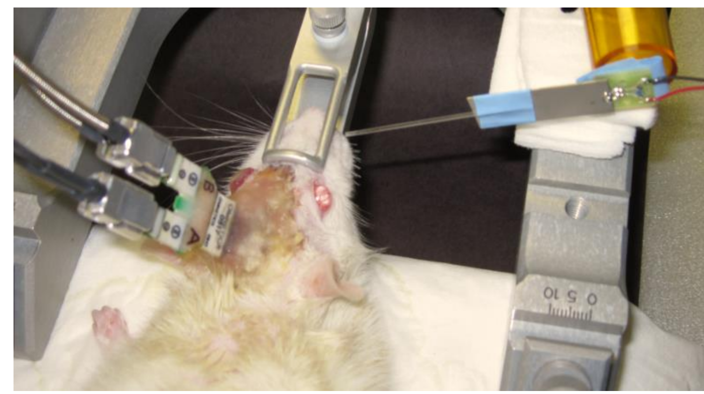
Microelectrodes

- Example of Microelectrode Arrays Recording:
  Moving rat’s whiskers activates neurons in the somastosensory cortex



Somatosensory Neuron Activity





II. Physical Measurements

- Displacement transducers can be used to measure muscle contraction

- **Inductive displacement transducers** are based on the inductance L of a coil given by

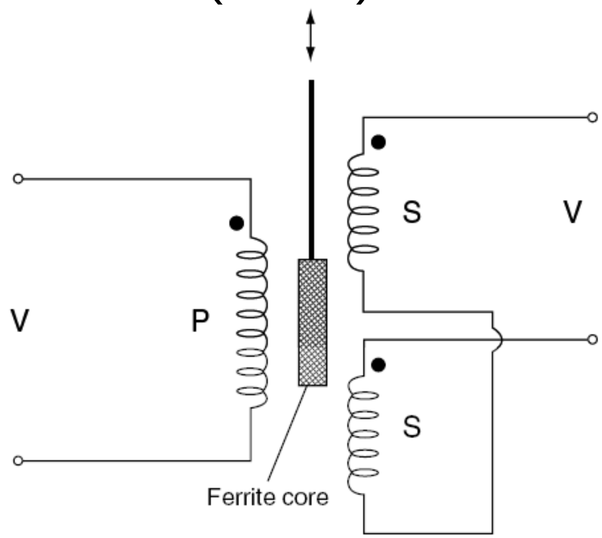
$$L = \mu \times n^2 \times l \times A$$

  where μ is the permeability of the medium inside the coil, n is the number of coil turns, l is the coil length and A is the cross-sectional area of the coil

- These types of transducers measure displacement by changing either the self-inductance of a single coil or the mutual inductance coupling between two or more stationary coils

Displacement Transducers

- A widely used inductive displacement transducer is the **linear variable differential transformer** (LVDT)

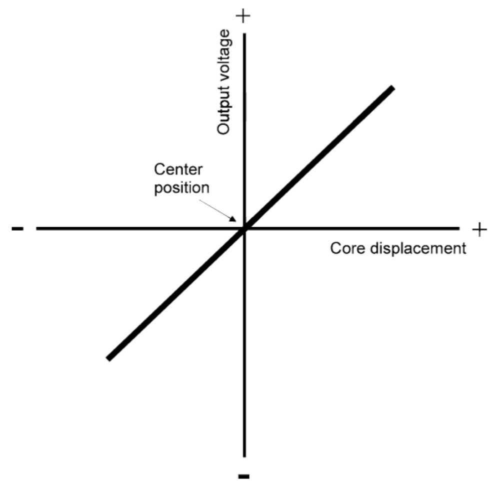


- The mutual inductance coupled between the coils is changed by the motion of a high-permeability slug

