An Introduction to Sensors

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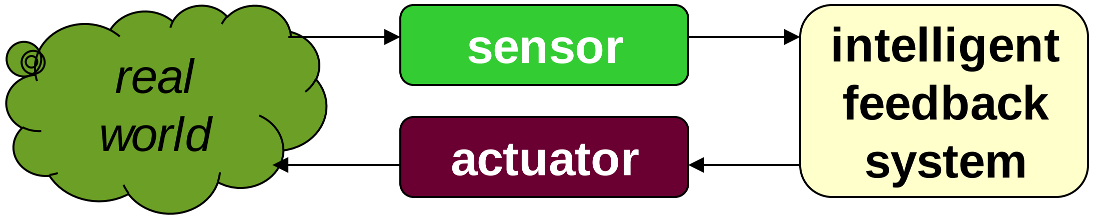
What are Sensors?

- Transducer
  - a device that converts a primary form of energy into a corresponding signal with a different energy form
    - Primary Energy Forms: mechanical, thermal, electromagnetic, optical, chemical, etc.
  - take form of a **sensor** or an **actuator**

- Sensor (e.g., thermometer)
  - a device that detects/measures a signal or stimulus
  - acquires information from the “real world”

- Actuator (e.g., heater)
  - a device that generates a signal or stimulus



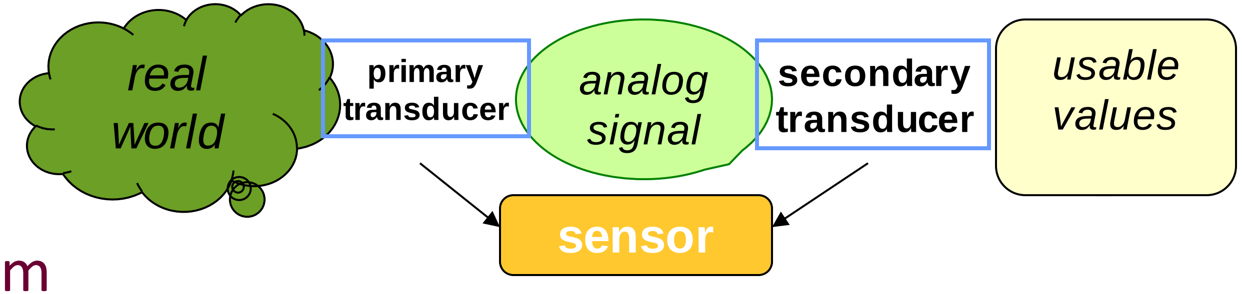
Sensor Systems

Typically interested in ***electronic sensor***

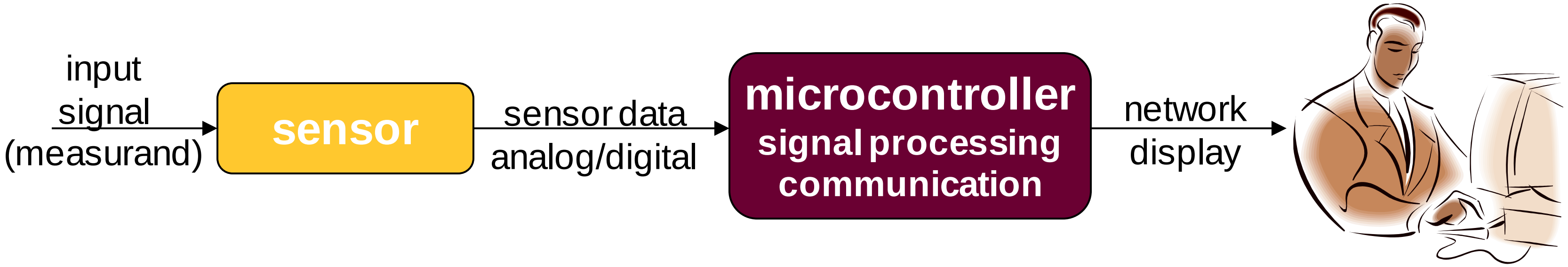
- convert desired parameter into electrically measurable signal

General Electronic Sensor

- primary transducer: changes "real world" parameter into electrical signal
- secondary transducer: converts electrical signal into analog or digital values



Typical Electronic Sensor System



Detectable Phenomenon

Stimulus	Quantity
Acoustic	Wave (amplitude, phase, polarization), Spectrum, Wave Velocity
Biological & Chemical	Fluid Concentrations (Gas or Liquid)
Electric	Charge, Voltage, Current, Electric Field (amplitude, phase, polarization), Conductivity, Permittivity
Magnetic	Magnetic Field (amplitude, phase, polarization), Flux, Permeability
Optical	Refractive Index, Reflectivity, Absorption
Thermal	Temperature, Flux, Specific Heat, Thermal Conductivity
Mechanical	Position, Velocity, Acceleration, Force, Strain, Stress, Pressure, Torque

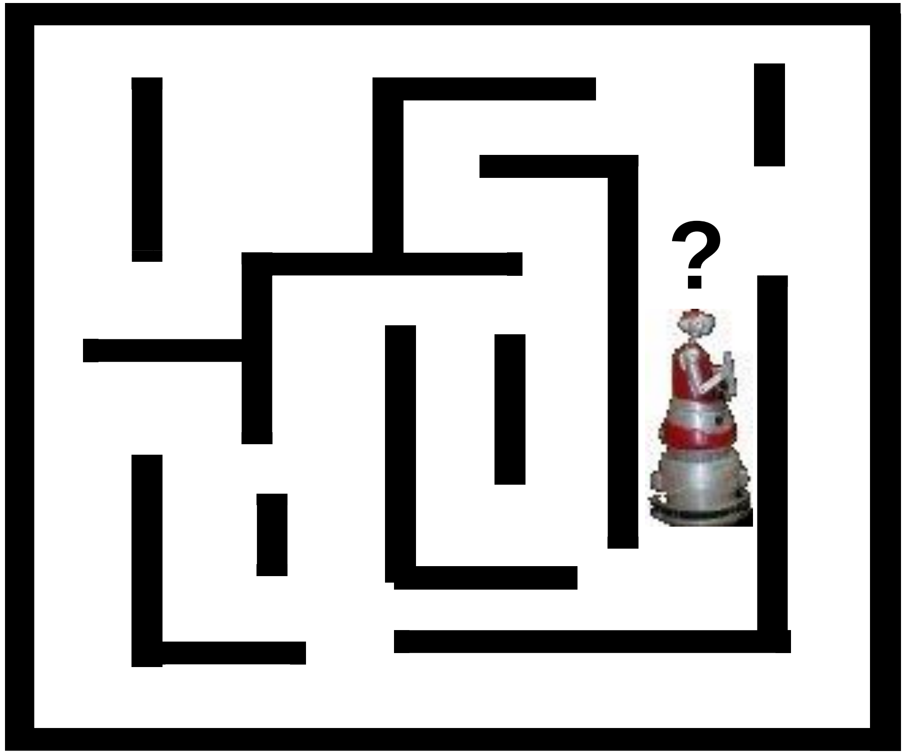
Do we need sensors?

