Lecture 09
Sensors

CE346 – Microprocessor System Design

Branden Ghena – Fall 2021

Some slides borrowed from:
Josiah Hester (Northwestern), Prabal Dutta (UC Berkeley)

Northwestern

Administrivia

- Every group should have now received feedback from me on their proposals

- Project Design presentations will be next week **Thursday**
  - I'll provide details tomorrow

Today's Goals

- Think about sensing and sensors

- Explore a variety of sensor types, how they are made, and what their capabilities are

- Discuss an example research platform with a custom sensor

Outline

- **Sensing Overview**

- Types of Sensors
  - Temperature
  - Light
  - Inertial
  - Others

- Research case study

Definitions

- A **sensor** is a device that measures a physical quantity
  - Temperature sensor
  - Light sensor
  - Microphone

- An **actuator** is a device that modifies a physical quantity
  - Heater
  - Motor
  - Speaker

Sensors transform quantity into an electric signal

- Microcontrollers can interact with analog signals
  - Generating an analog signal proportional to physical quantity makes the quantity able to be sensed

- How do we generate an electrical signal?
  - Ohm's Law: V = I * R (Voltage = Current * Resistance)
 - Vary any one of these three and an analog signal is created

Resistive sensors

$$R = \frac{\rho L}{A}$$

- L: length of the conductor
- A: area of the conductor
- ρ: resistivity of the conductor material

- Various materials have resistivity that is itself a function
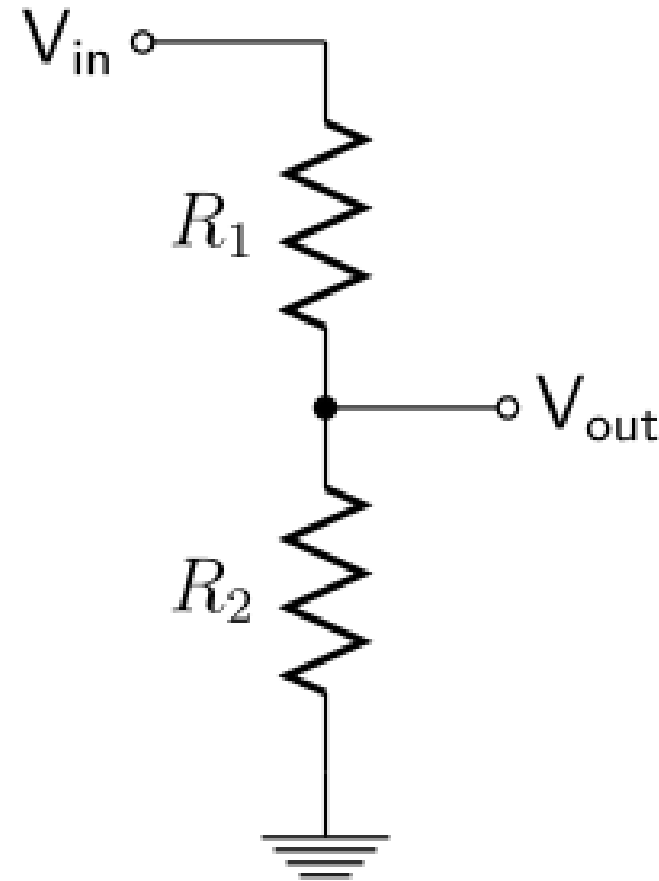 - Based on temperature, light, strain, etc.

Using a resistive sensor

- Place in series with another resistor
  - Between VCC and ground

- Measure voltage between the two relative to ground
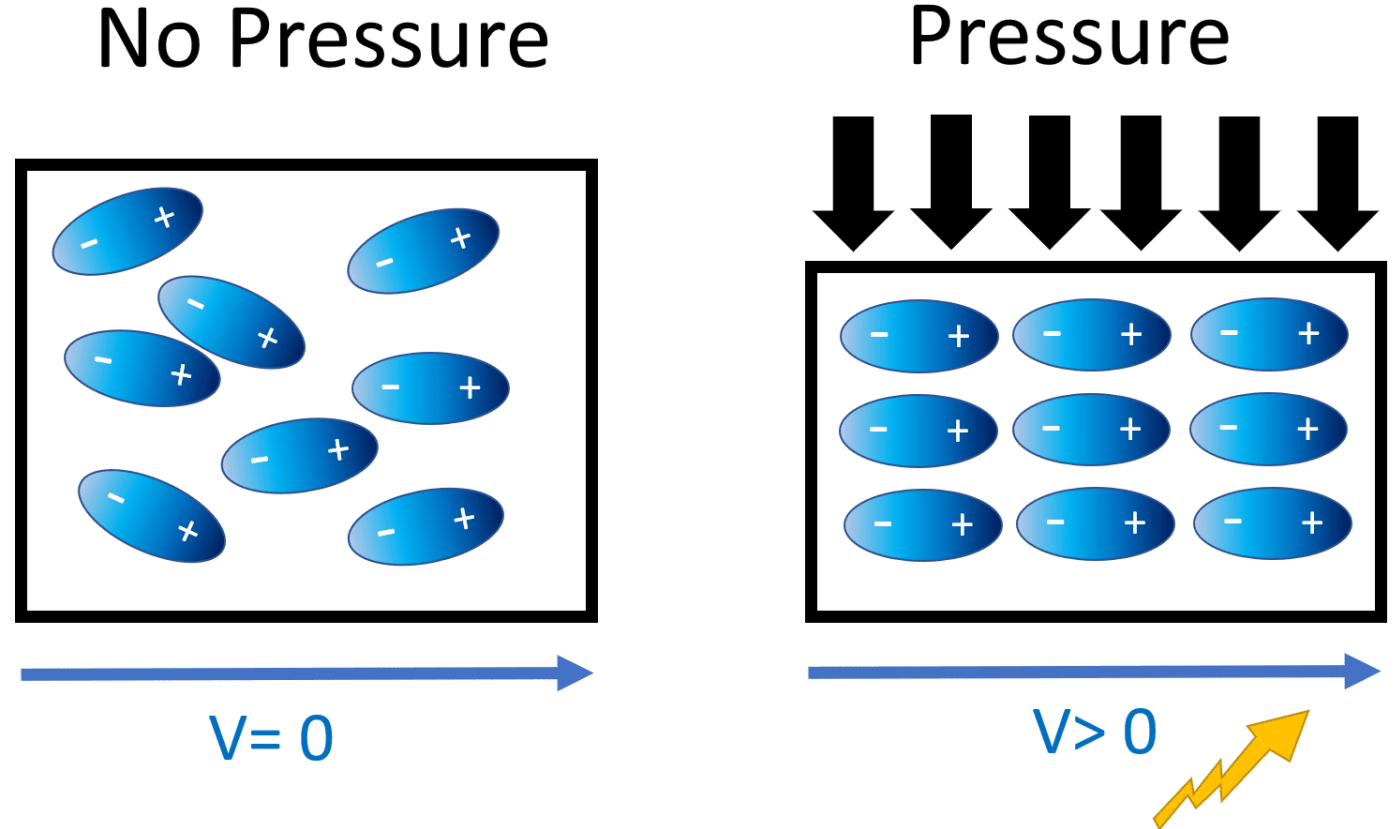
- Forms a "voltage divider"
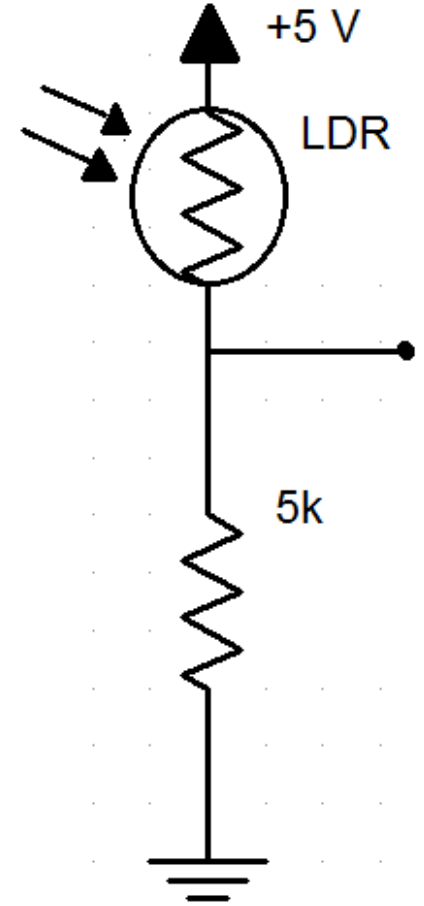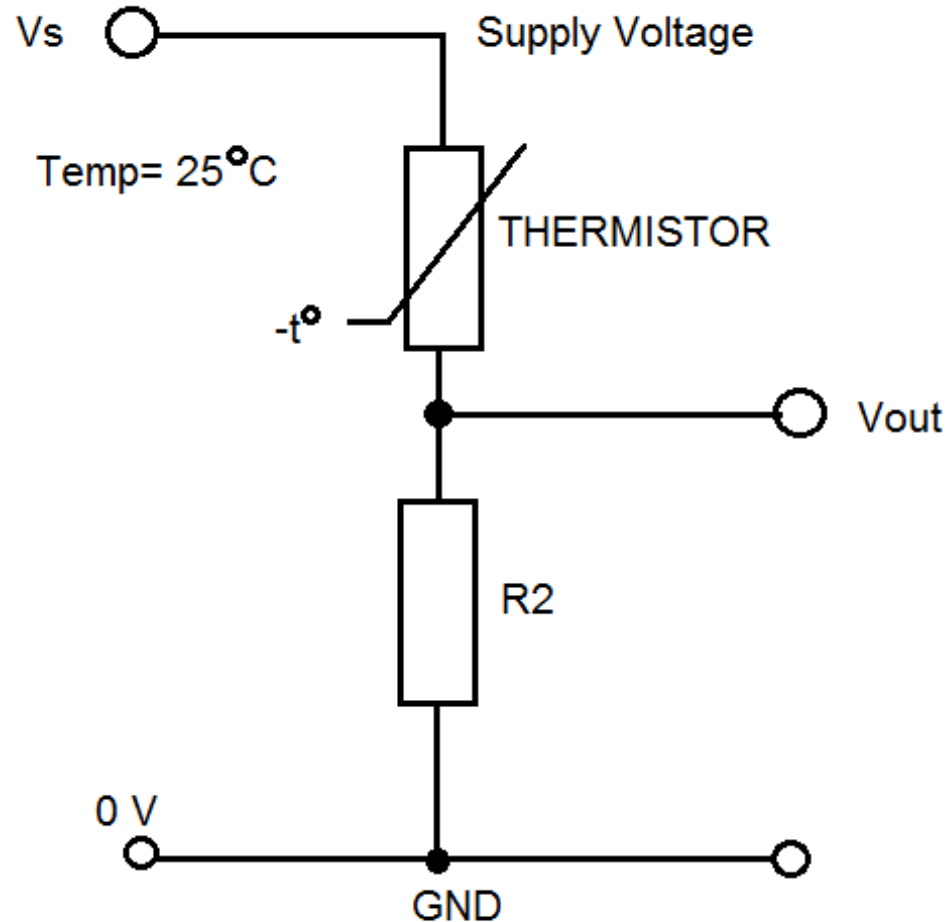
Voltage divider