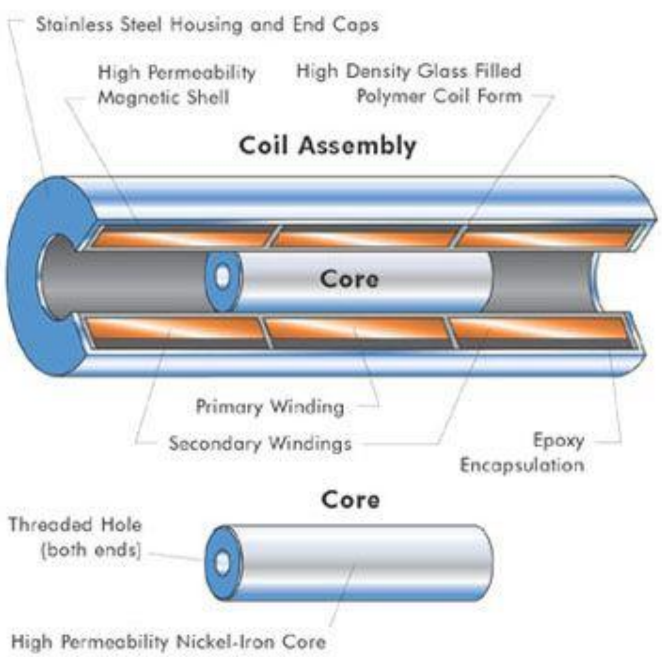
- The primary coil is usually excited by passing an AC current. When the slug is centered symmetrically with respect to the two secondary coils, the primary coil induces an alternating magnetic field in the secondary coils

Displacement Transducers

- When the core moves toward one coil, the voltage induced in that coil is increased in proportion to the displacement of the core while the voltage induced in the other coil is decreased proportionally

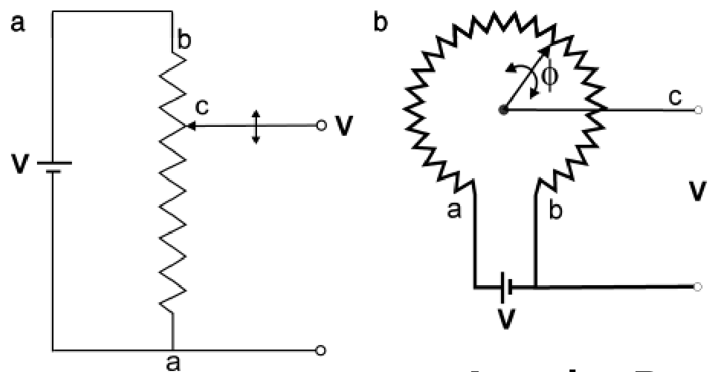


- Example of a LVDT sensor



Displacement Transducers

- A **potentiometer** is a resistive-type transducer that converts either linear or angular displacement into an output voltage



Translational Potentiometer **Angular Potentiometer**

- Example: Calculate the change in output voltage of a linear potentiometer transducer that undergoes a 20% change in displacement

Solution: Since $\Delta V = I \times \Delta R$ and $\mathrm{R} = \rho \times \dfrac{l}{A}$

