Biomedical Instrumentation

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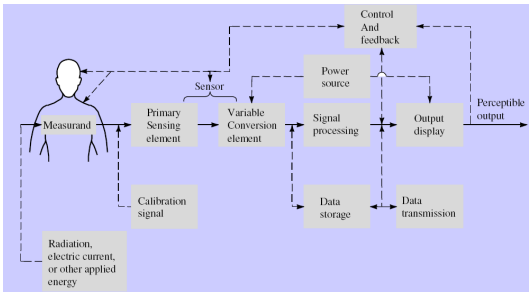
Basic Sensors and Principles



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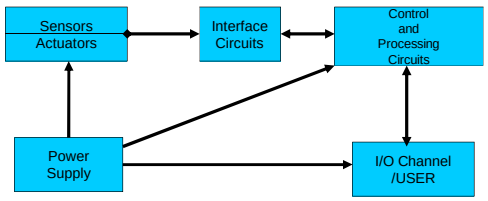
Transducer Systems



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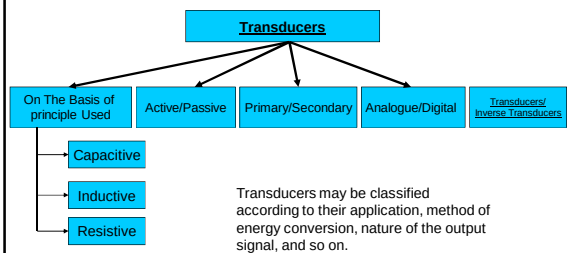
Classification of Transducers



Transducers may be classified according to their application, method of energy conversion, nature of the output signal, and so on.

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SPECIAL REQUIREMENTS OF SENSOR IN BIOMEDICAL APPLICATIONS

- Appliances for diagnosis: measuring or mapping a parameter at a given time
- Monitoring devices for measuring parameters within a given period
- Built-in controlling units containing not only sensors but also actuators

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Passive Transducers

TYPES OF TRANSDUCERS

Electrical parameter and class of transducer	*Principle of operation and nature of device*	*Typical application*
PASSIVE TRANSDUCERS (EXTERNALLY POWERED)		
Resistance		
Potentiometric device	Positioning of the slider by an external force varies the resistance in a potentiometer or a bridge circuit.	Pressure, displacement
Resistance strain gage	Resistance of a wire or semiconductor is changed by elongation or compression due to externally applied stress.	Force, torque, displacement
Pirani gage or hot-wire meter	Resistance of a heating element is varied by convection cooling of a stream of gas.	Gas flow, gas pressure
Resistance thermometer	Resistance of pure metal wire with a large positive temperature coefficient of resistance varies with temperature.	Temperature, radiant heat
Thermistor	Resistance of certain metal oxides with negative temperature coefficient of resistance varies with temperature.	Temperature
Resistance hygrometer	Resistance of a conductive strip changes with moisture content.	Relative humidity
Photoconductive cell	Resistance of the cell as a circuit element varies with incident light.	Photosensitive relay

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PASSIVE TRANSDUCERS (EXTERNALLY POWERED) (*cont.*)

Capacitance		
Variable capacitance pressure gage	Distance between two parallel plates is varied by an externally applied force	Displacement, pressure
Capacitor microphone	Sound pressure varies the capacitance between a fixed plate and a movable diaphragm.	Speech, music, noise
Dielectric gage	Variation in capacitance by changes in the dielectric.	Liquid level, thickness
Inductance		
Magnetic circuit transducer	Self inductance or mu ual inductance of ac-excited coil is va ied by changes in the magnetic circuit.	Pressure, displacement
Reluctance pickup	Reluctance of the magnetic circuit is varied by changing the position of the iron core of a coil.	Pressure, displacement, vibration, position
Differential transformer	The differential voltage of two secondary windings of a transformer is varied by positioning the magnetic core through an externally applied force.	Pressure, force, displacement, position
Eddy current gage	Inductance of a coil is varied by the proximity of an eddy current plate.	Displacement, thickness
Magnetostriction gage	Magnetic properties are varied by pressure and stress.	Force, pressure, sound
Voltage and current		
Hall effect pickup	A potential difference is generated across a semiconductor plate (germanium) when magnetic flux interacts with an applied current.	Magnetic flux, current
Ionization chamber	Electron flow induced by ionization of gas due to radioactive radiation.	Particle counting, radiation
Photoemissive cell	Electron emission due to incident radiation on photoemissive surface.	Light and radiation
Photomultiplier tube	Seconday electron emission due to incident radiation on photosensitive cathode.	Light and radiation, photosensitive relays

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Active Transducers

SELF-GENERATING TRANSDUCERS (NO EXTERNAL POWER)

Thermocouple and thermopile	An emf is generated across the junction of two dissimilar metals or semiconductors when that junction is heated	Temperature, heat flow, radiation
Moving-coil generator	Motion of a coil in a magnetic field generates a voltage.	Velocity, vibration
Piezoelectric pickup	An emf is generated when an external force is applied to certain crystalline materials, such as quartz.	Sound, vibration, acceleration, pressure changes
Photovoltaic cell	A voltage is generated in a semiconductor junction device when radiant energy stimulates the cell.	Light meter, solar cell

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Selecting a Transducer

- What is the physical quantity to be measured?
- Which transducer principle can best be used to measure this quantity?
- What accuracy is required for this measurement?
  - Fundamental transducer parameters
  - Physical conditions
  - Environmental conditions
  - Compatibility of the associated equipment
- Reducing the total measurement error :
  - Using in-place system calibration with corrections performed in the data reduction
  - Artificially controlling the environment to minimize possible errors

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Transducer, Sensor, and Actuator

- Transducer:
  - a device that converts energy from one form to another
- Sensor:
  - converts a physical parameter to an electrical output (a type of transducer, e.g. a microphone)
- Actuator:
  - converts an electrical signal to a physical output (opposite of a sensor, e.g. a speaker)

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Type of Sensors

- Displacement Sensors:
  - resistance, inductance, capacitance, piezoelectric
- Temperature Sensors:
  - Thermistors, thermocouples
- Electromagnetic radiation Sensors:
  - Thermal and photon detectors

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Displacement Measurements

- Used to measure directly and indirectly the size, shape, and position of the organs.
- Displacement measurements can be made using sensors designed to exhibit a resistive, inductive, capacitive or piezoelectric change as a function of changes in position.