- $V_{out} = \dfrac{R_2}{R_1 + R_2} * V_{in}$
  -
    V_{in} is a voltage source
    - R_1 and R_2 are resistors

- If $R_1 == R_2$
  - $V_{out} = V_{in}/2$

- Smaller R_1 means larger V_{out}
  - V_{out} approaches V_{in}

Generating voltage via piezoelectric effect

- Compression of the material generates a voltage

- Various sources of compression:
  - Air Pressure
  - Acceleration
  - Strain

No Pressure

V= 0

Pressure
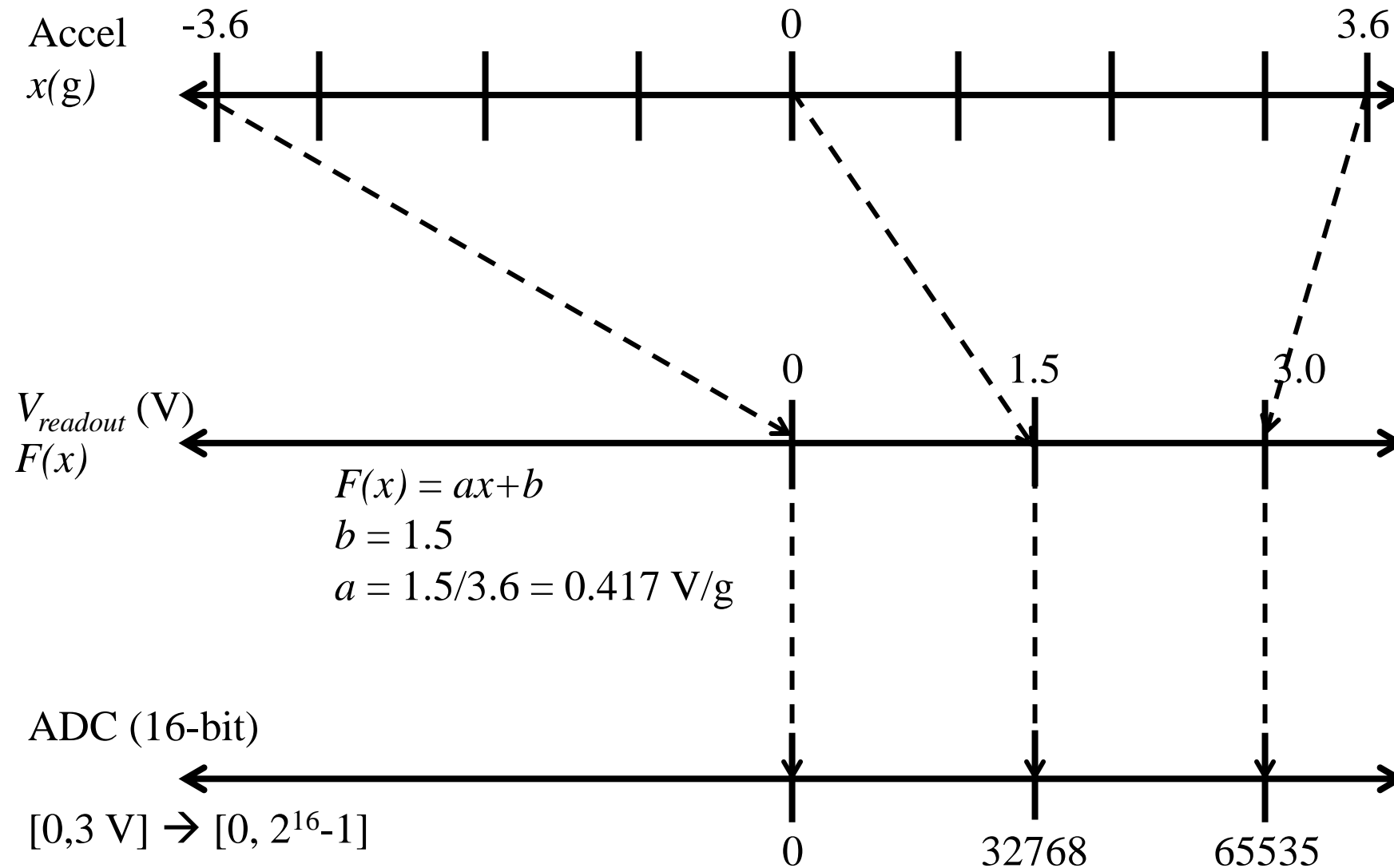
V> 0

Understanding sensor voltage

- Once you get a voltage, what do you do with it?

- Need to understand the transfer function between voltage and the sensed quantity
  - Examples for an accelerometer: senses acceleration

- Hopefully, function is linear
  - Occasionally, function is NOT

Affine sensor model (for linear sensors)

$$F(x) = ax + b$$

- x is the quantity being sensed
- F(x) is a voltage proportional to that quantity

- Parameters
  - a: sensitivity, units Volts/quantity
    - Change in voltage per change in quantity

  - b: bias, units Volts
    - Offset in voltage for zero of the quantity

Bias and sensitivity example

Accel
x(g)

-3.6   0   3.6

$V_{readout}$ (V)
$F(x)$

0   1.5   3.0

$F(x) = ax+b$
$b = 1.5$
$a = 1.5/3.6 = 0.417$ V/g

ADC (16-bit)

$[0,3$ V$] \rightarrow [0, 2^{16}-1]$

0   32768   65535

Understanding transfer function: ADXL330 datasheet

- Ratiometric
  - Relative to sensor voltage

- Bandwidth
 - Data update speed of the sensor

SPECIFICATIONS

$T_A = 25°C$, $V_S = 3$ V, $C_X = C_Y = C_Z = 0.1$ μF, acceleration = 0 g, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

Table 1.