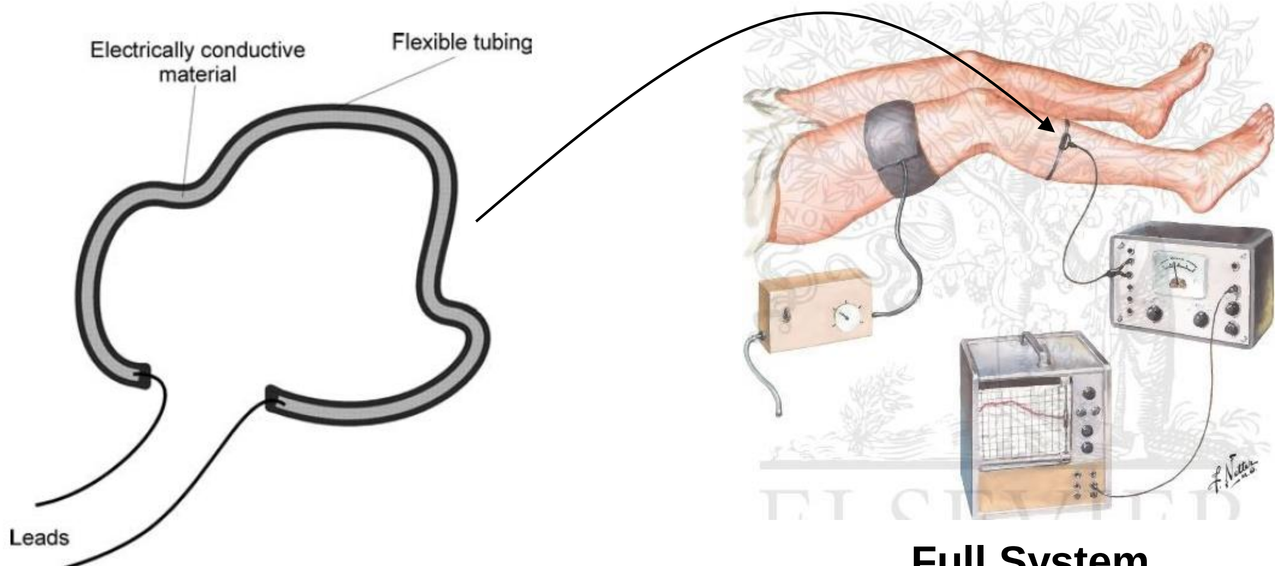
Since the resistance between the sliding contact and one terminal of the resistor is linearly proportional to the displacement, a 20% change in displacement will produce a 20% change in the output voltage of the transducer.

Displacement Transducers

- In certain clinical situations, it is desirable to measure changes in the peripheral volume of a leg when the venous outflow of blood from the leg is temporarily occluded by a blood pressure cuff
- This volume-measuring method is called **plethysmography** and can indicate the presence of large venous clots in the legs
- The measurement can be performed by wrapping an elastic resistive transducer around the leg and measuring the rate of change in resistance of the transducer as a function of time
- This change corresponds to relative changes in the blood volume of the leg
- If a clot is present, it will take more time for the blood stored in the leg to flow out through the veins after the temporary occlusion is removed

Displacement Transducers

- An elastic resistive transducer consists of a thin elastic tube filled with an electrically conductive material



Full System

- The resistance of the conductor inside the flexible tubing is given by

$$\mathrm{R} = \rho \times \frac{l}{A}$$

where ρ is the resistivity of the electrically conductive material, l is the length, and A is the cross-sectional area of the conductor

Displacement Transducers

- A similar transducer can be used to follow a patient's breathing pattern by wrapping the elastic band around the chest

- Example: A 10-cm long elastic resistive transducer with a resting resistance of 0.5kΩ is wrapped around the chest. Assume that the chest diameter during exhalation is 33 cm. Calculate the resistance of the transducer after it has been applied to the chest

  Solution:

  After the transducer is stretched around the chest, its new length will increase from 10 to 103.7 cm. Assuming that the cross-sectional area of the transducer remains unchanged after it is stretched, the resistance will increase to

$$R_{\text{stretched}} = 0.5\ \text{k}\Omega \times \left(\frac{103.7\ \text{cm}}{10\ \text{cm}}\right) = 5.18\ \text{k}\Omega$$

Displacement Transducers

- Example: For the previous example, calculate the change in voltage that is induced across the elastic transducer. Assume that normal breathing produces a 10% change in chest circumference and a constant current of 5mA is flowing through the transducer.