Sensors are omnipresent. They embedded in our bodies, automobiles, airplanes, cellular telephones, radios, chemical plants, industrial plants and countless other applications.

Without the use of sensors, there would be no automation !!

- Imagine having to manually fill Poland Spring water bottles

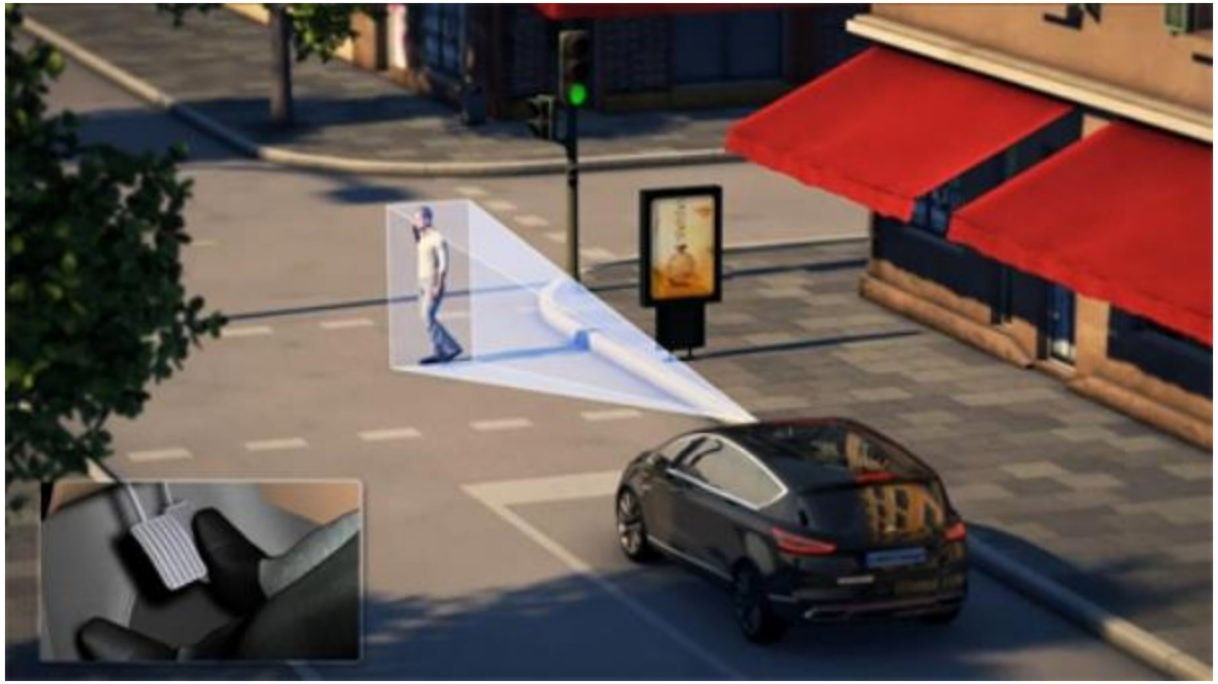
Why do robots need sensors?



Where am I?

Localization

Why do robots need sensors?



Will I hit anything?

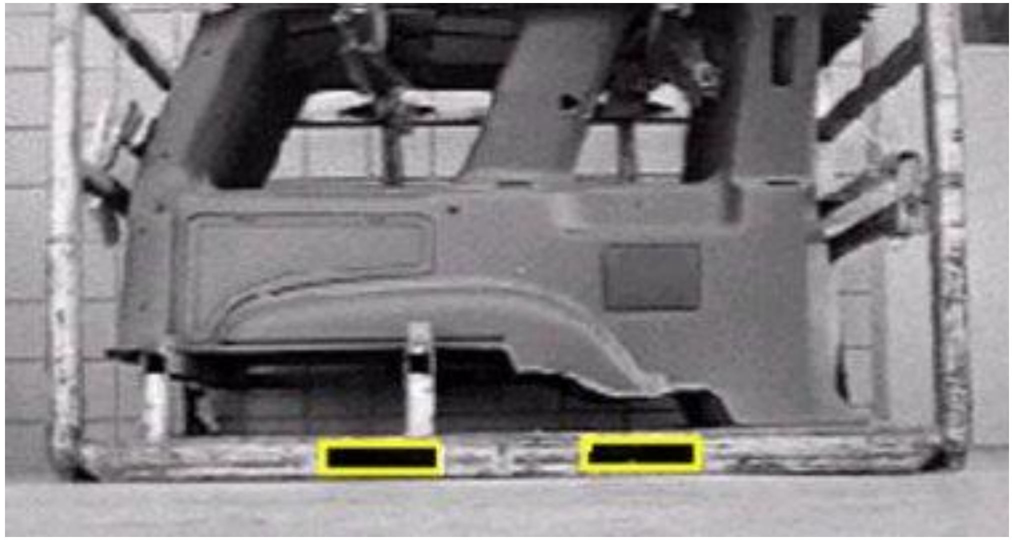
Obstacle Detection

Why do robots need sensors?

Where is the fruit?

Autonomous harvesting

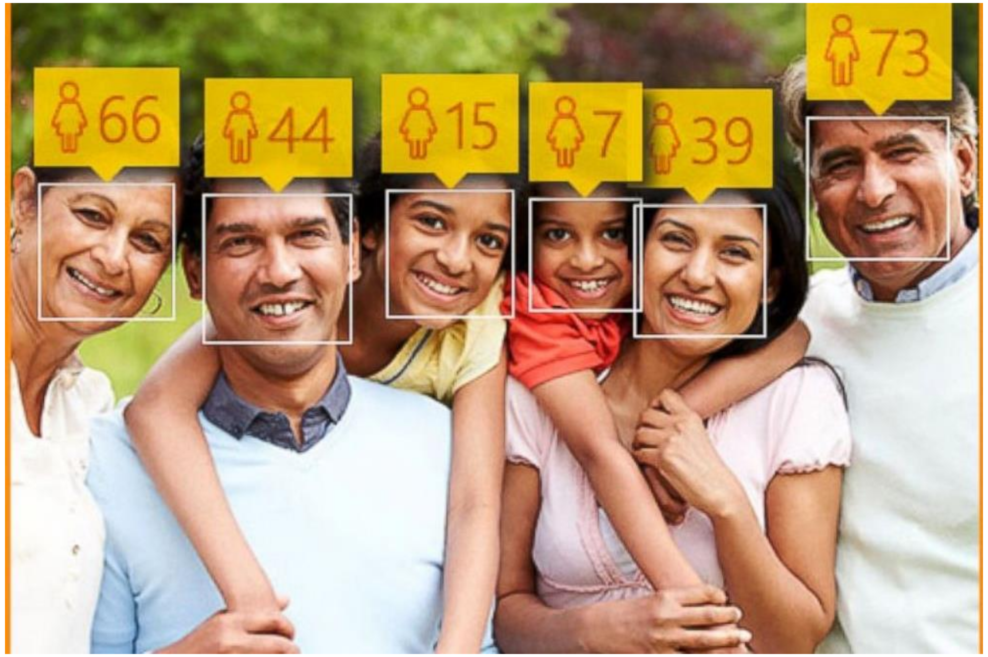
Why do robots need sensors?



