Sensor: device which detects changes in quantities of interest and provides a readable output.

Example

- Thermocouple converts temperature to voltage.
- Mercury thermometer converts temperature to a reading on a calibrated glass tube.
Instrument Characteristics: Resolution and Sensitivity

Resolution

- Smallest change measurable

Sensitivity

\[ = \frac{\Delta \text{signal}}{\Delta \text{measurand}} \]
A system is Linear if it has two superposition properties
• **Scaling** (ex: Doubling the input will double the output.)
• **Additivity** (ex: Adding inputs gives the sum of outputs.)

*Scaling* and *additivity* example:
Listening to two instruments at different distances

\[
y[n] = k_1 x_1[n] + k_2 x_2[n]
\]
Most systems have a **linear operating range**.

Outside this range we have the **maximum operating range** (that doesn’t damage the instrument).
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Range</th>
<th>Frequency, Hz</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood flow</td>
<td>1 to 300 mL/s</td>
<td>0 to 20</td>
<td>Electromagnetic or ultrasonic</td>
</tr>
<tr>
<td>Blood pressure</td>
<td>0 to 400 mmHg</td>
<td>0 to 50</td>
<td>Cuff or strain gage</td>
</tr>
<tr>
<td>Cardiac output</td>
<td>4 to 25 L/min</td>
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</tr>
<tr>
<td>Electrocardiography</td>
<td>0.5 to 4 mV</td>
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</tr>
<tr>
<td>Electromyography</td>
<td>0.1 to 5 mV</td>
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</tr>
<tr>
<td>Electoretinography</td>
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<tr>
<td>pH</td>
<td>3 to 13 pH units</td>
<td>0 to 1</td>
<td>pH electrode</td>
</tr>
<tr>
<td>pCO₂</td>
<td>40 to 100 mmHg</td>
<td>0 to 2</td>
<td>pCO₂ electrode</td>
</tr>
<tr>
<td>pO₂</td>
<td>30 to 100 mmHg</td>
<td>0 to 2</td>
<td>pO₂ electrode</td>
</tr>
<tr>
<td>Pneumotachography</td>
<td>0 to 600 L/min</td>
<td>0 to 40</td>
<td>Pneumotachometer</td>
</tr>
<tr>
<td>Respiratory rate</td>
<td>2 to 50 breaths/min</td>
<td>0.1 to 10</td>
<td>Impedance</td>
</tr>
<tr>
<td>Temperature</td>
<td>32 to 40 °C</td>
<td>0 to 0.1</td>
<td>Thermistor</td>
</tr>
</tbody>
</table>
Sensor Types:

- **Displacement Sensors:** measure movement
  - Resistive
  - Inductive
  - Capacitive
  - Piezoelectric

- **Temperature Measurement**
  - Thermistors
  - Thermocouples
Potentiometers

Construction

• Wire wound
• Carbon film
• Ceramic
• Conducting plastic

If we apply 10V across a single turn potentiometer with 50 wire turns covering 360°.

- What is sensitivity (in volts/degree)?
- What is resolution?
Strain gauge measures strain (deformation) by a change in resistance.

- Measurement circuits typically use “Wheatstone bridge” – describe next section

**Gauge Factor:** measure of gauge sensitivity

\[ GF = \left( \frac{\Delta R}{R} \right) / \text{strain} \]

- \( R \): undeformed resistance
- \( \Delta R \): change in \( R \) due to strain
- strain: fractional change in length \((\Delta L/L)\)
**Bonded:** (more typical) bonded to device with adhesive (superglue)

- Resistance Wire
- Foil
- Helical Wire

**Unbonded:** mounted freely (ends bounded to device)

Unbonded strain-gage pressure sensor. With increasing pressure, the strain on gage pair B and C is increased, while that on gage pair A and D is decreased.
Integrated pressure sensor. Diaphragm deforms if pressures on each side are unequal.