  Solution:

  From Ohm's law ($V = I \times R$)

  $$V = 5\ \text{mA} \times 5.18\ \text{k}\Omega = 25.9\ \text{V}$$

  If R changes by 10%, then

  $$V = 5\ \text{mA} \times 1.1 \times 5.18\ \text{k}\Omega = 28.5\ V$$
  $$\Delta V = 2.6\ \text{V}$$

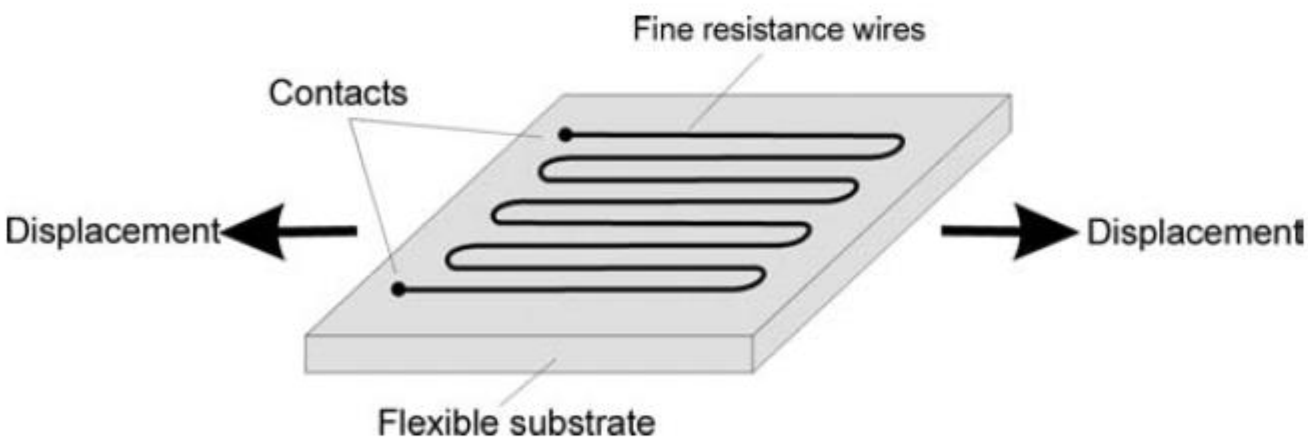
Displacement Transducers

- **Strain gauges** are displacement-type transducers that measure changes in the length of an object as a result of an applied force

- These transducers produce a resistance change that is proportional to the fractional change in the length of the object, also called strain, S, which is defined as

$$S = \frac{\Delta l}{l}$$

where Δl is the fractional change in length and l is the initial length of the object



Displacement Transducers

- Consider a fine wire conductor of length l, cross-sectional area A, and resistivity ρ

- Suppose that the wire is stretched within its elastic limit by a small amount, Δl, such that its new length becomes $(l + \Delta l)$

- Because the volume of the stretched wire must remain constant, the increase in the wire length results in a smaller cross-sectional area, $A_{stretched}$. Thus

$$lA = (l + \Delta l) \times A_{\text{stretched}}$$

- The resistance of the stretched wire is given by

$$\mathrm{R}_{\text{stretched}} = \rho \times \frac{l + \Delta l}{A_{\text{stretched}}}$$

- The increase in the resistance of the stretched wire ΔR is

$$\Delta \mathrm{R} = \mathrm{R}_{\text{stretched}} - \rho \times \frac{l}{A}$$

Displacement Transducers

- Therefore $$\Delta \mathrm{R} = \rho \times \frac{(l + \Delta l)^2}{l \times A} - \rho \times \frac{l}{A} = \frac{\rho \times (l^2 + 2l\Delta l + \Delta l^2 - l^2)}{l \times A}$$

- Assume that for small changes in length, $\Delta l << l$, this relationship simplifies to
$$\Delta \mathrm{R} = \rho \times \frac{2 \times \Delta l}{A} = \frac{2 \times \Delta l}{l} \times \mathrm{R}$$

- The fractional change in resistance ($\Delta R/R$) divided by the fractional change in length ($\Delta l/l$) is called the gauge factor, G

- For a common metal wire strain gauge made of constantan, G is approximately equal to 2

- Semiconductor strain gauges made of silicon have a gauge factor about 70 to 100 times higher and are therefore much more sensitive than metallic wire strain gauges (their resistivity changes with strain)