Parameter	Conditions	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Measurement Range		±3	±3.6		g
Nonlinearity	% of full scale		±0.3		%
Package Alignment Error			±1		Degrees
Inter-Axis Alignment Error			±0.1		Degrees
Cross Axis Sensitivity[1]			±1		%
SENSITIVITY (RATIOMETRIC)[2]	Each axis				
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	$V_S = 3$ V	270	300	330	mV/g
Sensitivity Change Due to Temperature[3]	$V_S = 3$ V		±0.015		%/°C
ZERO g BIAS LEVEL (RATIOMETRIC)	Each axis				
0 g Voltage at X_{OUT}, Y_{OUT}, Z_{OUT}	$V_S = 3$ V	1.2	1.5	1.8	V
0 g Offset vs. Temperature			±1		mg/°C
NOISE PERFORMANCE					
Noise Density X_{OUT}, Y_{OUT}			280		μg/√Hz rms
Noise Density Z_{OUT}			350		μg/√Hz rms
FREQUENCY RESPONSE[4]					
Bandwidth X_{OUT}, Y_{OUT}[5]	No external filter		1600		Hz
Bandwidth Z_{OUT}[5]	No external filter		550		Hz
R_{FILT} Tolerance			32 ± 15%		kΩ
Sensor Resonant Frequency			5.5		kHz

Active and passive sensing

Passive Sensing
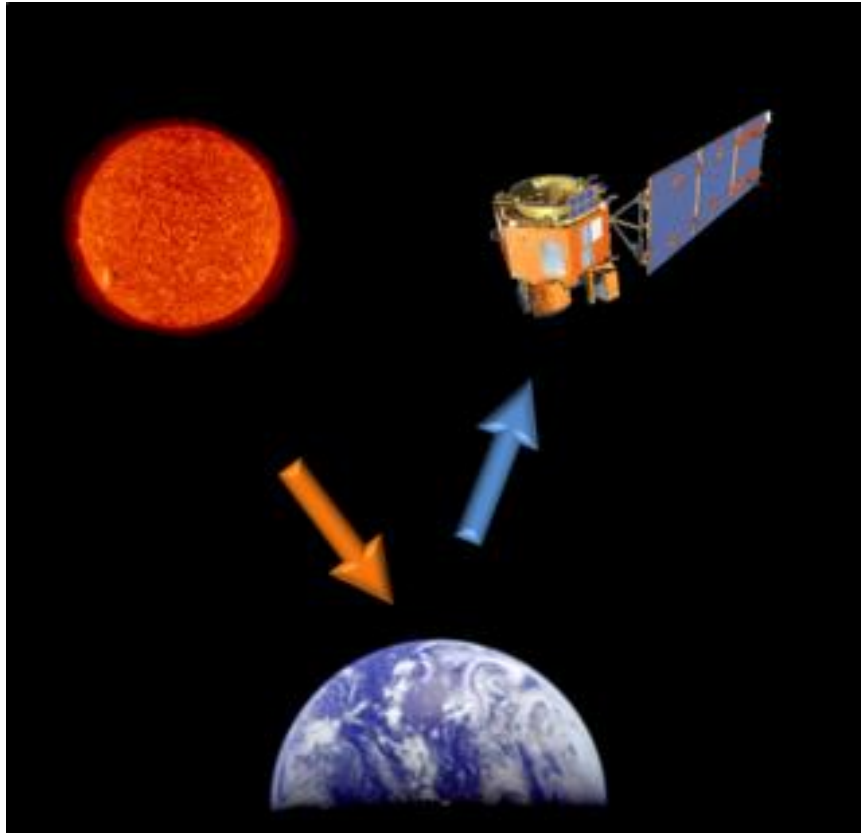
Active Sensing
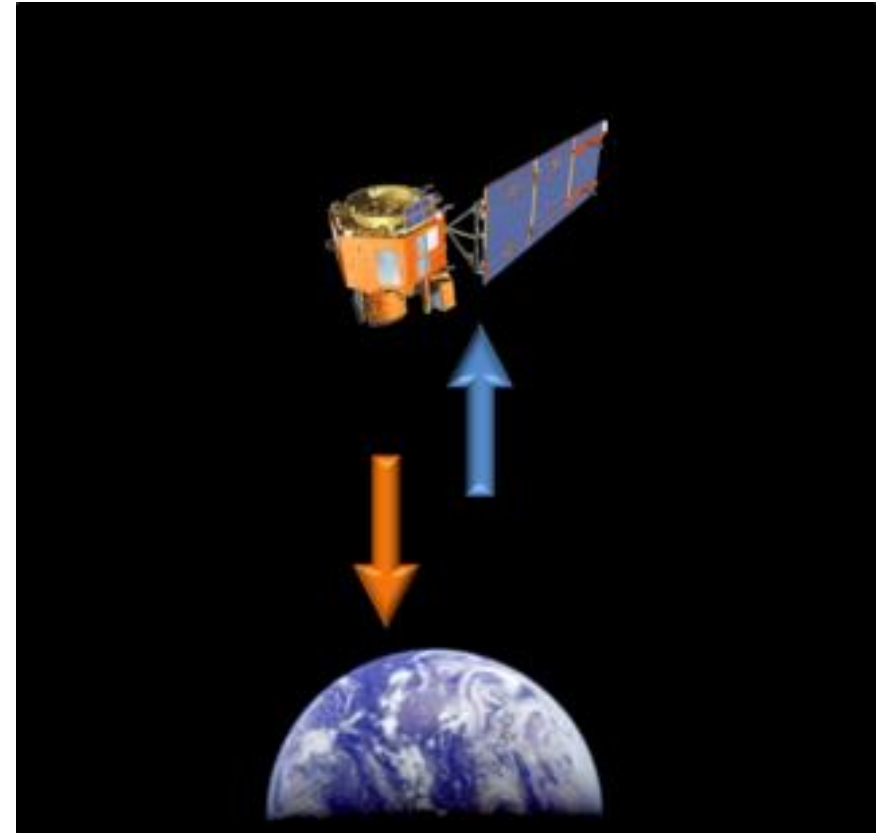
Active and passive sensing

- We usually focus on passive sensing
  - Cheaper and lower energy costs!

- Active sensing examples
  - Flash photography
  - Ultrasonic distance sensing
  - Lidar and Radar

Intelligent sensors

- Many embedded sensors are more intelligent than simple analog

- Combine it with a built-in ADC
  - Can be more finely tuned and calibrated for accuracy
  - Now gives digital output over some wired communication mechanism

- Combine it with additional circuitry / computation
  - Automatically filter data
  - Detect specific signal patterns and interrupt

- I pointed most groups at intelligent sensors (QWIIC)

Break + Question

- Accelerometer
  - Measures 0-5 g
  - Over a 0-5v range

- What is sensitivity?

- What is bias?

- What acceleration is the voltage reading 3.5 volts?