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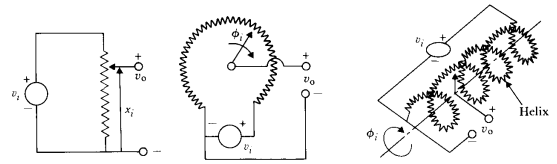
Resistive sensors - potentiometers

Measure linear and angular position
Resolution a function of the wire construction
Measure velocity and acceleration



(a) Translational (b) Single-turn (c) Multi-turn

2 to 500mm From 10° to more than 50°

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Resistive sensors – strain gages

Devices designed to exhibit a change in resistance as a result of experiencing strain to measure displacement in the order of nanometer.

For a simple wire: $R = \frac{\rho L}{A}$

A change in *R* will result from a change in ρ (resistively), or a change in *L* or *A* (dimension).

The gage factor, G, is used to compare various strain-gage materials

$$G = \frac{\Delta R / R}{\Delta L / L} = (1 + 2\mu) + \frac{\Delta \rho / \rho}{\Delta L / L}$$

μ Is Poisson's ratio $= -\frac{\Delta D / D}{\Delta L / L}$ for most metals μ=0.3

Semiconductor has larger G but more sensitive to temperature

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Table 2.1 Properties of Strain-gage Materials

Material	Composition (%)	Gage Factor	Temperature Coefficient of Resistivity ($°C^{-1} - 10^{-5}$)
Constantan (advance)	Ni_{45}, Cu_{55}	2.1	±2
Isoelastic	Ni_{36}, Cr_8 (Mn, Si, Mo)$_4$ Fe_{52}	3.52 to 3.6	+17
Karma	Ni_{74}, Cr_{20}, Fe_3 Cu_3	2.1	+2
Manganin	Cu_{84}, Mn_{12}, Ni_4	0.3 to 0.47	±2
Alloy 479	Pt_{92}, W_8	3.6 to 4.4	+24
Nickel	Pure	−12 to −20	670
Nichrome V	Ni_{80}, Cr_{20}	2.1 to 2.63	10
Silicon	(*p* type)	100 to 170	70 to 700
Silicon	(*n* type)	−100 to −140	70 to 700
Germanium	(*p* type)	102	
Germanium	(*n* type)	−150	

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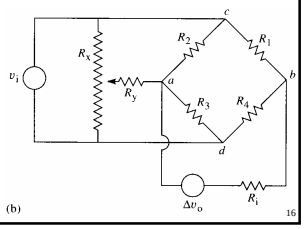
Wheatstone Bridge

Δv_0 is zero when the bridge is balanced- that is when $R_1 / R_2 = R_4 / R_3$

If all resistor has initial value R_0 then if R_1 and R_3 increase by ΔR, and R_2 and R_4 decreases by ΔR, then

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



(b)

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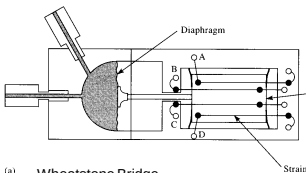
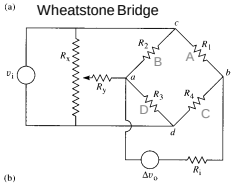
Unbonded strain gage:

With increasing pressure, the strain on gage pair **B** and **C** is increased, while that on gage pair **A** and **D** is decreased.



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

(a) Wheatstone Bridge



(b)

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

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

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

Error in Fig. 2.2 legend: R_1 = A, R_2 = B, R_3 = D, R_4 = C

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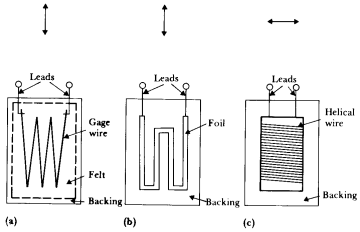
Bonded strain gage:

- Metallic wire, etched foil, vacuum-deposited film or semiconductor is cemented to the strained surface



(a) (b) (c)

Rugged, cheap, low mass, available in many configurations and sizes

To offset temperature use dummy gage wire that is exposed to temperature but not to strain

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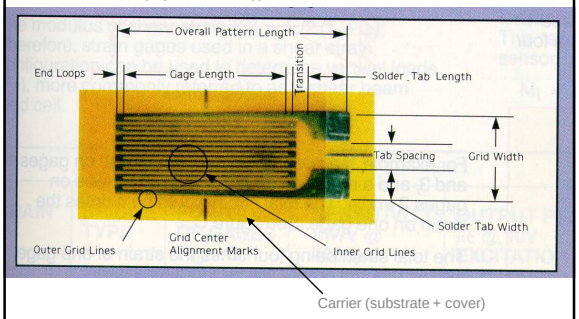
Bonded strain gage terminology:



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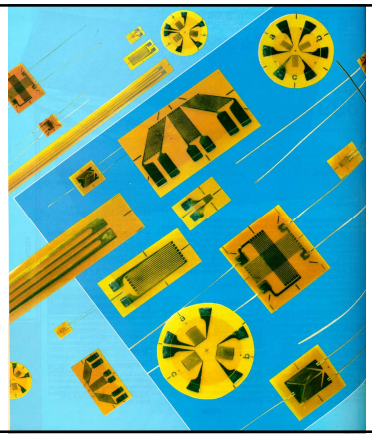

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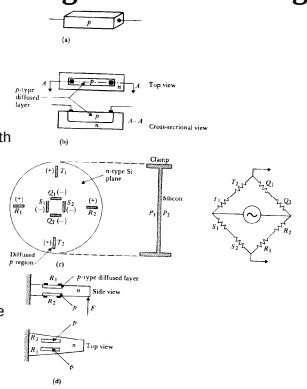
Semiconductor Integrated Strain Gages

Pressure strain gages sensor with high sensitivity



Integrated cantilever-beam force sensor

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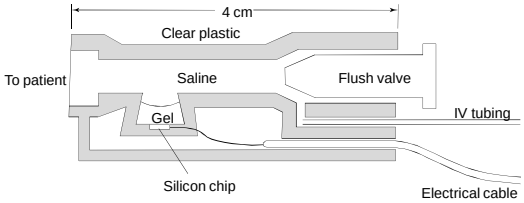

Isolation in a disposable blood-pressure sensor.
Disposable blood pressure sensors are made of clear plastic so air bubbles are easily seen. Saline flows from an intravenous (IV) bag through the clear IV tubing and the sensor to the patient. This flushes blood out of the tip of the indwelling catheter to prevent clotting. A lever can open or close the flush valve. The silicon chip has a silicon diaphragm with a four-resistor Wheatstone bridge diffused into it. Its electrical connections are protected from the saline by a compliant silicone elastomer gel, which also provides electrical isolation. This prevents electric shock from the sensor to the patient and prevents destructive currents during defibrillation from the patient to the silicon chip.