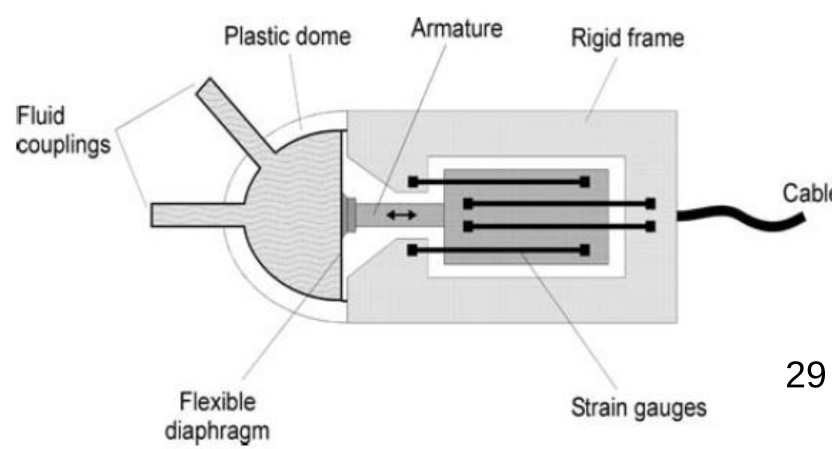
Displacement Transducers

- Example: Calculate the strain in a metal wire gauge for a fractional change in resistance of 10%

  Solution:

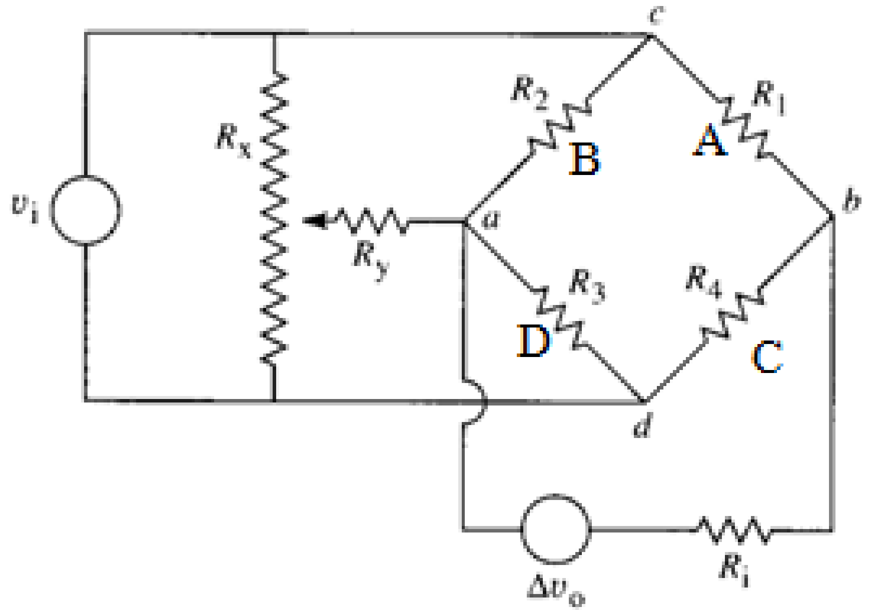
$$\frac{\Delta R}{R} = \frac{2 \times \Delta l}{l} = 2 \times S$$
$$\frac{0.1}{R} = 2 \times S$$
$$S = \frac{0.05}{R}$$

- An unbonded strain gauge consists of multiple resistive wires (typically four) stretched between a fixed and a movable rigid frame. It's used for blood pressure measurement