- Deforming strain gauges
- References gauges
Sensors
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Strain Gauge: analysis

Analysis of SG

\[ R = \frac{\rho L}{A} \]

\[ \frac{\partial R}{R} = \frac{L}{A} \frac{\partial \rho}{\rho} + \frac{\rho}{A} \frac{\partial L}{L} - \frac{L}{A^2} \frac{\partial A}{A} \]

\[ \frac{\partial R}{R} = \frac{\partial \rho}{\rho} + \frac{\partial L}{L} - \frac{\partial A}{A} \]

\[ \frac{\partial R}{R} = \frac{\partial \rho}{\rho} + (1 + 2 \mu) \frac{\partial L}{L} \]

\[ G = \frac{\partial R/R}{\partial L/L} = 1 + 2 \mu + \frac{\partial \rho/\rho}{\partial L/L} \]

Length (\( l \))

Area (\( A \))

resistivity (\( \rho \))

Poisson’s Ratio (\( \mu \))

\[ \frac{\partial A}{2A} = -\mu \frac{\partial L}{L} \]

For incompressible media \( \mu=0.5 \).

Calculate from

Vol = \( D^2L \) is const
Strain Gauge: analysis

Gage Factor

\[ G = \frac{\partial R/R}{\partial L/L} = 1 + 2\mu + \frac{\partial \rho/\rho}{\partial L/L} \]

Dimensional Effect
Piezoresistive Effect
- Metals \( \approx 0 \)
- Ceramics / Semiconductors have large effect

Examples:
- Metals \( G = 1+2(0.3) = 1.6 \)
- n-Si \( G \approx 100 \)
- p-Si \( G \approx -100 \)
  (large temperature drift in semis)
Mercury plethysmograph measures change in leg blood volume after pressure cuff applied (venous occlusion)

- \( \mu \) for Hg is 0.5
- Calculate \( \Delta R/R \) if blood makes 10% increase in leg cross section
Inductive Sensors

• Inductance: \[ L = n^2 G \mu \]

  \( n \) = number of turns
  \( G \) = geometry factor
  \( \mu \) = permeability of medium

Inductance sensor measures displacement by changes in geometry.

Tend to be non-linear, since geometry to inductance relationship is non-linear

Many applications: metal detectors, proximity detector, traffic light car presence detector
Inductive sensor types

Self-inductance

Mutual inductance

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Inductive sensor: LVDT

Linear Variable Differential Transformer (LVDT)

AC current in primary, causes a voltage induced in each secondary proportional to its mutual inductance with the primary.

As the core moves, these mutual inductances change, causing the voltages induced in the secondaries to change. The coils are connected in reverse series.

When the core at the central position, equal but opposite voltages are induced, so the output voltage is zero.

When the core is displaced in one direction, the voltage in one coil increases as the other decreases. When the core moves in the other direction, its phase is opposite.

Output voltage is proportional to distance (up to its limit of travel)

Because the sliding core does not touch the inside of the tube, it can move with low friction, sealed against the environment

Capacitive sensors

- Low cost, small, mechanically strong
- Quite non-linear, better to indicate contact

Capacitive sensors

Electromagnetic analysis

\[ C = \varepsilon_0 \varepsilon_r \frac{A}{x} \]

\[ \varepsilon_0 = 8.86 \times 10^{-12} \frac{F}{m} \]

Permittivity of free space
Relative Permittivity

\[ K = \frac{dC}{dx} = -\varepsilon_0 \varepsilon_r \frac{A}{x^2} \]

Non-linear
Sensitivity

Electronic Circuit
Piezoelectricity is the ability of some materials to generate an electric potential to applied mechanical stress.

- Apply stress → Generate voltage
- Apply voltage → Generate stress

Piezoelectric materials

- Crystals (most common is quartz)
- Certain ceramics, including bone
- Films (polyvinylidenechloride: PVDC)

Disadvantage

- Because of very high impedance, charge leaks away.
- Can’t be used to measure static forces
Analysis of sensitivity

\[ q = kf \quad q : \text{charge} \]

\[ V = \frac{q}{C} = \frac{kfx}{\varepsilon_0 \varepsilon_r A} \]

\[ K = \frac{dV}{df} = \frac{kx}{\varepsilon_0 \varepsilon_r A} \]

Note that most piezosensors are very stiff, so we can assume that \( x \) is constant

Example: Calculate \( V \) for 10g weight on a 1cm\(^2\) area 1mm thick quartz. \( k= 2.3\text{pC/N}, \varepsilon_r = 10 \)

\[
V = \frac{(2.3\frac{\text{pC}}{\text{N}})(10\text{g})(\frac{9.8\text{N}}{1000\text{g}})(1\text{mm})(\frac{1\text{m}}{1000\text{mm}})}{(8.86 \times 10^{-12}\frac{\text{F}}{\text{m}})(10)(1\text{cm}^2)(\frac{1\text{m}}{100\text{cm}})^2} = 25.4\text{mV}
\]

Relative Permittivity
Piezosensors act as a high pass filter.