Break + Question

- Accelerometer
  - Measures 0-5 g
  - Over a 0-5v range

- What is sensitivity?   1 v/g

- What is bias?   0 v

- What acceleration is the voltage reading 3.5 volts?
  - 3.5 v = 1v/g * x + 0v -> 3.5 g

Outline

- Sensing Overview

- **Types of Sensors**
  - **Temperature**
  - Light
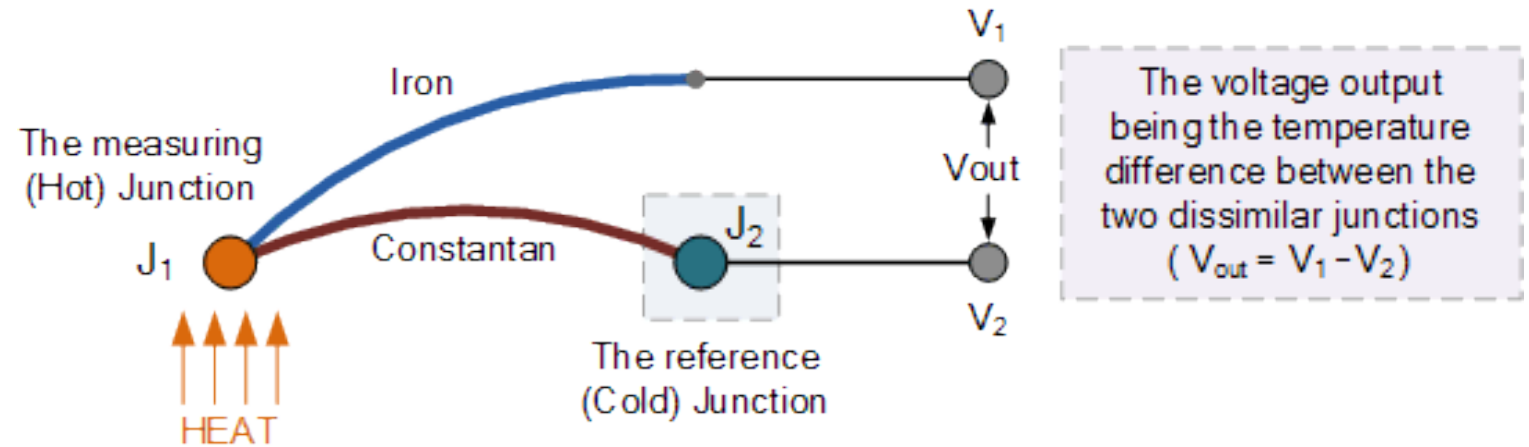 - Inertial
  - Others

- Research case study

Digital temperature sensor

- **Thermostat**
  - Original meaning of the word

- Heat bends a strip of two different metals

- Switches circuit on/off based on the temperature

Electrical connection

Bi-metallic strip

Higher Metal Strip
Lower Metal Strip

Electrical Contacts Closed

Electrical Contacts

Electrical connection

Electrical Contacts open due to Heat

Contact Movement

Open circuit condition

Fixed Point

HEAT
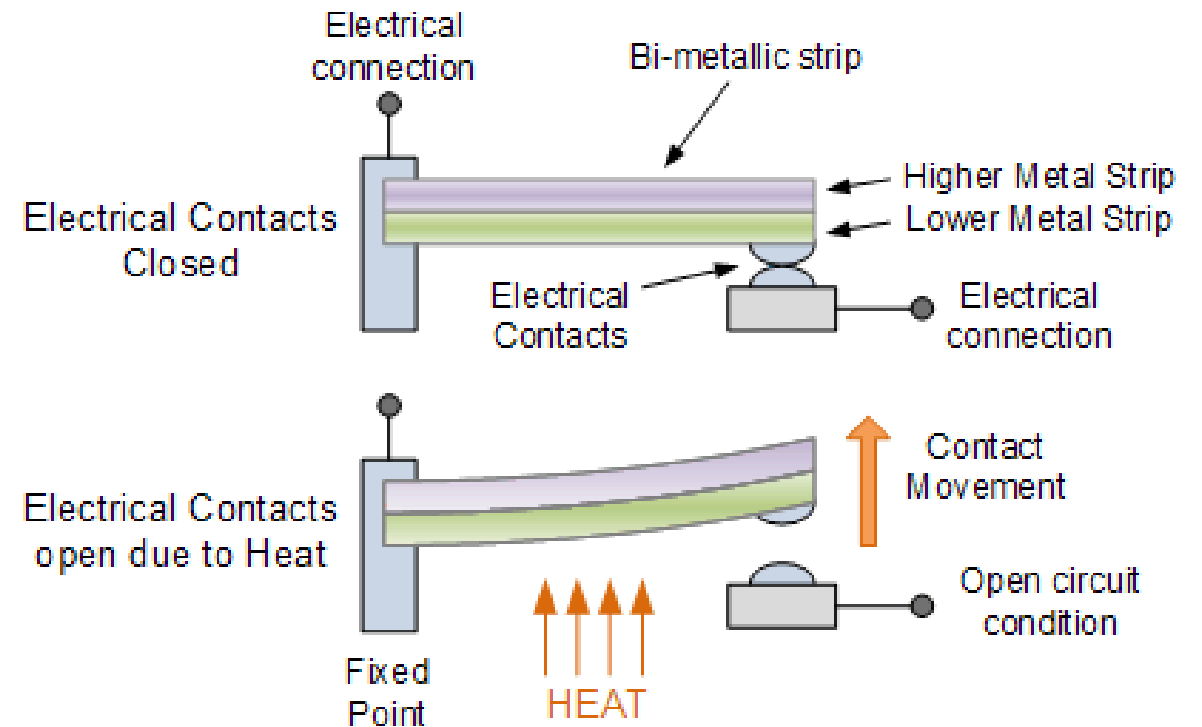
Thermo-electric temperature sensing

- **Thermocouple** generates a voltage based on temperature

- Can be used to harvest energy to run system
  - Part of RTG design

Resistive temperature sensing

- **Thermistor** varies resistance based on temperature

- Set up as a voltage divider to measure

- Advantages: extremely cheap and easy to use
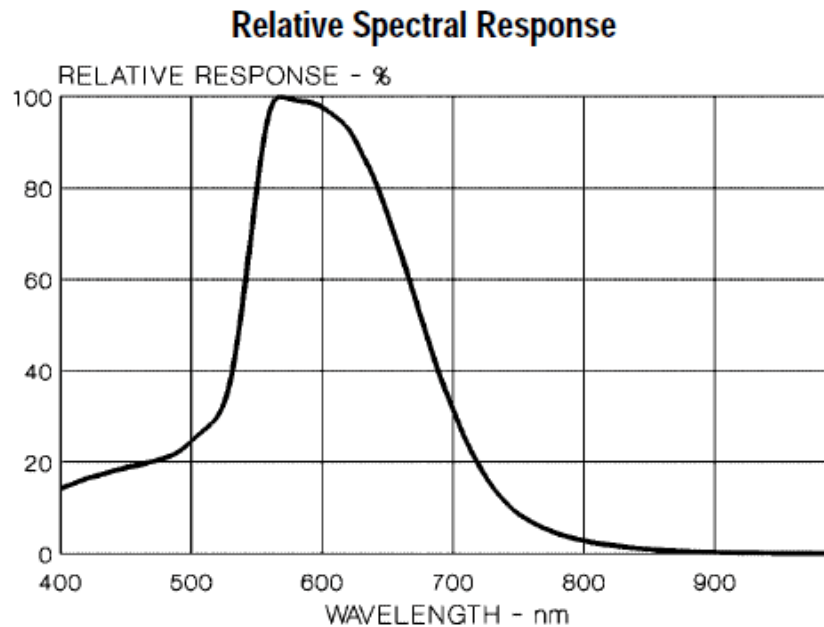
- Disadvantages: non-linear transfer function
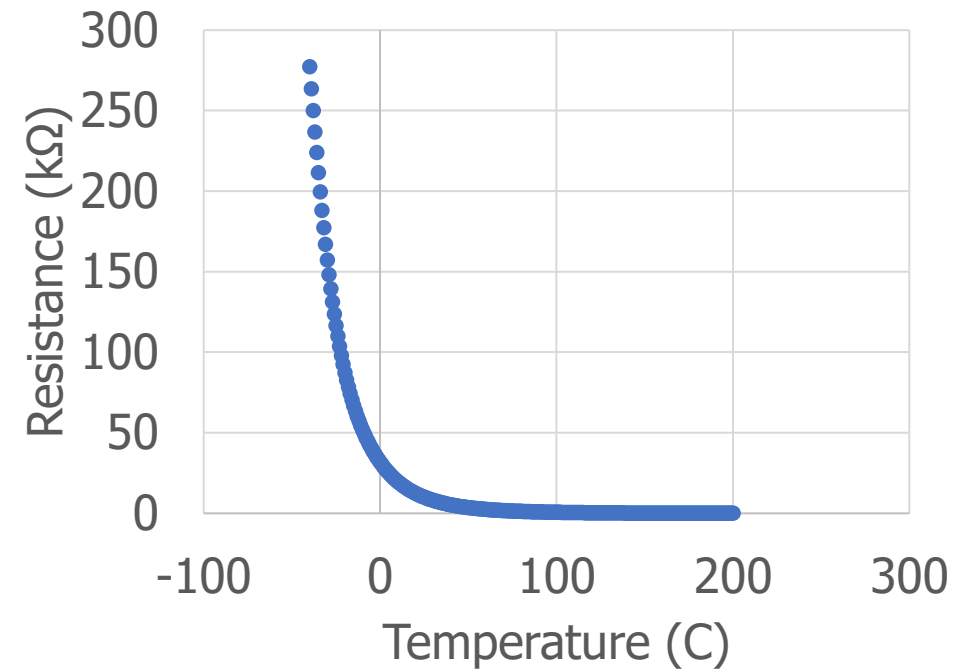
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Measuring light