Displacement Transducers

- The unbonded strain gauge uses Wheatstone Bridge



- Δv_o is zero when the bridge is balanced- that is when $R_1 / R_2 = R_4 / R_3$

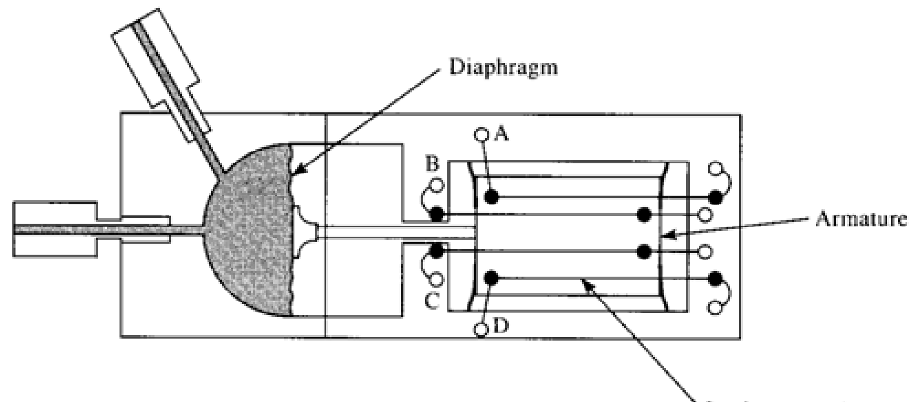
- If all resistors have initial value R_0 then if R_1 and R_3 increase by ΔR, and R_2 and R_4 decrease by ΔR, then

$$\Delta v_0 = \frac{\Delta R}{R_0} v_i$$

Displacement Transducers

- With increasing pressure, the strain on gauge pair B and C is increased, while that on gauge pair A and D is decreased

Initially before any pressure $R_1 = R_4$ and $R_3 = R_2$

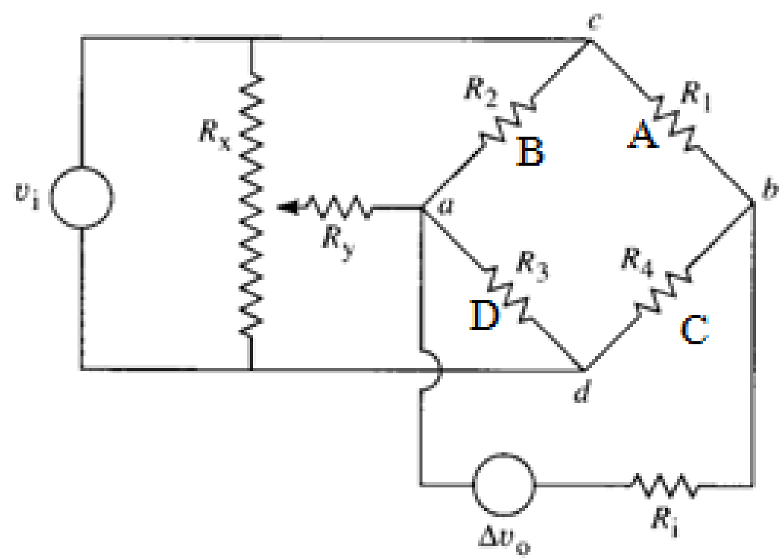


(a)

$$V_a = V_i\left(\frac{R_3}{R_2+R_3}\right) \qquad V_b = V_i\left(\frac{R_4}{R_1+R_4}\right)$$

$$V_o = V_a - V_b = V_i\left(\frac{R_3}{R_2+R_3} - \frac{R_4}{R_1+R_4}\right)$$

$$V_o = V_i\left(\frac{R_3(R_1+R_4) - R_4(R_2+R_3)}{(R_2+R_3)(R_1+R_4)}\right)$$



Temperature Measurement

- Body temperature is one of the most tightly controlled physiological variables and one of the four basic vital signs used in the daily assessment of a patient's health

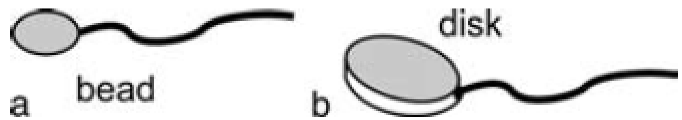
- The interior temperature in the body is remarkably constant, about 37^{o}C for a healthy person, and is normally maintained within ±0.5^{o}C

- There are two distinct areas in the body where temperature is measured routinely from the surface of the skin under the armpit or inside a body cavity such as the mouth