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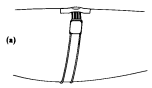
Elastic-Resistance Strain Gages

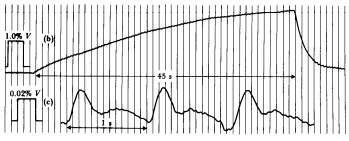
Extensively used in Cardiovascular and respiratory dimensional and volume determinations.

As the tube stretches, the diameter decreases and the length increases, causing the resistance to increase



b) venous-occlusion plethysmography

c) arterial-pulse plethysmography



Filled with a conductive fluid (mercury, conductive paste, electrolyte solution.
Resistance = 0.02 - 2 Ω/cm, linear within 1% for 10% of maximal extension

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Inductive Sensors

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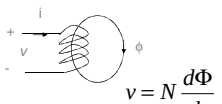
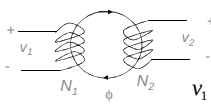
Ampere's Law: flow of electric current will create a magnetic field
Faraday's Law: a magnetic field passing through an electric circuit will create a voltage



$$v = N\frac{d\Phi}{dt}$$



$$v_1 = \frac{N_1}{N_2}v_2$$

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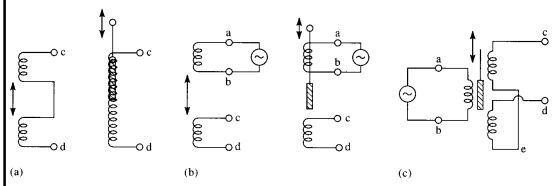
Inductive Sensors

Ampere's Law: flow of electric current will create a magnetic field
Faraday's Law: a magnetic field passing through an electric circuit will create a voltage



Self-inductance | Mutual inductance | Differential transformer

$$L = n^2 G\mu$$

$$v = L\frac{di}{dt}$$

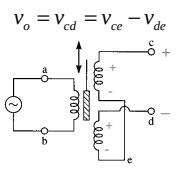
n = number of turns of coil
G = geometric form factor
μ = effective magnetic permeability of the medium

LVDT : Linear variable differential transformer
- full-scale displacement of 0.1 to 250 mm
- 0.5-2 mV for a displacement of 0.01mm
- sensitivity is much higher than that for strain gages

Disadvantage requires more complex signal processing

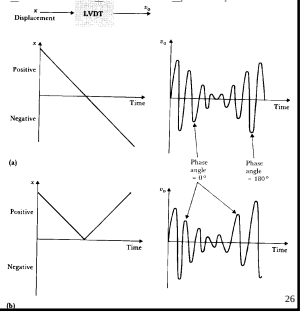
http://www.macrosensors.com/lvdt_macro_sensors/lvdt_tutorial/lvdt_primer.pdf

$$v_o = v_{cd} = v_{ce} - v_{de}$$



(c)

(a) As *x* moves through the null position, the phase changes 180° , while the magnitude of v_o is proportional to the magnitude of x. (b) An ordinary rectifier-demodulator cannot distinguish between (a) and (b), so a phase-sensitive demodulator is required.

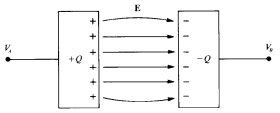


Capacitive Sensors

Capacitive sensors
For a parallel plate capacitor: $C = \varepsilon_0 \varepsilon_r \frac{A}{x}$

ε_0 = dielectric constant of free space
ε_r = relative dielectric constant of the insulator
A = area of each plate
x = distance between plates

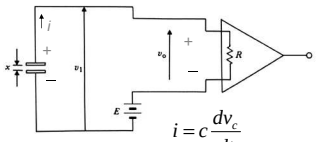
Change output by changing ***ε_r*** (substance flowing between plates), ***A*** (slide plates relative to each other), or ***x.***



Sensitivity of capacitor sensor, ***K*** $= \frac{\Delta C}{\Delta x} = -\varepsilon_0 \varepsilon_r \frac{A}{x^2}$

Sensitivity increases with increasing plate size and decreasing distance

When the capacitor is stationary x_o the voltage $v_1 = E$.
A change in position $\Delta x = x_1 - x_0$ produces a voltage $v_o = v_1 - E$.



$$i = c\frac{dv_c}{dt}$$

$$\frac{V_o(j\omega)}{X_1(j\omega)} = \frac{(E/x_o)j\omega\tau}{j\omega\tau + 1}$$

Characteristics of capacitive sensors:
High resolution (<0.1 nm)
Dynamic ranges up to 300 μm (reduced accuracy at higher displacements)
High long term stability (<0.1 nm / 3 hours)
Bandwidth: 20 to 3 kHz

Example 2.1

For a 1 cm^2 capacitance sensor, *R* is 100 MΩ. Calculate *x*, the plate spacing required to pass sound frequencies above 20 Hz.

Answer:

From the corner frequency, $C = 1/2\pi fR = 1/(2\pi 20\times 10^8) = 80$ pF.

x can be calculated as follows:

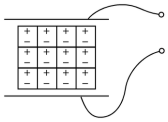
$$x = \varepsilon_0 \varepsilon_r \frac{A}{C} = \frac{(8.854\times 10^{-12})(1\times 10^{-4})}{80\times 10^{-12}}$$

$$x = 1.11\times 10^{5}\ \text{m} = 1.11\ \mu\text{m}$$

Piezoelectric Sensors

- Measure physiological displacement and record heart sounds

- Certain materials generate a voltage when subjected to a mechanical strain, or undergo a change in physical dimensions under an applied voltage.
- Uses of Piezoelectric
  - External (body surface) and internal (intracardiac) phonocardiography
  - Detection of Korotkoff sounds in blood-pressure measurements
  - Measurements of physiological accelerations
  - Provide an estimate of energy expenditure by measuring acceleration due to human movement.



$$q = kf$$

k = piezoelectric constant, C/N
(typically pC/N, a material property)

k for Quartz = 2.3 pC/N

k for barium titanate = 140 pC/N

To find V_o, assume system acts like a capacitor (with infinite *leak resistance*):

$$V_o = \frac{q}{C} = \frac{kf}{C} = \frac{kfx}{\varepsilon_0 \varepsilon_r A}$$

Capacitor:

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

For piezoelectric sensor of 1-cm^2 area and 1-mm thickness with an applied force due to a 10-g weight, the output voltage *v* is
0.23 mV for quartz crystal
14 mV for barium titanate crystal.