Where are the fork holes?

Autonomous material handling

Why do robots need sensors?



Who are these people?
How old are they?

Face detection & tracking

Temperature Sensor

- Temperature sensors appear in building, chemical process plants, engines, appliances, computers, and many other devices that require temperature monitoring

- Many physical phenomena depend on temperature, so we can often measure temperature indirectly by measuring pressure, volume, electrical resistance, and strain

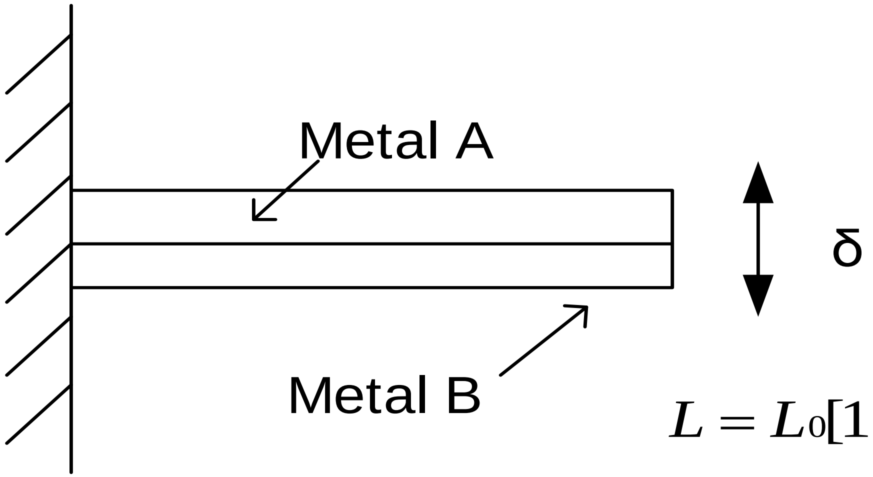
- Type of common temperature transducer
  - Resistance Temperature Detector (RTD)
  - Thermistors
  - Thermocouples

Thermocouple

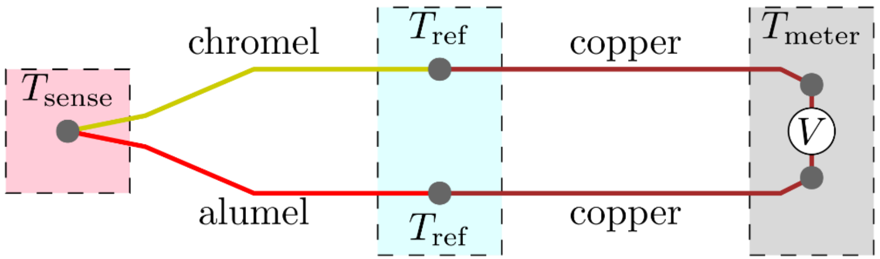
- A thermocouple is constructed by twisting or welding together at one end, two conductors made from dissimilar metals.

- The generated voltage is non-linear

- The thermocouple are designated as classes such as type E,K,J,N or T. Each type has a different temperature range/voltage response curve

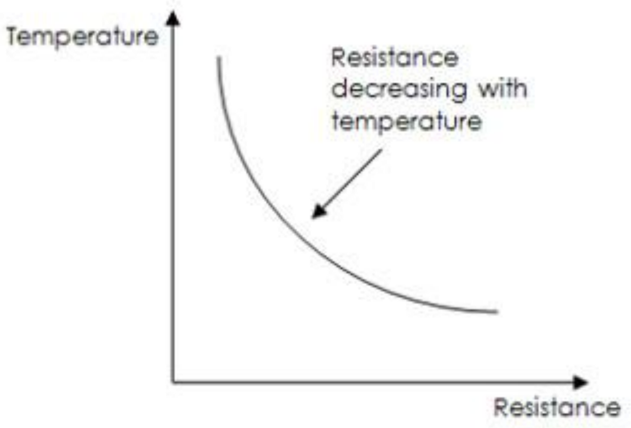


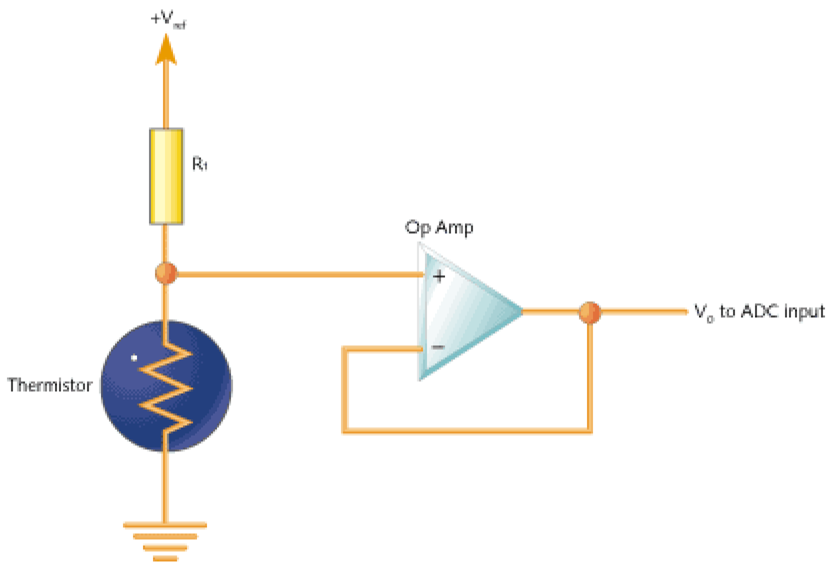
$$L = L_0[1+\beta(T-T_0)]$$



Thermistor

- A thermistor is a type of resistor with resistance varying according to its temperature. The resistance is measured by passing a small, measured direct current through it and measuring the voltage drop produced.