- **Thermistors** are temperature-sensitive transducers made of compressed sintered metal oxides (such as nickel, manganese, or cobalt) that change their resistance with temperature

Temperature Measurement

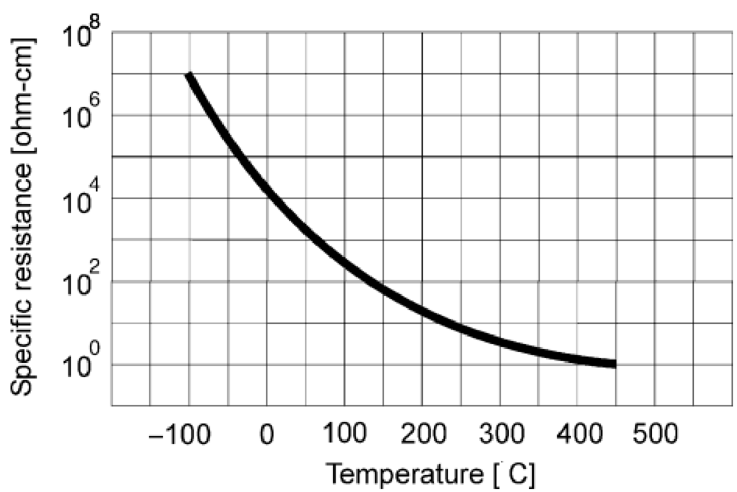
- Commercially available thermistors range in shape from small beads to large disks



- The resistance-temperature characteristic of a thermistor can be approximated by

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

where R_0 is the resistance at a reference temperature, T_0 (expressed in degrees K), R_T is the resistance at temperature T (expressed in degrees K), and β is a material constant, typically between 2500 and 5500 K



Temperature Measurement

- Example:

  A thermistor with a material constant β of 4500K is used as a thermometer. Calculate the resistance of this thermistor at 25^{o}C. Assume that the resistance of this thermistor at body temperature (37^{o}C) is equal to 85 Ω.

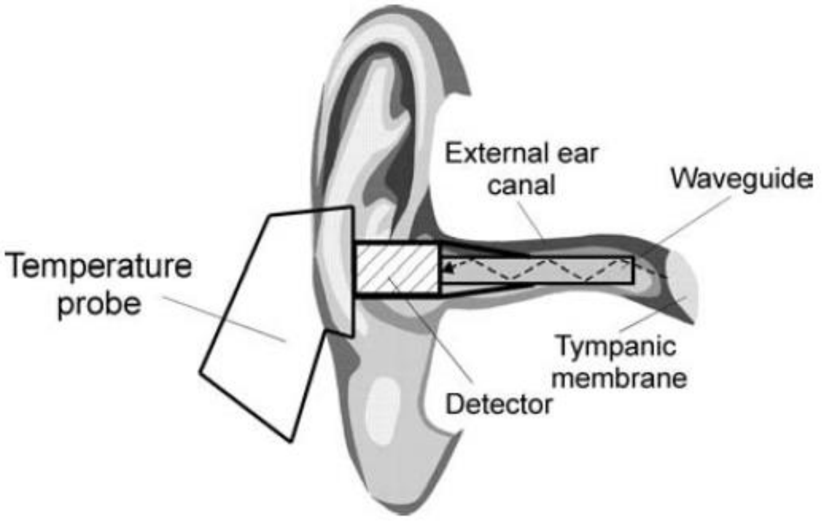
  Solution:

  Using the resistance-temperature characteristic of a thermistor

$$R_T = 85 \times \exp\left[4500 \times \left(\frac{1}{298} - \frac{1}{310}\right)\right] = 152.5\ \Omega$$

Temperature Measurement

- Noncontact thermometers measure the temperature of the ear canal near the tympanic membrane



- Infrared radiation from the tympanic membrane is channeled to a heat-sensitive detector through a metal waveguide

- The detector, which is either a thermopile or a pyroelectric sensor converts heat flow into an electric current