Force creates a current, which is held on a capacitance. Charge leaks via internal and amplifier leaks.

Response:

Time const: \( \tau \)

\[
\tau = C \left( R_{\text{internal}} \parallel R_{\text{amplifier}} \right)
\]
High-frequency circuit model for piezoelectric sensor.

- $R_s$: sensor leakage resistance
- $C_s$: the capacitance.
- $L_m$, $C_m$, and $R_m$: mechanical system.

![Diagram](image-url)
Questions

• What is the Gauge factor? What kinds of materials have large G? When is this useful?
• Why is temperature coefficient (tempco) in a strain gauge a problem? What strategies can be used to help deal with it?
• Name some applications for inductive sensors?
• What makes the LVDT linear, when most inductive sensors aren't?
• Since capacitive sensors are highly non-linear, what kinds of applications are they useful for?
• Are piezo-electric sensors linear? What are some advantages and disadvantages?
Why measure temperature

- Body is a heat engine. We burn food + oxygen to get energy for life. Temperature monitors the functioning of the engine
- Temperature increase – hyperthermia
  - typical cause: infection
- Temperature decrease – hypothermia
  - typical cause: shock

Instruments

- Thermistors
- Thermocouples
- Radiation
thermistor is a type of resistor with resistance varying according to its temperature.

thermal and resistor = thermistor

- Biomedical applications: thermometers, flow sensing, breathing (nasal thermistor)
- All resistors have some temperature variation. Thermisors have large tempco (%change/°C)
- material is generally a ceramic or polymer
As temperature increases, the thermistor resistance decreases, yielding more current that flows through $R_f$, thus $V_0$ increases.

Many different sizes:

- Small Thermistors are more fragile, faster (2s)
- Larger Thermistors respond slowly (10s)
Typical thermistor zero-power resistance ratio-temperature characteristics for various materials.

Linear model:

$$\Delta R = k \Delta T$$

where

- $\Delta R =$ change in resistance
- $\Delta T =$ change in temperature
- $k =$ first-order temperature coefficient of resistance

Linear model only works over small range
Based on Seebeck effect: when a conductor (such as a metal) is subjected to a thermal gradient, it will generate a voltage.

Thermocouples measure the temperature difference, not absolute temperature.

Traditionally, one of the junctions—the cold junction—was maintained at a known (reference) temperature, while the other end was attached to a probe.

Thermocouples are faster, smaller, more robust, more linear than thermistors.

One way to determine the temperature of $J_2$ is to physically put the junction into an ice bath, forcing its temperature to be 0°C and establishing $J_2$ as the Reference Junction. Since both voltmeter terminal junctions are now copper-copper, they create no thermal emf and the reading $V$ on the voltmeter is proportional to the temperature difference between $J_1$ and $J_2$.

Now the voltmeter reading is (see Figure 5):

$$V = (V_1 - V_2) \equiv \alpha (t_{J_1} - t_{J_2})$$
The hot junction is at the thermocouple. The LT1025 electronic cold junction compensates for ambient temperature changes. The noninverting amplifier provides a high input impedance and high gain.

Type K (chromel–alumel) commonly used general purpose thermocouple. Inexpensive. Available in the $-200^\circ C$ to $+1350^\circ C$ range. Sensitivity $\approx 41 \, \mu V/\circ C$. 
Thermocouple or thermistor?

- Cheap
- Mechanically strong
- Simplest electrical circuit
- Capable of high temperatures
- Fastest response

Which has the highest sensitivity (V/°C) at 50°C

- Type K thermocouple
- Thermistor with constant current of 1mA. \( R_0 = 1k\Omega \). \( B = 40000K \).
• How does a thermistor differ from a thermocouple? Which is more linear? Which is less brittle? Which can have the fastest response?
• What would you build the temperature cut-off switch in a computer from?
• Why does a thermocouple need a reference circuit?
• What are some advantages / disadvantages of radiation based thermal measurement?
• What strategies are used to help reduce drift in radiation thermal detectors?