Temperature Sensor Summary

Category	Thermocouples	Resistance Temperature Detectors	Thermistors
Temperature Range (degree Celsius)	-180 to 2320	-200 to 500	-90 to 130
Response Time	Fast (micro seconds)	Slow (seconds)	Slow (seconds)
Accuracy	Low	Medium	High

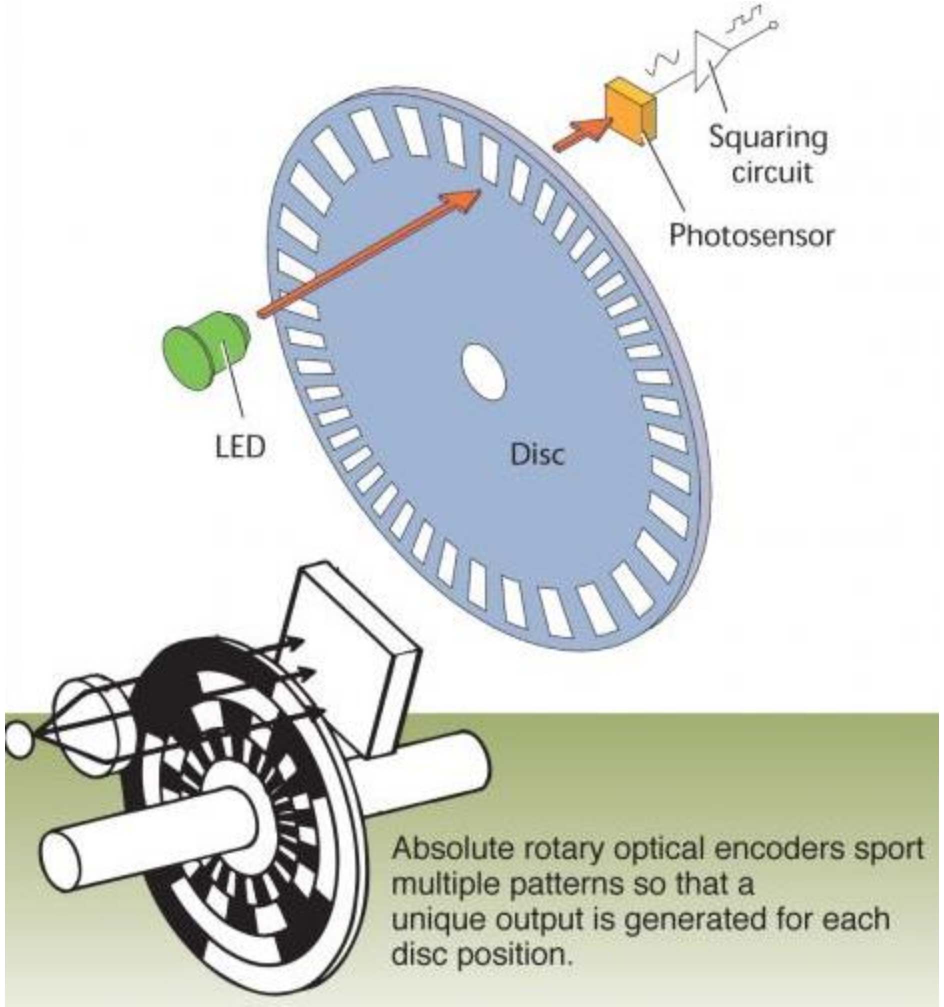
Encoders

- Encoders measure rotational motion

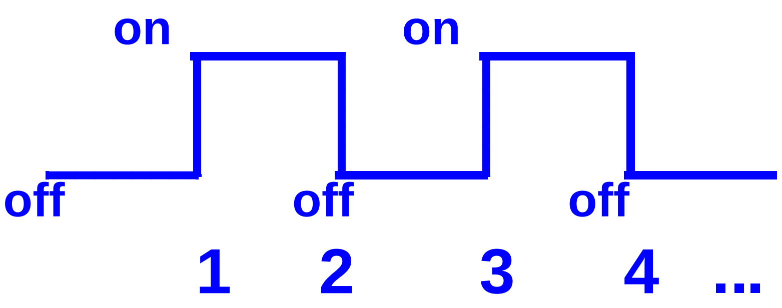
- They can be used to measure the rotation of a wheel

- **Servo motors:** Used in conjunction with an electric motor to measure the motor’s position and, in turn, control its position

Encoders



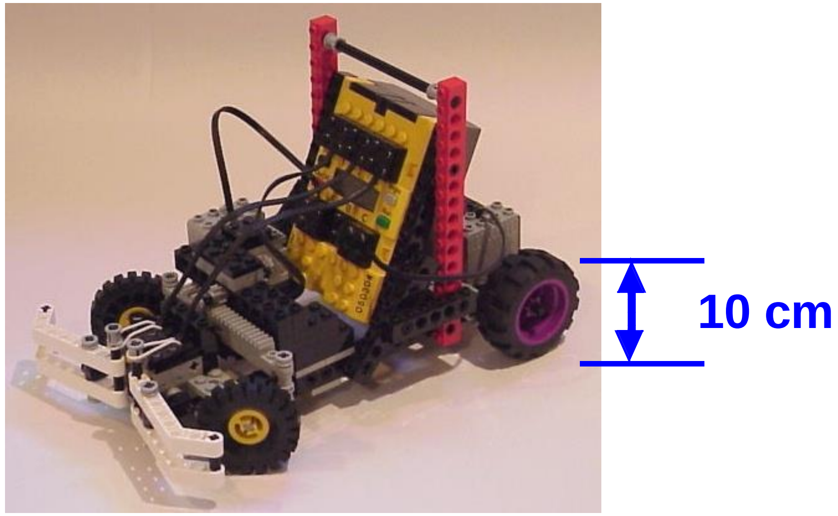
Voltage square wave



Important spec:
Number of counts per revolution

Sample problem: Sensor Analysis

16 counts per rev.

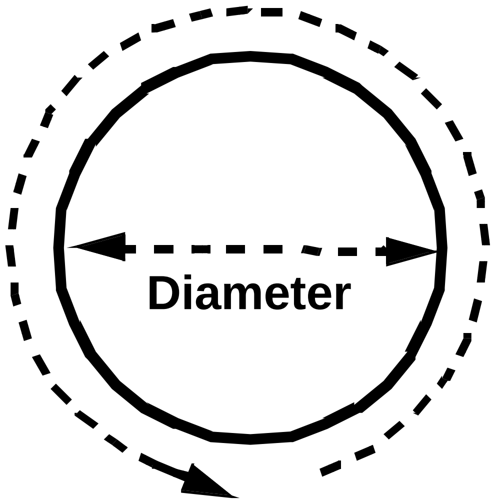


10 cm wheel diameter

- How far does the wheel travel for 1 encoder count?
- What happens if we change the wheel diameter?
- How many counts are there per meter of travel?