- Lux: unit of illuminance

- Beware spectrum sensitivity

Relative Spectral Response

RELATIVE RESPONSE - %

WAVELENGTH - nm

Illuminance	Example
0.002 lux	Moonless clear night sky
0.2 lux	Design minimum for emergency lighting (AS2293).
0.27 - 1 lux	Full moon on a clear night
3.4 lux	Dark limit of civil twilight under a clear sky
50 lux	Family living room
80 lux	Hallway/toilet
100 lux	Very dark overcast day
300 - 500 lux	Sunrise or sunset on a clear day. Well-lit office area.
1,000 lux	Overcast day; typical TV studio lighting
10,000 - 25,000 lux	Full daylight (not direct sun)
32,000 - 130,000 lux	Direct sunlight

Resistive light sensing

• **Photocell** changes resistance with light (non-linear)

Electrodes
Clear coating over entire top surface
Cold weld contacts
Photoconductive material over top surface
Ceramic
Wire terminals

ABSOLUTE MAXIMUM RATING (TA)= 23°C UNLESS OTHERWISE NOTED

SYMBOL	PARAMETER	MIN	MAX	UNITS
V_{pk}	Applied Voltage		150	V
$P_{d \, \Delta po/\Delta t}$	Continuous Power Dissipation		100	mW/°C
T_O	Operating and Storage Temperature	-30	+75	°C
T_S	Soldering Temperature*		+260	°C

* 0.200 inch from base for 3 seconds with heat sink.

ELECTRO-OPTICAL CHARACTERISTICS RATING (TA)= 23°C UNLESS OTHERWISE NOTED

SYMBOL	CHARACTERISTIC	TEST CONDITIONS	MIN	TYP	MAX	UNITS
R_D	Dark Resistance	After 10 sec. @ 10 Lux @ 2856 °K	0.2			MΩ
R_I	Illuminated Resistance	10 Lux @ 2856 °K	3		11	KΩ
S	Sensitivity	LOG(R100)-LOG(R10)** / LOG(E100)-LOG(E10)***		0.6		Ω/Lux
λrange	Spectral Application Range	Flooded	400		700	nm
λpeak	Spectral Application Range	Flooded		520		nm
t_r	Rise Time	10 Lux @ 2856 °K		55		ms
T_f	Fall Time	After 10 Lux @ 2856 °K		20		ms

**R100, R10: cell resistances at 100 Lux and 10 Lux at 2856 °K respectively .
***E100, E10: luminances at 100 Lux and 10 Lux 2856 °K respectively.
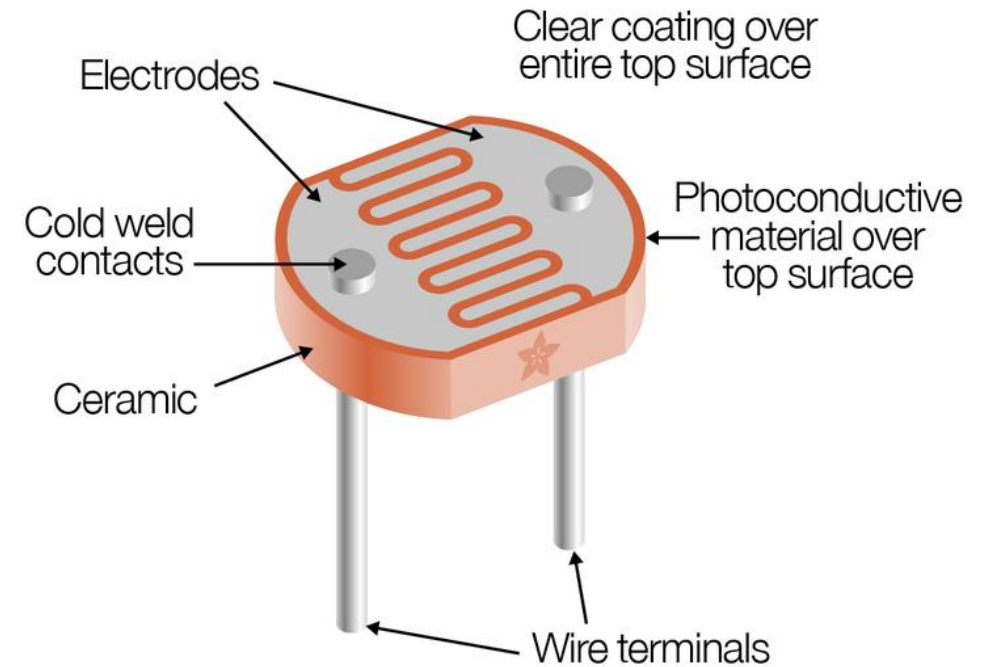
Kit version:
• 10 kΩ when dark
• 1 kΩ when light

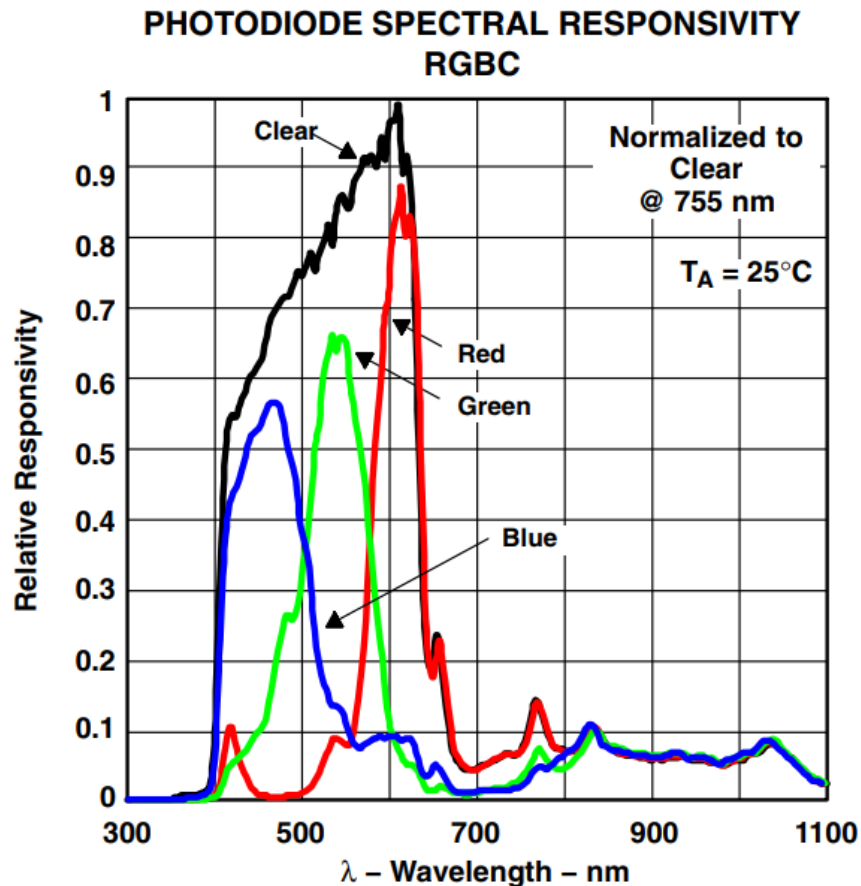# Photodiodes leak current based on light levels

- When voltage is applied in reverse to an ideal diode, no current flows

- But some small amount of current leaks for real-world diodes
  - Proportional to light levels!