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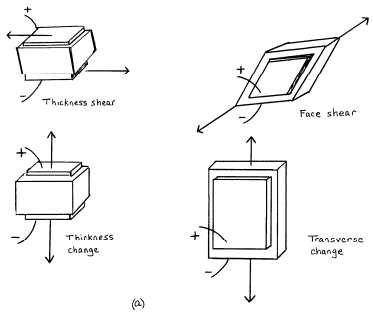
Models of Piezoelectric Sensors



Piezoelectric polymeric films, such as polyvinylidence fluoride (PVDF). Used for uneven surface and for microphone and loudspeakers.

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Transfer Function of Piezoelectric Sensors

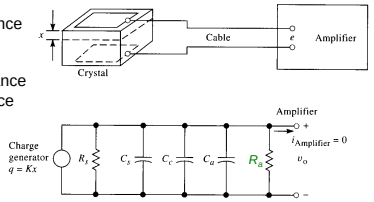
View piezoelectric crystal as a charge generator:

$q = Kx$

K = proportionality constant

x = deflection

R_s: sensor leakage resistance
C_s: sensor capacitance
C_c: cable capacitance
C_a: amplifier input capacitance
R_a: amplifier input resistance



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Transfer Function of Piezoelectric Sensors

Convert charge generator to current generator:

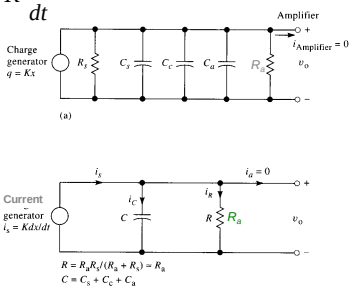
$$q = Kx \qquad i_s = \frac{dq}{dt} = K\frac{dx}{dt}$$

$$i_s = i_c + i_R$$

$$i_c = i_s - i_R$$

$$C\left(\frac{dV_o}{dt}\right) = K\frac{dx}{dt} - \frac{V_o}{R}$$

$$\frac{V_o(j\omega)}{X(j\omega)} = \frac{K_s j\omega\tau}{j\omega\tau + 1}$$



$K_s = K/C$, sensitivity, V/m
$\tau = RC$, time constant

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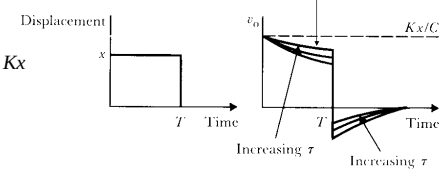
Voltage-output response of a piezoelectric sensor to a step displacement *x*.

Decay due to the finite internal resistance of the PZT



$$q = VC = Kx$$

$$V_0 = \frac{Kx}{C}$$

The decay and undershoot can be minimized by increasing the time constant $\tau = RC$.

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Example 2.2

A piezoelectric sensor has C = 500 pF. Sensor leakage resistanse is 10 GΩ. The amplifier input impedance is 5 MΩ. What is the low corner frequency?

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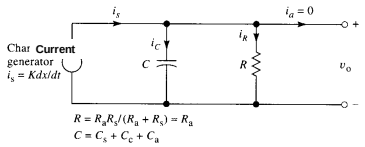
Example 2.2

C = 500 pF
R_{leak} = 10 GΩ
R_a = 5 M Ω
What is $f_{c,low}$?



$$f_{c,low} = \frac{1}{2\pi RC} = \frac{1}{2\pi(5\times10^{6})(500\times10^{-12})} = 64 \text{ Hz}$$

If input impedance is increased 100 times:
(R_a = 500 M Ω)
Then the $f_{c,low}$:

$$f_{c,low} = \frac{1}{2\pi(500\times10^{6})(500\times10^{-12})} = 0.64 \text{ Hz}$$

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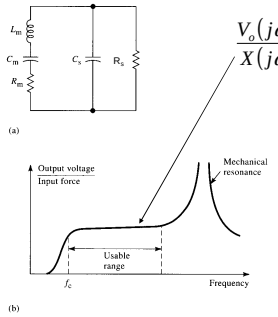
High Frequency Equivalent Circuit



$$\frac{V_o(j\omega)}{X(j\omega)} = \frac{K_s j\omega\tau}{j\omega\tau + 1}$$

38

Temperature Measurement

- The human body temperature is a good indicator of the health and physiological performance of different parts of the human body.
- **Temperature indicates:**
  - Shock by measuring the big-toe temperature
  - Infection by measuring skin temperature
  - Arthritis by measuring temperature at the joint
  - Body temperature during surgery
  - Infant body temperature inside incubators
- **Temperature sensors type**
  - Thermocouples
  - Thermistors
  - Radiation and fiber-optic detectors
  - *p-n* junction semiconductor (2 mV/°C)

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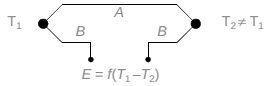
Thermocouple

- Electromotive force (emf) exists across a junction of two dissimilar metals. Two independent effects cause this phenomena:
  1- Contact of two unlike metals and the junction temperature (Peltier)

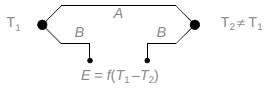


  2- Temperature gradients along each single conductor (Lord Kelvin)
  $E = f(T_1^2 - T_2^2)$
- **Advantages of Thermocouple**
  - fast response (τ=1ms), small size (12 μm diameter), ease of fabrication and long-term stability
- **Disadvantages**
  - Small output voltage, low sensitivity, need for a reference temperature

40

Thermocouple

- Empirical calibration data are usually curve-fitted with a power series expansion that yield the Seebeck voltage.