Sample problem: Sensor Analysis

- How far does the wheel travel for 1 encoder count?



$$C = \pi D$$

$$C = 10\pi \text{ cm}$$

$$\frac{10\pi \text{ cm}}{1 \text{ rev}} \times \frac{1 \text{ rev}}{16 \text{ counts}} = \frac{1.96 \text{ cm}}{\text{count}}$$

Sample problem: Sensor Analysis

- Suppose I want 1.0 cm / count
- What should my wheel diameter be?

$$\frac{1.0\ \text{cm}}{\text{count}} \times \frac{16\ \text{counts}}{1\ \text{rev}} = \frac{16\ \text{cm}}{\text{rev}}$$

$$C = 16\ \text{cm}$$

$$D = \frac{C}{\pi} = \frac{16}{\pi} = 5.09\ \text{cm}$$

Sample problem: Sensor Analysis

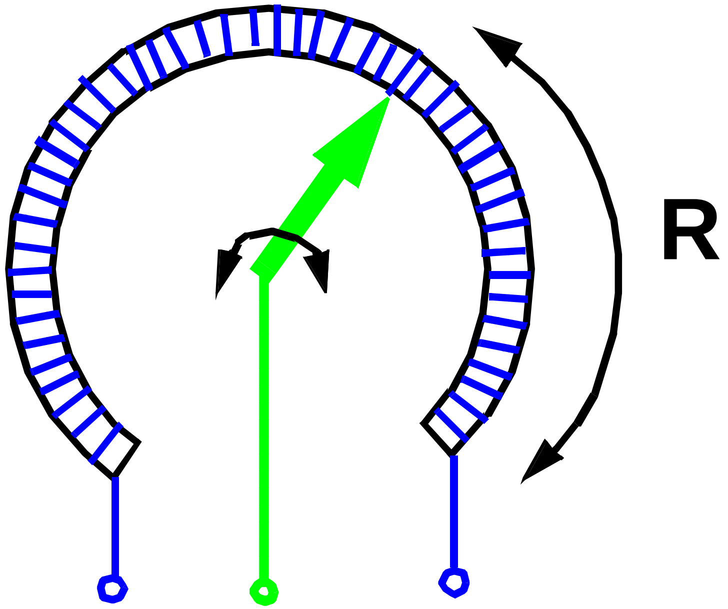
- For my 10 cm wheel, how many encoder counts will there be for 1 meter of travel?

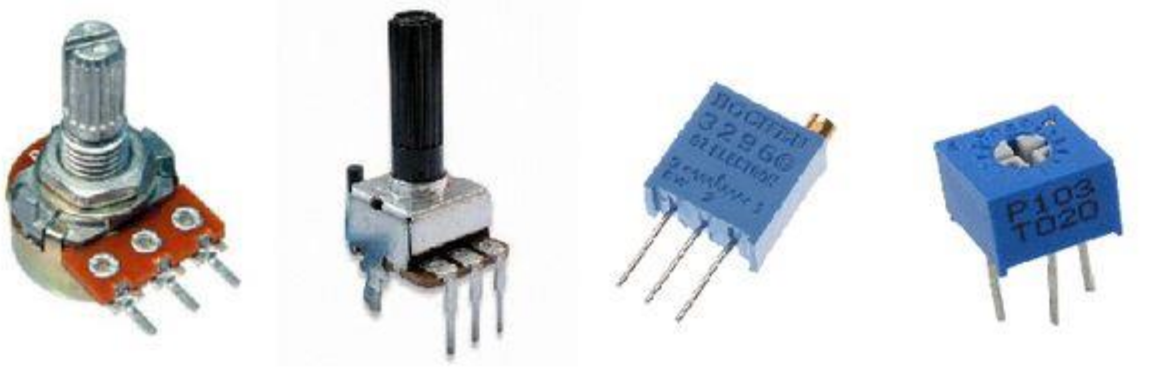
$$\frac{1.96\ \text{cm}}{\text{count}} \times \frac{1\ \text{meter}}{100\ \text{cm}} = \frac{0.0196\ \text{m}}{\text{count}}$$

$$\frac{1}{0.0196\ \text{m/ct}} = 51\ \text{counts/m}$$

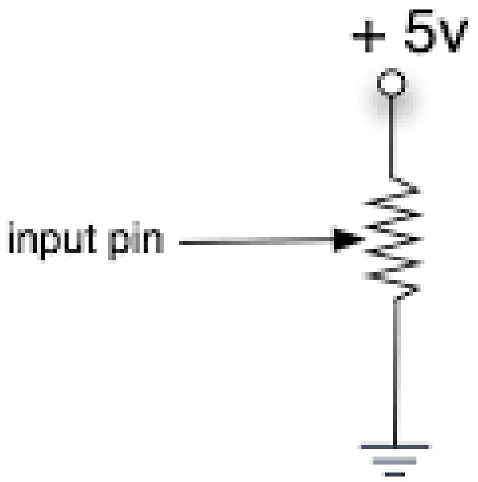
Potentiometer

Another rotational sensor



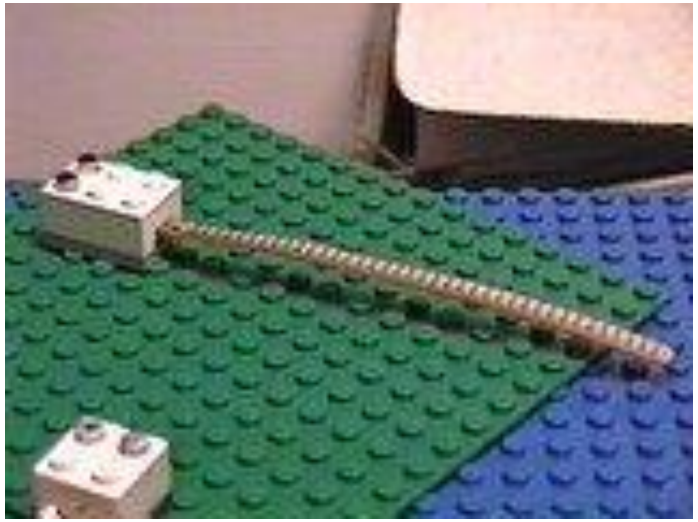


Resistance changes
with position of dial



Bend sensor

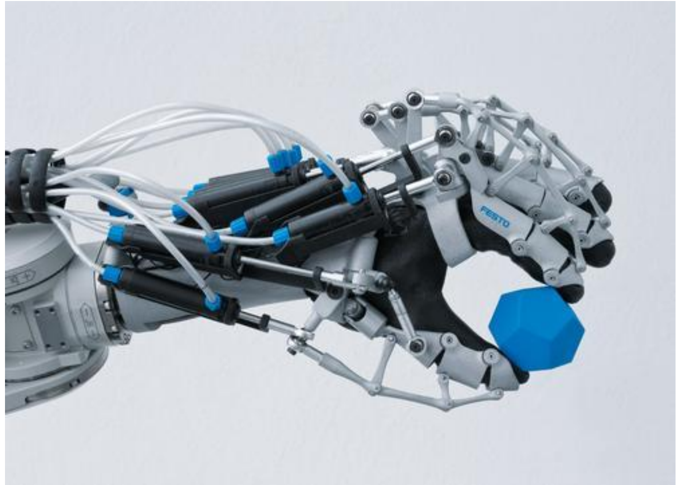
A variable resistor



resistance changes
as it bends

$$V = I \times R$$

assuming constant current, the measured voltage changes with resistance



Force Sensor

- Detect and measure a relative change in force or applied load
- Detect and measure the rate of change in force
- Identify force thresholds and trigger appropriate action
- Detect contact and/or touch

- Applications:
  - Touch Pads (i.e. VR Gloves, Joysticks)
  - Alarm Systems
  - Airbag Force
  - Aerospace
  - Robotic Grip Force
  - Compression Moldings