- LEDs can be used as (crappy) photodiodes as well!
  - Apply reverse voltage
  - Read in leak current as voltage across a resistor using ADC

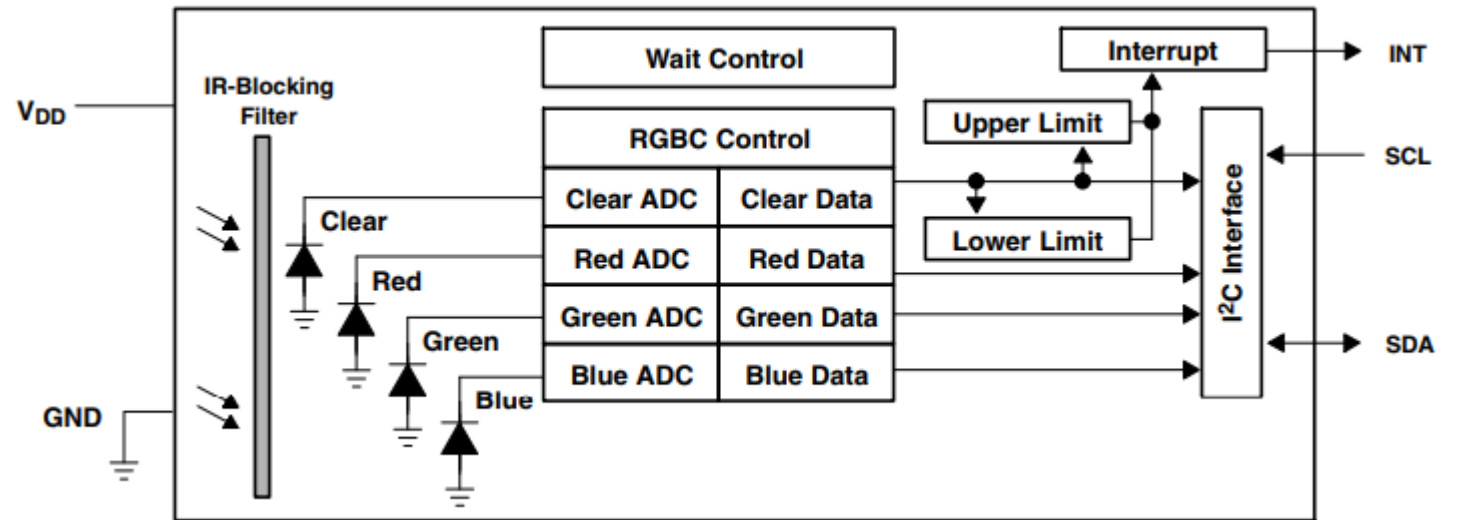https://wiki.analog.com/university/courses/electronics/electronics-lab-led-sensor
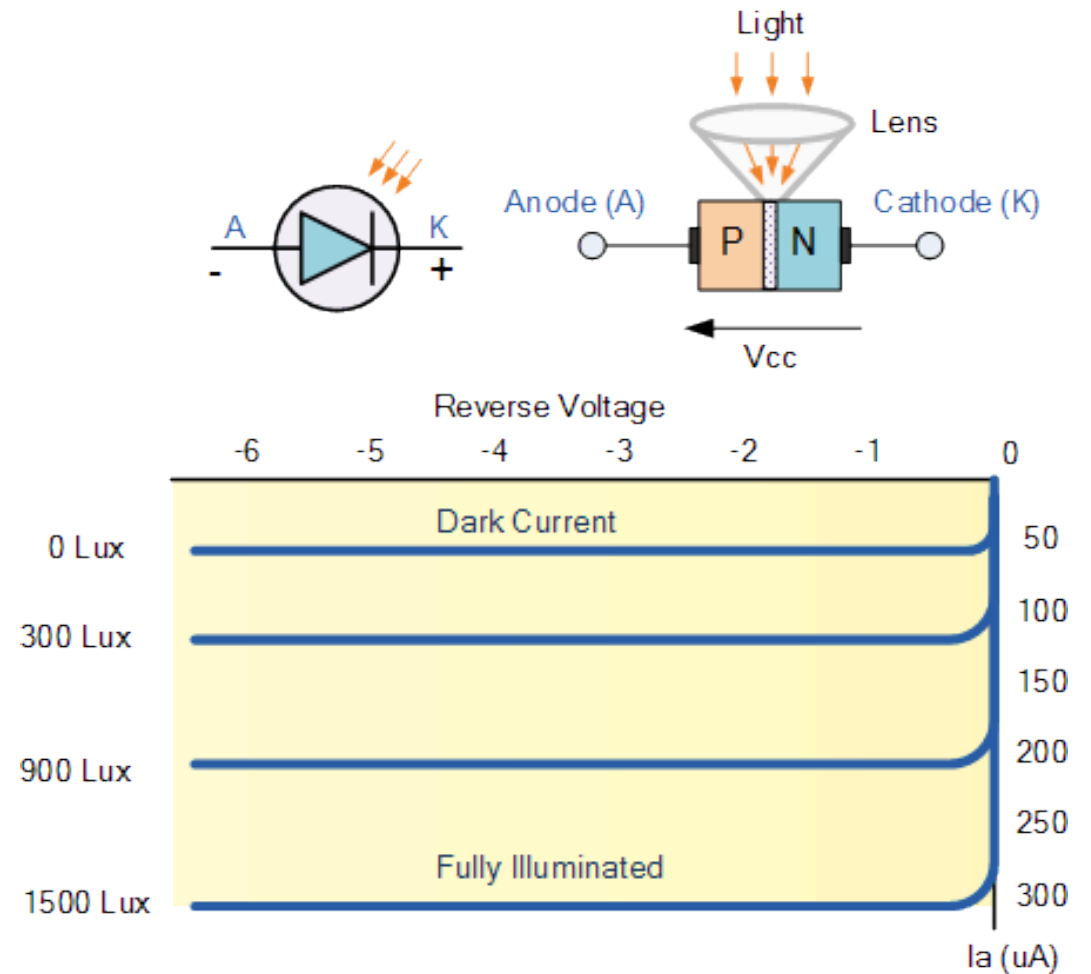
Light color sensing

- Respond to specific light colors separately

PHOTODIODE SPECTRAL RESPONSIVITY RGBC

- Intelligent sensor: photodiodes combined with ADCs and a wired interface (I2C)
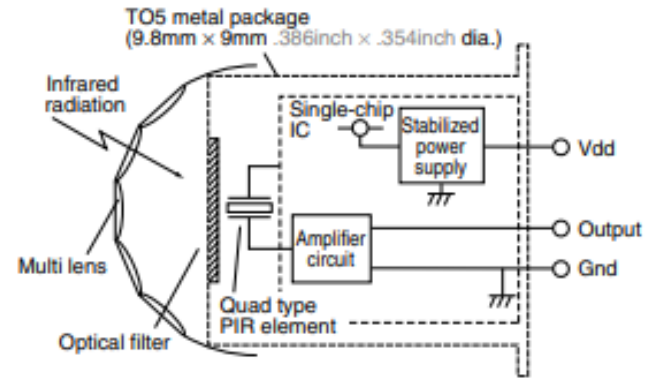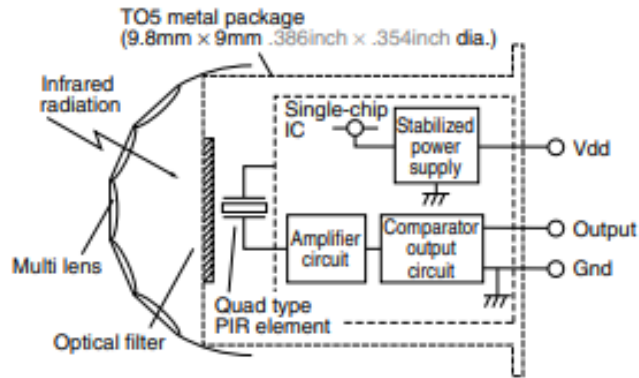- Allows interrupting based on comparator too