$$E = aT + \frac{1}{2}bT^2 + \ldots.$$

T: Temperature in Celsius
Reference junction is at 0 °C

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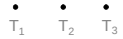
Thermocouple Laws

1- *Homogeneous Circuit law*: A circuit composed of a single homogeneous metal, one cannot maintain an electric current by the application of heat alone. See **Fig**. 2.12b (next slide)

2- *Intermediate Metal Law*: The net emf in a circuit consisting of an interconnection of a number of unlike metals, maintained at the same temperature, is zero. See **Fig**. 2.12c (next slide)
- Second law makes it possible for lead wire connections

3- *Successive or Intermediate Temperatures Law*: See **Fig**. 2.12d (next slide)
- The third law makes it possible for calibration curves derived for a given reference-junction temperature to be used to determine the calibration curves for another reference temperature.

$$E_{23} = E_{13} - E_{12} = a_1T_3 + \frac{1}{2}b_1T_3 - a_1T_2 - \frac{1}{2}b_1T_2$$



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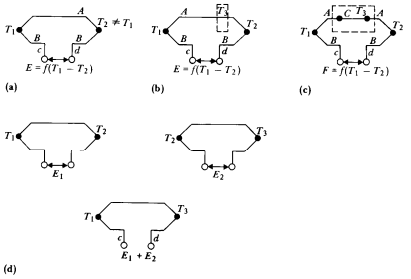

Figure 2.12 Thermocouple circuits (a) Peltier emf. (b) Law of homogeneous circuits. (c) Law of intermediate metals. (d) Law of intermediate temperatures.

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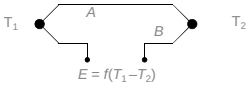
Thermoelectric Sensitivity α

- For small changes in temperature: $\Delta E = \alpha \Delta T$



$$E = aT + \frac{1}{2}bT^2 + \cdots$$

- Differentiate above equation to find α, the Seebeck coefficient, or thermoelectric sensitivity. Generally in the range of 6.5 - 80 μV/ºC at 20 ºC.

$$\alpha = \frac{dE}{dT} = a + bT + \cdots$$

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Thermistors

- Thermistors are semiconductors made of ceramic materials whose resistance decreases as temperature increases.
- **Advantages**
  - Small in size (0.5 mm in diameter)
  - Large sensitivity to temperature changes (-3 to -5% /ºC)
    - Blood velocity
  - Temperature differences in the same organ
  - Excellent long-term stability characteristics (ΔR=0.2% /year)
- **Disadvantages**
  - Nonlinear
  - Self heating
  - Limited range

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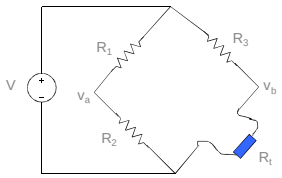
Circuit Connections of Thermistors

- Bridge Connection to measure voltage



- Amplifier Connection to measure currents

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Thermistors Resistance

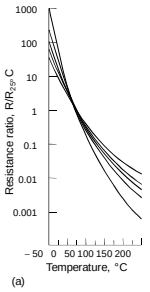
- Relationship between Resistance and Temperature at zero-power resistance of thermistor.

$$R_t = R_0 e^{[\beta(T_0 - T)/TT_0]}$$

β = material constant for thermistor, K (2500 to 5000 K)
T_0 = standard reference temperature, K
T_0 = 293.15 K = 20C = 68F

$$\alpha = \frac{1}{R_t}\frac{dR_t}{dT} = -\frac{\beta}{T^2} \qquad (\%/K)$$

α is a nonlinear function of temperature



(a)

(a) Typical thermistor zero-power resistance ratio-temperature characteristics for various materials.

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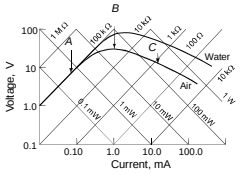
Voltage-Versus-Current Characteristics

- The temperature of the thermistor is that of its surroundings. However, above specific current, current flow generates heat that make the temperature of the thermistor above the ambient temperature.



(b)

(b) Thermistor voltage-versus-current characteristic for a thermistor in air and water. The diagonal lines with a positive slope give linear resistance values and show the degree of thermistor linearity at low currents. The intersection of the thermistor curves and the diagonal lines with the negative slope give the device power dissipation. Point A is the maximal current value for no appreciable self-heat. Point B is the peak voltage. Point C is the maximal safe continuous current in air.

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Radiation Thermometry

- The higher the temperature of a body the higher is the electromagnetic radiation (EM).
- **Electromagnetic Radiation Transducers**
  - Convert energy in the form of EM radiation into an electrical current or potential, or modify an electrical current or potential.
  - Medical thermometry maps the surface temperature of a body with a sensitivity of a few tenths of a Kelvin.
- **Application**
  - Breast cancer, determining location and extent of arthritic disturbances, measure the depth of tissue destruction from frostbite and burns, detecting various peripheral circulatory disorders (venous thrombosis, carotid artery occlusions)

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http://en.wikipedia.org/wiki/Blackbody_radiation

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Radiation Thermometry

- **Sources of EM radiation:**
  - Acceleration of charges can arise from thermal energy. Charges movement cause the radiation of EM waves.
- The amount of energy in a photon is inversely related to the wavelength:

$$E \propto \frac{1}{\lambda}$$

$$1\,eV = 1.602\times10^{-19}\,J$$

- *Thermal sources* approximate ideal blackbody radiators:
  - *Blackbody radiator*:
    - an object which absorbs all incident radiation, and emits the maximum possible thermal radiation (0.7 μm to 1mm).

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Power Emitted by a Blackbody Stefan-Boltzman law

Power emitted at a specific wavelength:

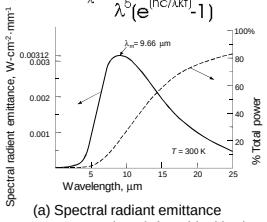
$$W_\lambda = \frac{\varepsilon C_1}{\lambda^5\left(e^{C_2/\lambda T}-1\right)}$$

$$P_\lambda = \frac{2\pi hc^2}{\lambda^5(e^{(hc/\lambda kt)}-1)}$$

Unit : W/cm². μm
C_1 = 3.74x10⁴ (W. μm⁴/cm²)
C_2 = 1.44x10⁴ (μm. K)
T = blackbody temperature, K
ε = emissivity (ideal blackbody = 1)

Wavelength for which W_λ is maximum:

$$\lambda_m = \frac{2898}{T} \quad (\mu m)$$



(a) Spectral radiant emittance versus wavelength for a blackbody at 300 K on the left vertical axis; percentage of total energy on the right vertical axis.