Sample problem

Bend sensor specs:

100 Ω when straight
1000 Ω when bent

$$V = I \times R$$

$$I = \frac{V}{R}$$

Given a 5 V source, what is the min. and max. current that is drawn?

$$\text{min} = \frac{5}{1000} = 5 \text{ mA}$$

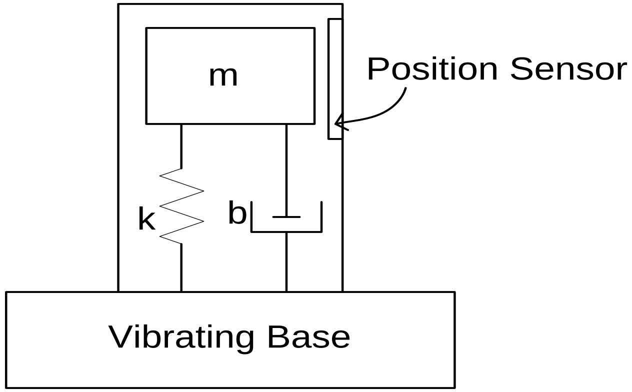
$$\text{max} = \frac{5}{100} = 50 \text{ mA}$$

Accelerometers

Accelerometers are used to measure along one axis and is insensitive to orthogonal directions

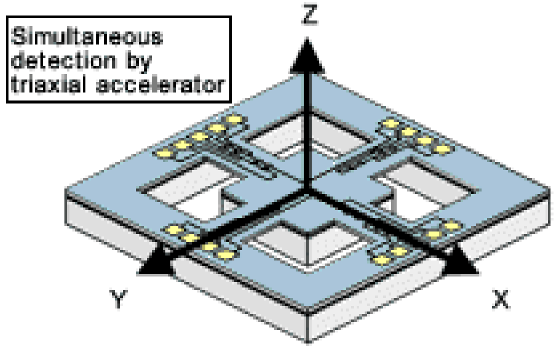
Applications

- Vibrations, blasts, impacts, shock waves
- Air bags, washing machines, heart monitors, car alarms



Accelerometers

- Used to measure acceleration
  - Common SI units meters/second2 (m/s^2) or popularly in terms of g-force (1g is earth's gravity)

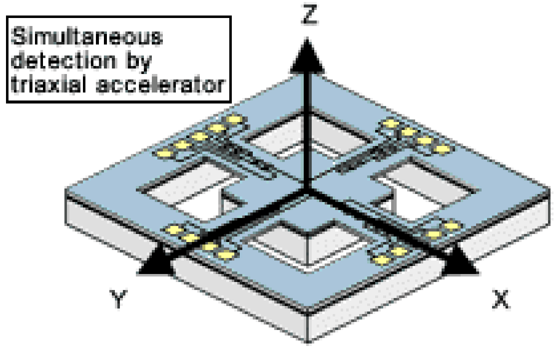


- At rest an acceleration will measure 1g in the vertical direction

- They can come in 1, 2 or 3 axis configurations
  - With 3 axis it gives a vector of the accelerations direction (after accounting for gravity)

Accelerometers

- Because of earth’s gravity, the sensor will read 1 to 0 g as the sensor is rotated from being vertical to horizontal.
  - This can be used to measure angle the of tilt



- Each sensor has a range that it works in.

- Most have analog outputs that need amplification
  - Some have built-in amplifiers for direct connection into microcontroller

Accelerometers: Operation

1. Red electrode has enough mass to move up and down when the unit is tilted or moved.

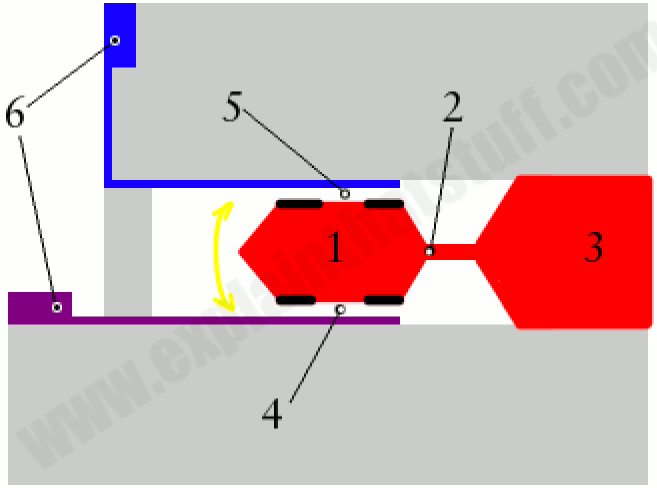
2. The electrode is supported by a tiny beam (cantilever) that's rigid enough to hold it but flexible enough to allow it to move.

3. An electrical connection is present from the cantilever and electrode to the outside of the chip so it can be wired into a circuit

4. Second electrode (purple). The air gap between the two electrodes (red and purple) work together as a capacitor. As you move the accelerometer and the red electrode moves up and down, the distance between the red and purple electrodes changes, and so does the capacitance between them.

5. The same principle applies between the red electrode and blue electrode.

6. The electrodes are connected to electrical terminals for external signal analysis



Accelerometers: Applications

- Can be used to sense orientation, vibration and shocks.

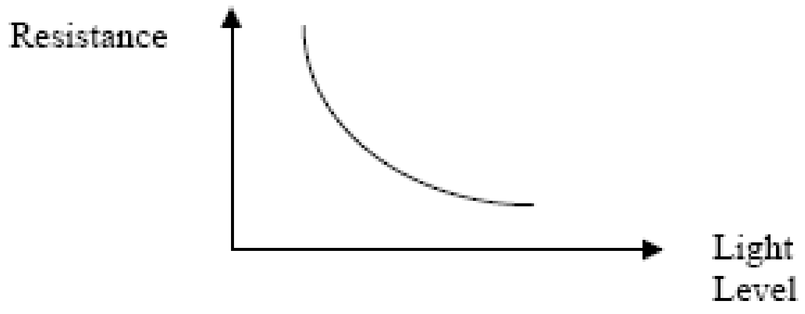
- Used in electronics like the Wii and iPhone for user input.

- Acceleration integrated once gives velocity, integrated a second time gives position.
  - The integration process is not precise and introduces error into the velocity and position.