Passive Infrared (PIR) sensor

- Detect movement in the environment
  - By detecting change in IR levels

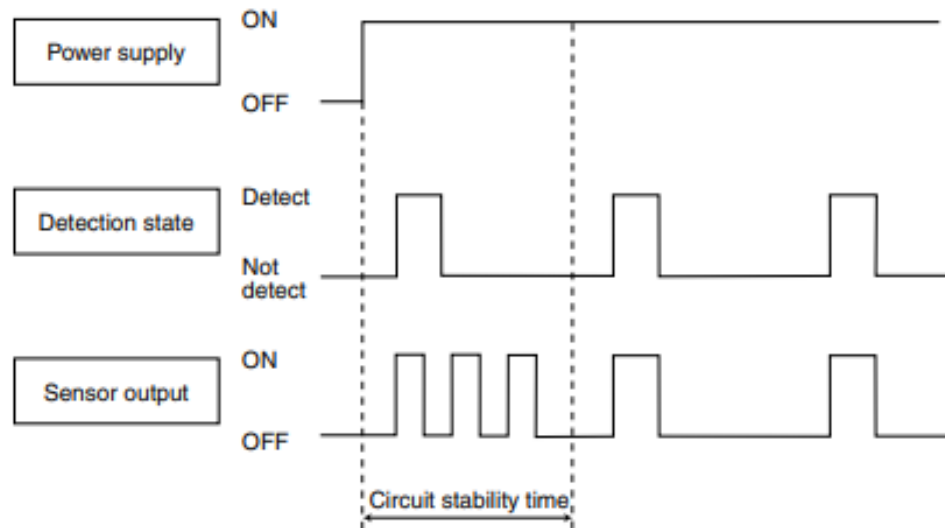- Often come with plastic lens cover to improve field of view and range
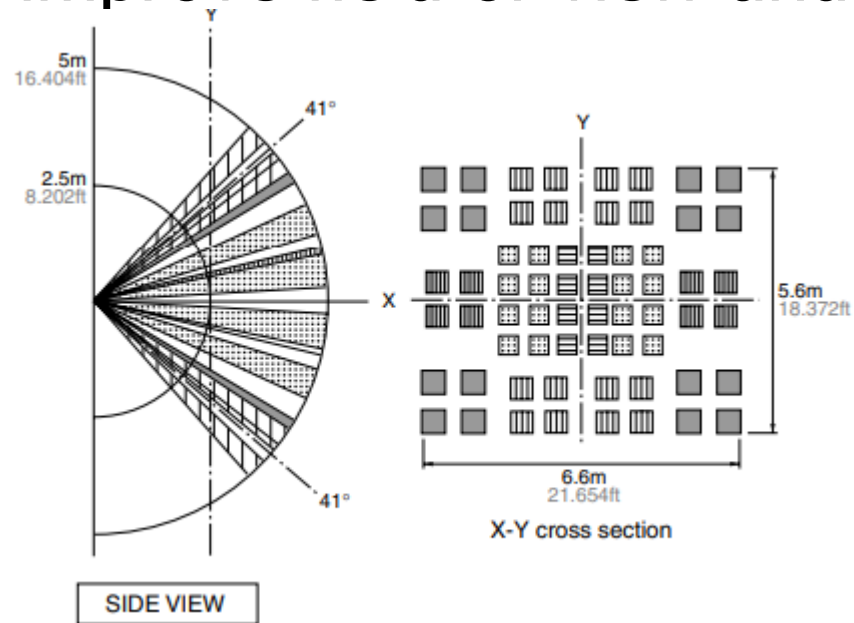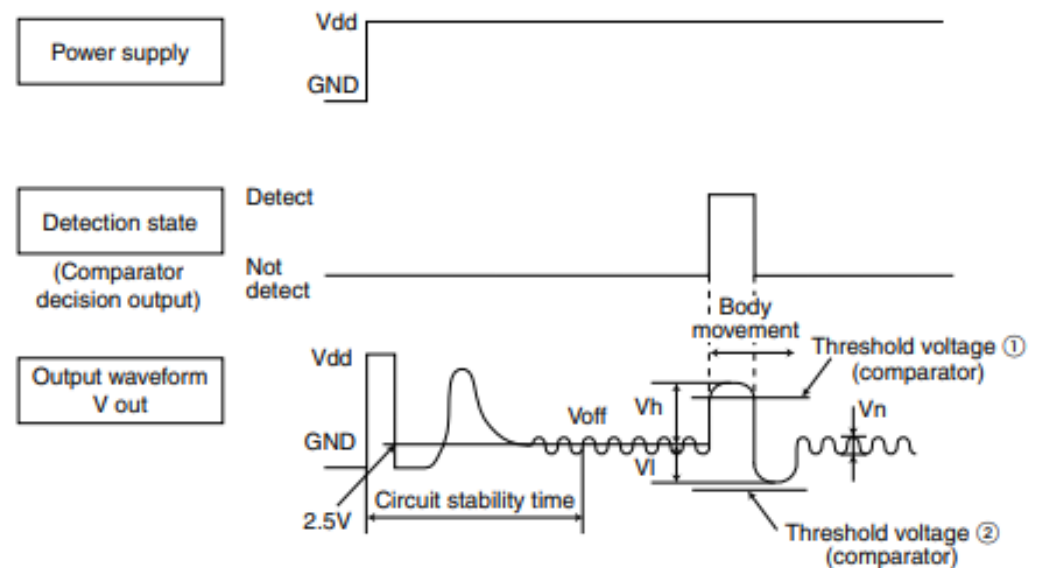
PIR sensors come in digital and analog forms

TO5 metal package
(9.8mm × 9mm .386inch × .354inch dia.)

Infrared radiation
Multi lens
Optical filter
Quad type PIR element
Single-chip IC
Stabilized power supply
Amplifier circuit
Comparator output circuit
Vdd
Output
Gnd

TO5 metal package
(9.8mm × 9mm .386inch × .354inch dia.)

Infrared radiation
Multi lens
Optical filter
Quad type PIR element
Single-chip IC
Stabilized power supply
Amplifier circuit
Vdd
Output
Gnd

4. Timing chart

1) Digital output

Power supply — ON / OFF
Detection state — Detect / Not detect
Sensor output — ON / OFF
Circuit stability time

2) Analog output

Power supply — Vdd / GND
Detection state (Comparator decision output) — Detect / Not detect
Output waveform V out — Vdd / GND
Body movement
Threshold voltage ① (comparator)
Voff, Vh, Vn, Vi
Threshold voltage ② (comparator)
2.5V
Circuit stability time

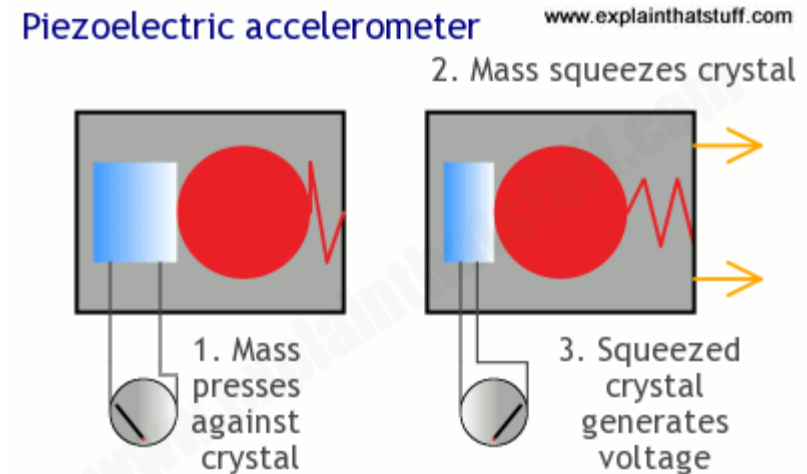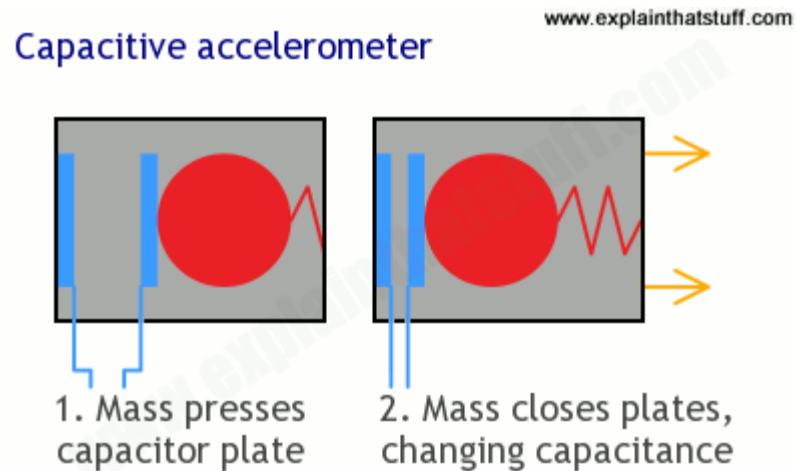Digital includes a preconfigured comparator

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Inertial Measurement Unit (IMU)

- IMUs (a.k.a 9 degree-of-freedom, 9DOF) are used for tracking motion of a device
  - Acceleration (X, Y, Z axes)
  - Rotation (X, Y, Z axes)
  - Magnetism (X, Y, Z axes)

  - Sometimes 6DOF with Acceleration + one of the others

- Intelligent sensing: combines multiple sensors, ADCs, and computation with a wired interface
  - 9 analog inputs would otherwise be too many

- Can be used to track motion, determine transportation method
  - Smartphones, Robotics, etc.