λ_m varies inversely with T - Wien's displacement law

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Power Emitted by a Blackbody Stefan-Boltzman law

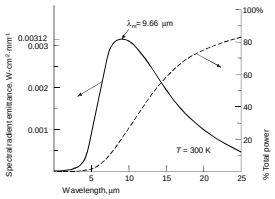
$$W_\lambda = \frac{\varepsilon C_1}{\lambda^5\left(e^{C_2/\lambda T}-1\right)}$$

Total radiant power:

$$W_t = \int_{\lambda_1}^{\lambda_2} W_\lambda d\lambda = \varepsilon\sigma T^4$$

Unit : W/cm². μm

σ = Stefan's constant = $5.67\times10^{-12}\ (W/cm^2)K^4$



80% of the total radiant power is found in the wavelength band from 4 to 25 μm

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Thermal Detector Specifications

Infrared Instrument Lens Properties;
-pass wavelength > 1 μm
-high sensitivity to the weak radiated signal
-Short response
-Respond to large bandwidth

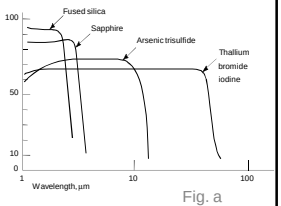

Fig. a

Thermal Detectors
-Law sensitivity
-Respond to all wavelength
Photon (Quantum) Detector
-higher sensitivity
-Respond to a limited wavelength

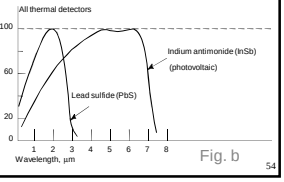

Fig. b

Fig. a) Spectral transmission for a number of optical materials. (b) Spectral sensitivity of photon and thermal detectors.

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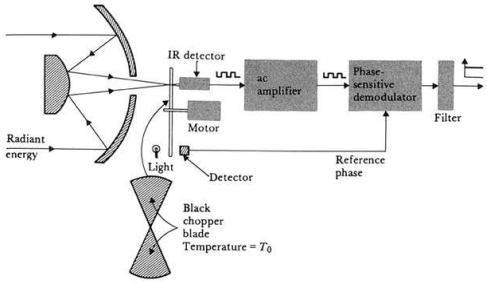
Radiation Thermometer System



Stationary chopped-beam radiation thermometer

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Application of Radiation Thermometer

- Measuring the core body temperature of the human by measuring the magnitude of infrared radiation emitted from the tympanic membrane and surrounding ear canal.
  - Response time is 0.1 second
  - Accuracy of 0.1 ^{o}C

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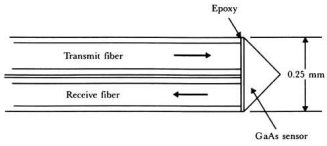
Fiber-Optic Temperature Sensors

- Small and compatible with biological implantation.
- Nonmetallic sensor so it is suitable for temperature measurements in a strong electromagnetic heating field.



Gallium Arsenide (GaAs) semiconductor temperature probe. The amount of power absorbed increases with temperature

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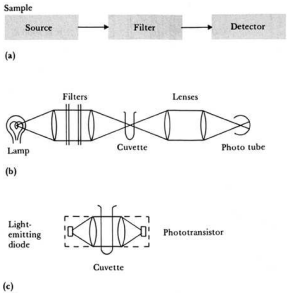
Optical Measurements

Applications:

1- Clinical-chemistry lab (analyze sample of blood and tissue)
2- Cardiac Catheterization (measure oxygen saturation of hemoglobin and cardiac output)

Components: Sources, filters, and detectors.

General block diagram of an optical instrument. (b) Highest efficiency is obtained by using an intense lamp, lenses to gather and focus the light on the sample in the cuvette, and a sensitive detector. (c) Solid-state lamps and detectors may simplify the system.



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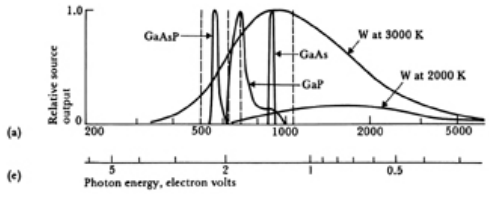
Radiation Sources

1- Tungsten Lamps
- Coiled filaments to increase emissivity and efficiency.
- Ribbon filaments for uniform radiation
- Tungsten-halogen lamps have iodine or bromine to maintain more than 90% of their initial radiant.



Spectral characteristics of sources, (a) Light sources, Tungsten (W) at 3000 K has a broad spectral output. At 2000 K, output is lower at all wavelengths and peak output shifts to longer wavelengths.

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Radiation Sources

2- ARC Discharges
- Low-pressure lamp: Fluorescent lamp filled with Argon-Mercury (Ar-Hg) mixture. Accelerated electron hit the mercury atom and cause the radiation of 250 nm (5 eV) wavelength which is absorbed by phosphor. Phosphor will emits light of longer visible wavelengths.
- Fluorescent lamp has low radiant so it is not used for optical instrument, but can be turned on in 20 µsec and used for tachistoscope to provide brief stimuli to the eye.
- High pressure lamp: mercury, sodium, xenon lamps are compact and can provide high radiation per unit area. Used in optical instruments.

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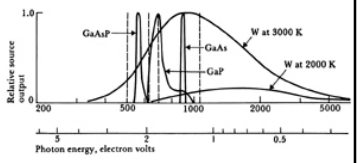
Radiation Sources

3- Light-Emitting Diodes (LED)
A *p-n* junction devices that are optimized to radiant output.
-GaAs has a higher band gap and radiate at 900 nm. Switching time 10 nsec.
-GaP LED has a band gap of 2.26 eV and radiate at 700 nm
-GaAsP absorb two photons of 940 nm wavelength and emits one photon of 540 nm wavelength.

Advantages of LED: compact, rugged, economical, and nearly monochromatic.