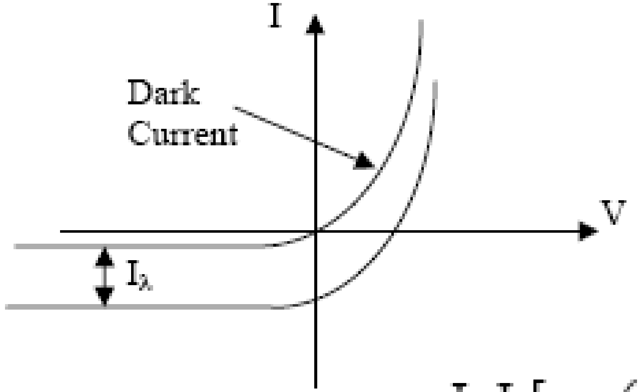
Light Sensor

- photoconductor
  - light → ΔR
- photodiode
  - light → ΔI

Photoconductor: (Light sensitive semiconductor resistor)



Photodiode:



$I = I_o[\exp(eV/kT) - 1] - I_\lambda$

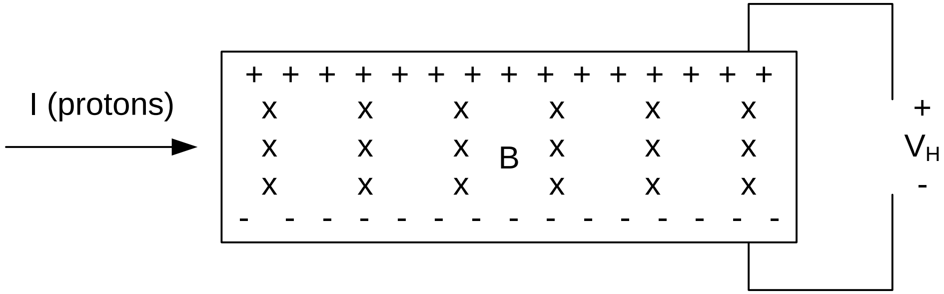
I_λ is proportion to the light level

Magnetic Field Sensor

- Magnetic Field sensors are used for power steering, security, and current measurements on transmission lines

- Hall voltage is proportional to magnetic field

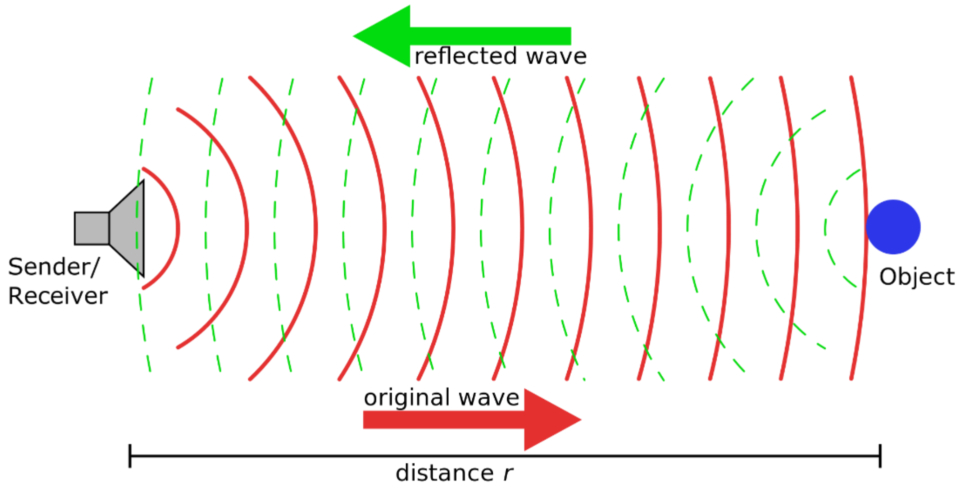
- Many of these sensors operate by detecting effects of the Lorentz force (a change in voltage or resonant frequency may be measured electronically, or a mechanical displacement may be measured optically)



$$V_H = \frac{I \cdot B}{n \cdot q \cdot t}$$

Sensors based on Sound

SONAR: **So**und **N**avigation **a**nd **R**anging



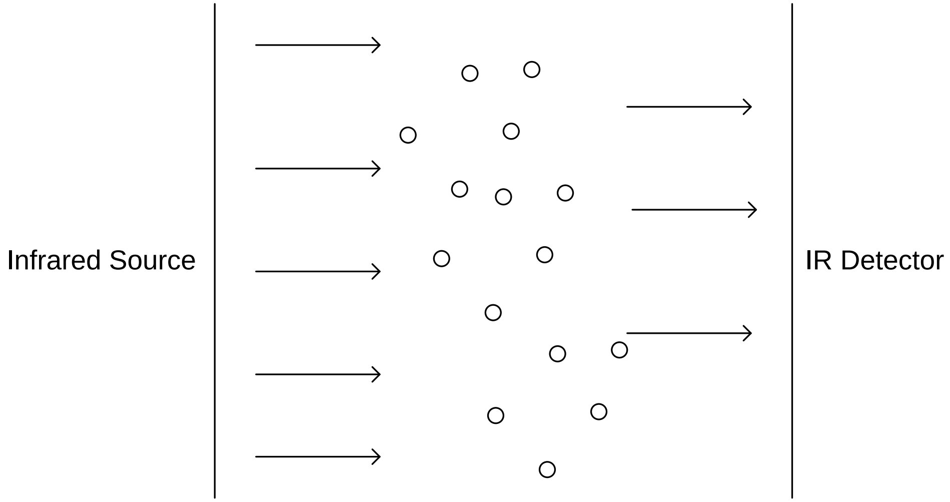
- bounce sound off of something
- measure time for reflection to be heard - gives a range measurement
- measure change in frequency - gives the relative speed of the object (Doppler effect)
- bats and dolphins use it with amazing results
- robots use it with less than amazing results

Photogate

- Used in counting applications (e.g. finding period of period motion)
- Infrared transmitter and receiver at opposite ends of the sensor
- Time at which light is broken is recorded

CO_2 Gas Sensor

- CO_2 sensor measures gaseous CO_2 levels in an environment
- Measures CO_2 levels in the range of 0-5000 ppm
- Monitors how much infrared radiation is absorbed by CO_2 molecules



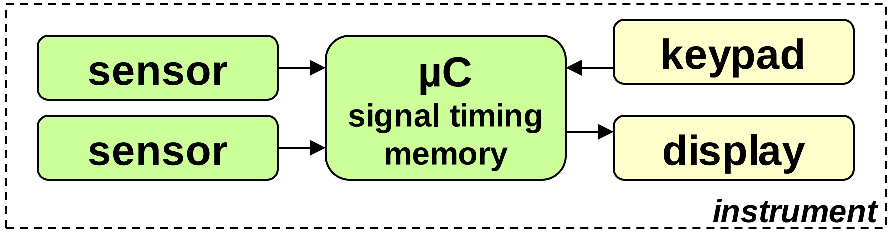
Connecting Sensors to Microcontrollers

Analog

- many microcontrollers have a built-in A/D
  - 8-bit to 12-bit resolution common
  - many have multi-channel A/D inputs

Digital

- serial I/O
  - use serial I/O port, store data in memory to analyze later
  - synchronous (with clock)
    - must match byte format, stop/start bits, parity check, etc.
  - asynchronous (no clock): more common for communication
    - must match baud rate and bit width, transmission protocol, etc.



Connecting Smart Sensors to PC/Network

"Smart sensor" = sensor with built-in signal processing & communication

- e.g., combining a "dumb sensor" and a microcontroller

Data Acquisition Cards (DAQ)

- PC card with analog and digital I/O
- interface through LabVIEW or user-generated code

Communication Links Common for Sensors

- asynchronous serial communication
  - universal asynchronous receive and transmit (UART)
    - 1 receive line + 1 transmit line. nodes must match baud rate & protocol
  - RS232 Serial Port on PCs uses UART format (but at +/- 12V)
    - can buy a chip to convert from UART to RS232
- synchronous serial comm.
  - serial peripheral interface (SPI)
    - 1 clock + 1 bidirectional data + 1 chip select/enable
- I^2C = Inter Integrated Circuit bus
  - designed by Philips for comm. inside TVs, used in several commercial sensor systems
- IEEE P1451: Sensor Comm. Standard
  - several different sensor comm. protocols for different applications

Sensor Calibration

Sensors can exhibit non-ideal effects

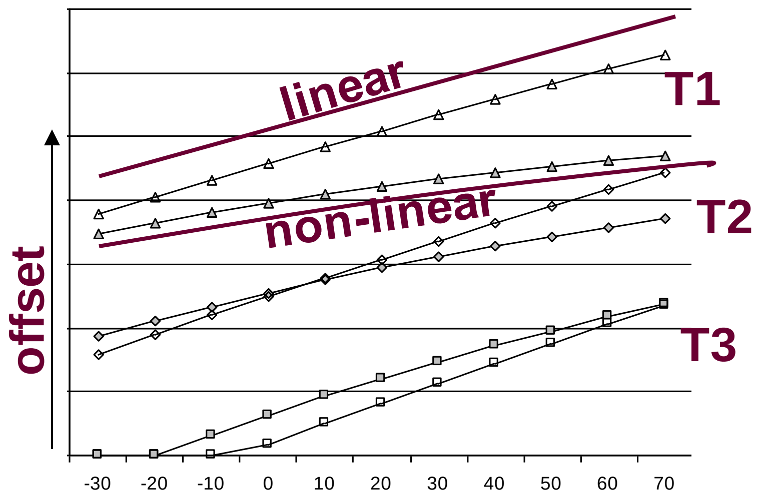
- offset: nominal output ≠ nominal parameter value
- nonlinearity: output not linear with parameter changes
- cross parameter sensitivity: secondary output variation with, e.g., temperature

Calibration - adjusting output to match parameter

- analog signal conditioning
- look-up table
- digital calibration
  - $T = a + bV + cV^2$,
    - T= temperature; V=sensor voltage;
    - a,b,c = calibration coefficients

Compensation

- remove secondary sensitivities
- must have sensitivities characterized
- can remove with polynomial evaluation
  - $P = a + bV + cT + dVT + e V^2$, where P=pressure, T=temperature



Choosing a Sensor

Environmental Factors	Economic Factors	Sensor Characteristics
Temperature range	Cost	Sensitivity
Humidity effects	Availability	Range
Corrosion	Lifetime	Stability
Size		Repeatability
Overrange protection		Linearity
Susceptibility to EM interferences		Error
Ruggedness		Response time
Power consumption		Frequency response
Self-test capability		

Describing Sensor Performance

Range

- maximum and minimum values that can be measured

Resolution or discrimination

- smallest discernible change in the measured value

Error

- difference between the measured and actual values
  - random errors
  - systematic errors

Accuracy, inaccuracy, uncertainty

- accuracy is a measure of the maximum expected error

Linearity

- maximum deviation from a 'straight-line' response
- normally expressed as a percentage of the full-scale value

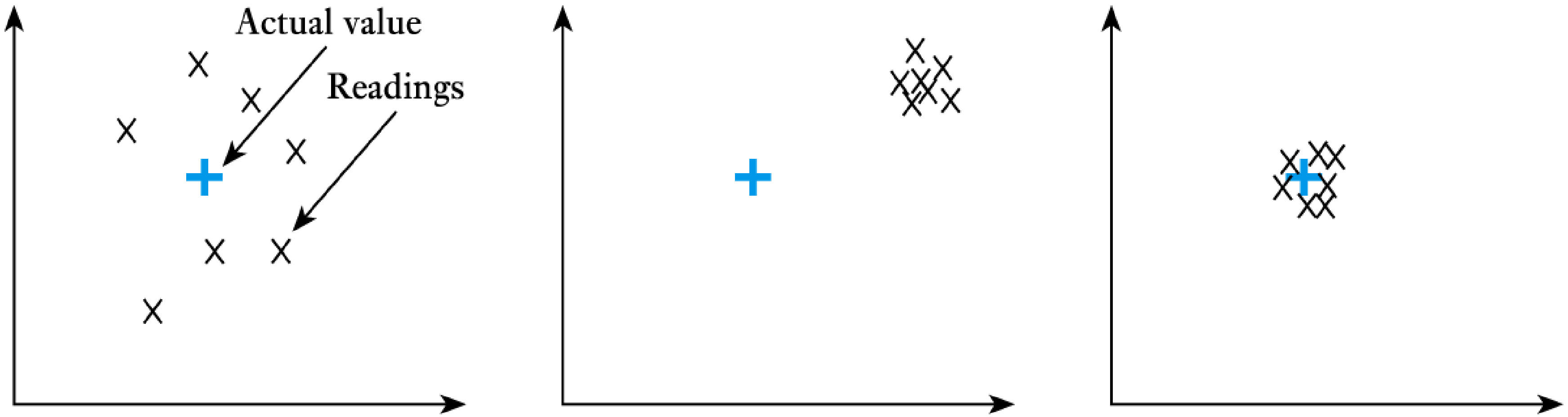
Sensitivity

- a measure of the change produced at the output for a given change in the quantity being measured

Describing Sensor Performance

Precision

- a measure of the lack of random errors (scatter)



(a) Low precision, low accuracy

(b) High precision, low accuracy

(c) High precision, high accuracy

Sensor Fusion

- Process of combining several kinds of sensor date to reveal more about context than a single sensor.
- Thermal sensor placed in a room alone cannot tell what caused temperature change.
- Combine data with sensors such as PIR and light, an IoT system can identify that change is due to a large number of people congregated in a close area.

- Centralized Mode: Raw data is streamed and aggregated to a central service and fusion occurs on cloud
- De-centralized Mode: Data is correlated at the sensor (or close to it)

- Correlation done through central limit theorem

$$x_3 = (\sigma_1^{-2} + \sigma_2^{-2})^{-1}(\sigma_1^{-2}x_1 + \sigma_2^{-2}x_2)$$

x_1, x_2 = sensor measurements x_3 = correlated measurement

Problem: Sensor Choice

What sensors to employ ?

E.g. mapping

- ranging - laser, sonar, IR, stereo camera pair
- salient feature detection - doors using color

Factors

- accuracy, cost, information needed etc etc.

Problem: Sensor Placement

Where do you place them?

On/off board (e.g. localization using odometry vs. localization using beacons)

If onboard - where ?

- Reasonable arrangements - heuristic
- Optimal arrangements - mathematically rigorous