Spectral characteristics of sources, (a) Light-emitting diodes yield a narrow spectral output with GaAs in the infrared, GaP in the red, and GaAsP in the green.



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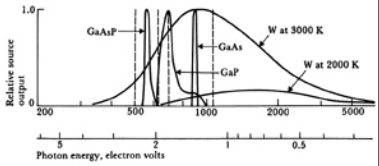
Radiation Sources

4- Laser (Light Amplification by Stimulated Emission of Radiation)
-He-Ne lasers operate at 633 nm with 100 mW power.
-Argon laser operates at 515 nm with the highest continuous power level with 1-15 W power.
-CO_2 lasers provide 50-500 W of continuous wave output power.
-Ruby laser is a solid state lasers operate in pulsed mode and provide 693 nm with 1-mJ energy.

The most medical use of the laser is to mend tear in the retina.

Spectral characteristics of sources, (a) Monochromatic outputs from common lasers are shown by dashed lines; Ar, 515 nm; HeNe, 633 nm; ruby, 693 nm; Nd, 1064 nm



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Optical Filters

- Optical filters are used to control the distribution of radiant power or wavelength.
- **Power Filters**
  - Glass partially silvered: most of power are reflected
  - Carbon particles suspended in plastic: most of power are absorbed
  - Two Polaroid filters: transmit light of particular state of polarization
- **Wavelength Filters**
  - Color Filters: colored glass transmit certain wavelengths
  - Gelatin Filters: a thin film of organic dye dried on a glass (Kodak 87) or combining additives with glass when it is in molten state (corning 5-56).
  - Interference Filters: Depositing a reflective stack of layers on both sides of a thicker spacer layer. LPF, BPF, HPF of bandwidth from 0.5 to 200nm.
  - Diffraction grating Filters: produce a wavelength spectrum.

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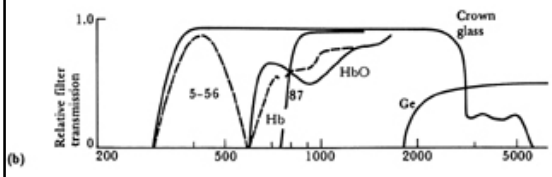
Optical Filters

Spectral characteristics of filters (b) Filters. A Corning 5-65 glass filter passes a blue wavelength band. A Kodak 87 gelatin filter passes infrared and blocks visible wavelengths. Germanium lenses pass long wavelengths that cannot be passed by glass. Hemoglobin Hb and oxyhemoglobin HbO pass equally at 805 nm and have maximal difference at 660 nm.



Optical method for measuring fat in the body (fat absorption 930 nm
Water absorption 970 nm

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Classifications of Radiation Sensors

- **Thermal Sensors**:
- absorbs radiation and change the temperature of the sensor.
  - Change in output could be due to change in the ambient temperature or source temperature.
  - Sensitivity does not change with wavelength
  - Slow response

  Example: Pyroelectric sensor: absorbs radiation and convert it to heat which change the electric polarization of the crystals.
- **Quantum Sensors**:
- absorb energy from individual photons and use it to release electrons from the sensor material.
  - sensitive over a restricted band of wavelength
  - Fast response
  - Less sensitive to ambient temperature

  Example: Eye, Phototube, photodiode, and photographic emulsion.

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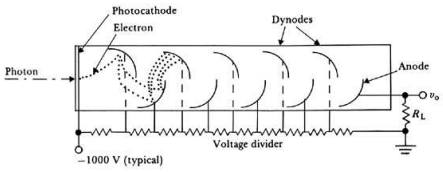
Photoemissive Sensors

Phototube: have photocathode coated with alkali metals. A radiation photon with energy cause electron to jump from cathode to anode.
Photon energies below 1 eV are not large enough to overcome the work functions, so wavelength over 1200nm cannot be detected.



Photomultiplier An incoming photon strikes the photocathode and liberates an electron. This electron is accelerated toward the first dynode, which is 100 V more positive than the cathode. The impact liberates several electrons by secondary emission. They are accelerated toward the second dynode, which is 100 V more positive than the first dynode, This electron multiplication continues until it reaches the anode, where currents of about 1 μA flow through R_L. Time response < 10 nsec

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Photoconductive Cells

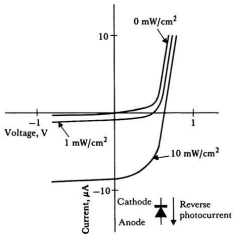
- Photoresistors: a photosensitive crystalline materials such as cadmium Sulfide (CdS) or lead sulfide (PbS) is deposited on a ceramic substance.
- The resistance decrease of the ceramic material with input radiation. This is true if photons have enough energy to cause electron to move from the valence band to the conduction band.

Photojunction Sensors

Photojunction sensors are formed from *p-n* junctions and are usually made of silicon. If a photon has enough energy to jump the band gap, hole-electron pairs are produced that modify the junction characteristics.

Photodiode: With reverse biasing, the reverse photocurrent increases linearly with an increase in radiation.

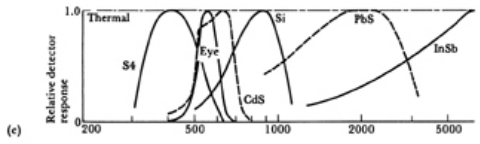
Phototransistor: radiation generate base current which result in the generation of a large current flow from collector to emitter. Response time = 10 microsecond



Voltage-current characteristics of irradiated silicon p-n junction. For 0 irradiance, both forward and reverse characteristics are normal. For 1 mW/cm², open-circuit voltage is 500 mV and short-circuit current is 8 μA.

Photovoltaic Sensors

Photovoltaic sensors is a *p-n* junction where the voltage increases as the radiation increases.



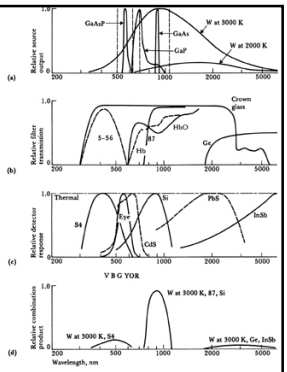
Spectral characteristics of detectors, (c) Detectors. The S4 response is a typical phototube response. The eye has a relatively narrow response, with colors indicated by VBGYOR. CdS plus a filter has a response that closely matches that of the eye. Si p-n junctions are widely used. PbS is a sensitive infrared detector. InSb is useful in far infrared. Note: These are only relative responses. Peak responses of different detectors differ by 107.

Optical Combinations

Total effective irradiance, is found by breaking up the spectral curves into many narrow bands and then multiplying each together and adding the resulting increments.

$$E_e = \sum S_\lambda F_\lambda D_\lambda \Delta\lambda$$

S_λ= relative source output;
F_λ= relative filter transmission
D_λ= relative sensor responsivity



Spectral characteristics of combinations thereof (d) Combination. Indicated curves from (a), (b), and (c) are multiplied at each wavelength to yield (d), which shows how well source, filter, and detector are matched.

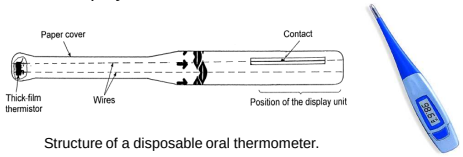
Measuring Core Temperature

Because skin temperature cannot directly be correlated with interior body temperature, *body (core) temperature* measurement is traditionally performed inside a body cavity

An old and traditional device used for body temperature measurement is the mercury thermometer that does not contain sensors. Its drawbacks are slow operation and difficult reading and registration of the result

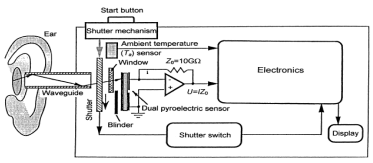
Electronic thermometers

They generally contain diodes as temperature-sensing elements with a special package design that can assure small thermal capacity and good thermal conductivity to the environment. They have relatively short response times and good visible display units



Structure of a disposable oral thermometer.

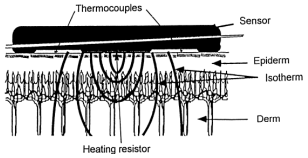
Radiation Ear Thermometer



This version is based on a pyroelectric sensor. Thermal radiation flux from the auditory canal is channeled by the optical waveguide toward the pyroelectric sensor. When pressing the start button, the shutter opens momentarily, exposing the sensor to thermal radiation and replacing the radiation coming from the shutter itself. An ambient temperature sensor element is behind the shutter. The radiation reaches the sensor where it is converted into electric current impulse due to the pyroelectric effect

Skin Blood-Flow Sensor

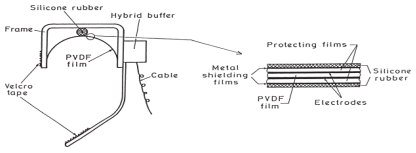
Skin blood flow (SBF) or skin perfusion is a complex phenomenon that occurs in capillaries. In perfused tissue, thermal conductivity depends not only on the thermal conductivity of the tissue materials, but also on the heat convection transferred by the blood flow in capillaries. Thus, thermal conductivity of the skin can vary within a wide range; its minimum value, 2.5 mW/cm℃



A Thermal Conductivity Sensor for the Measurement of Skin Blood Flow

Sensors for Pressure Pulses and Movement

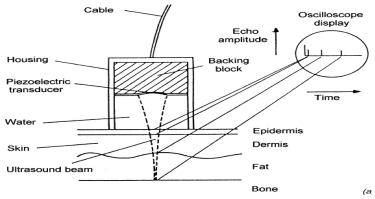
Pulse sensing is a convenient and efficient way of acquiring important physiological information concerning the cardiovascular system. Finger pulse pickups can be employed in systems that measure blood pressure, heart rate, and blood flow



The pulse-wave signal is sent through the buffer to the signal-processing electronics. The PVDF film is in direct contact with the finger therefore, its metallized surfaces have to be shielded on both sides with thin metallized protecting polymer films and sealed with highly insulating silicone rubber to avoid damage to the surface electrodes

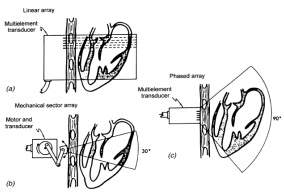
SENSORS IN ULTRASOUND IMAGING

The first and simplest ultrasound imaging systems applied the *A-mode (amplitude modulation)* imaging illustrated in Figure



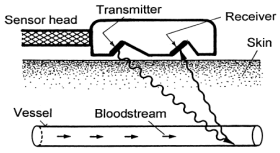
ULTRASOUND IMAGING

In *B-mode (brightness modulation)* imaging, all echo impulses are represented by a pixel on the display, and the brightness corresponds to the amplitude of the echo. To get a two-dimensional cross-sectional image, an appropriate scanning of the desired cross section is necessary



Scanning methods in B-mode ultrasound imaging: (a) sequential linear array scanner, (b) mechanical sector scanner, and (c) phased array sector scanne

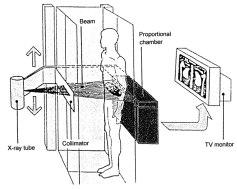
The Doppler blood-flow measurement



Doppler blood flow detectors operate by means of continuous sinusoidal excitation. The frequency difference calibrated for flow velocity can be displayed or transformed by a loudspeaker into an audio output.

X-ray Imaging System

In optically coupled CCD X-ray imaging system, X rays are impinged into a fluorescent screen and the image produced is then transferred onto the surface of an individual CCD by optical lenses



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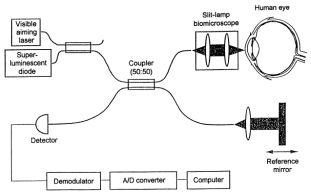
Optical Coherence Tomography

The technique of *optical coherence tomography (OCT)* provides a micronscale resolution cross-sectional image from the overall eyeball, not only from the retina. OCT is similar to B-scan ultrasonic imaging



Schematic diagram of optical coherence tomography instrumentation

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Project (Sensors)

Resistive Sensors
Strain Gages (Bounded and Unbonded)
Blood Pressure Sensors
Inductive Sensor (LVDT)
Capacitive Sensors
Piezoelectric Sensors
Temperature Sensors (Thermocouple, Thermistors)
Radiation Thermometry
Infrared Thermometer Sensors
Fiber Optic temperature Sensors
Radiation Sources (ARC, LEDs)
Thermal Sensors
Quantum Sensors
Photoemissive Sensors
Photoconductive cells
Photojunction Sensors
Photovoltaic Sensors

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