Sensing acceleration

- Goal: create a voltage that changes based on force

Capacitive accelerometer — www.explainthatstuff.com
1. Mass presses capacitor plate
2. Mass closes plates, changing capacitance

Piezoelectric accelerometer — www.explainthatstuff.com
2. Mass squeezes crystal
1. Mass presses against crystal
3. Squeezed crystal generates voltage

Microelectromechanical Systems (MEMS)

- Same concept, but within an IC and 1 to 100 micrometers in size
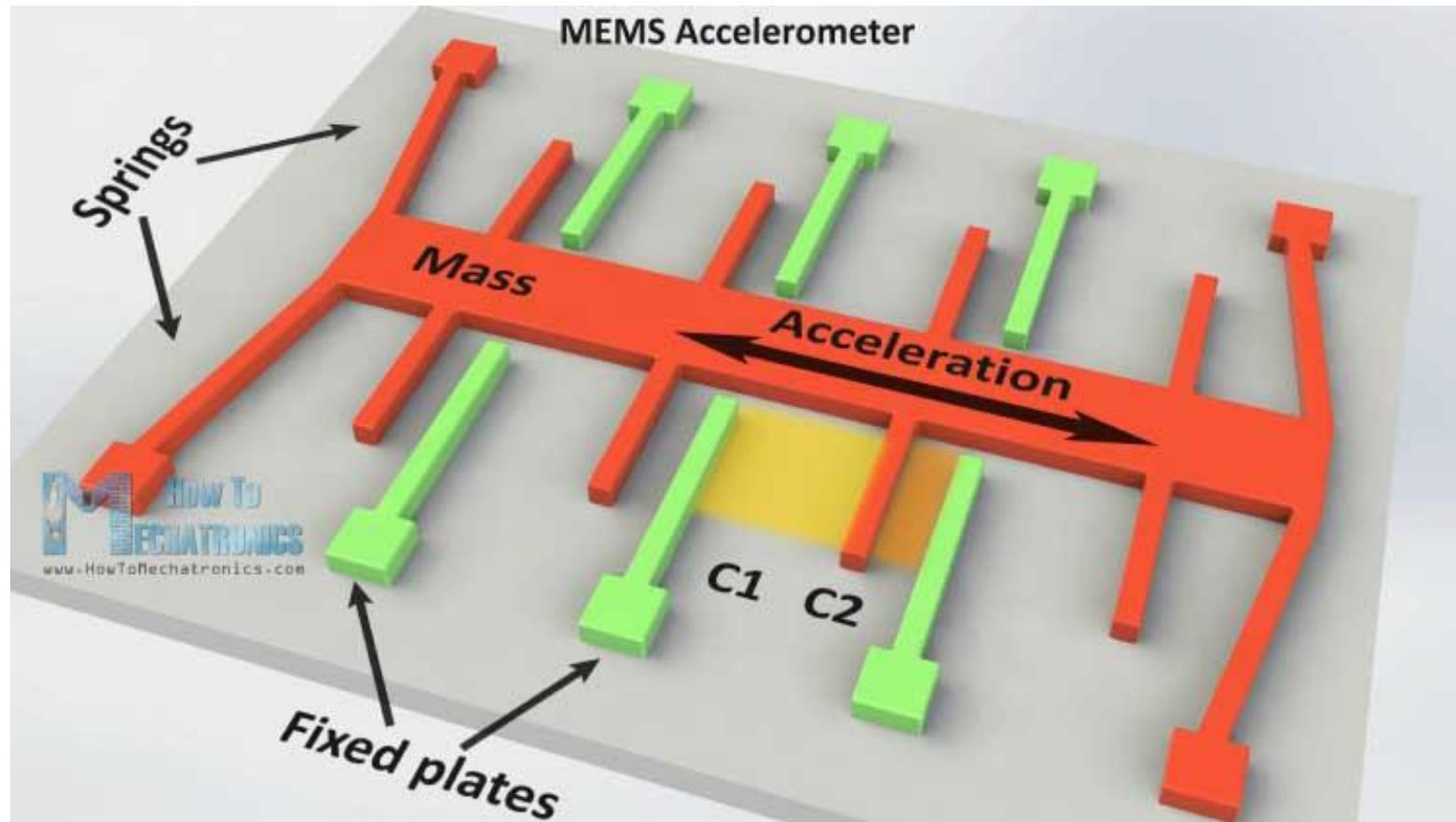
Using accelerometers

- Accelerometers usually measure in g's
  - Where 1 g equals acceleration due to Earth gravity

- Determining distance from acceleration is possible
  - But messy. Error is squared when integrating
  - Needs careful filtering and is only accurate over short periods
  - Often fills in gaps between GPS samples (or other localization systems)

- Accelerometers also work as tilt sensors
  - Constantly sensing pull of gravity
  - $A[x] = 1\,g\,*\,\sin(\theta)$
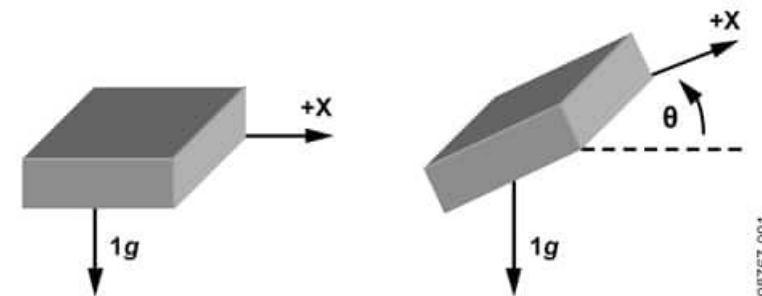
Gyroscopes

- Measures angular velocity
  - Usually lower limit than you might hope
  - <10 rotations per second

- Usually, we want angle instead of rotation speed
  - Integrate signal to determine current angle
  - Combine noise and DC bias with integration and you get a continuously accumulating error: drift
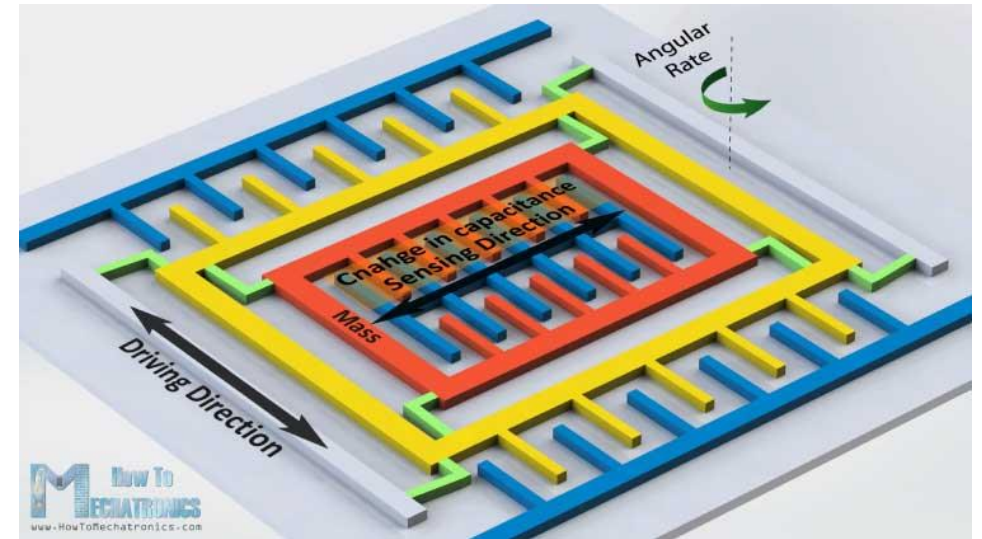
Magnetometer

- Measures the magnetic field

- Usually used in devices as a compass
  - Detect Earth's magnetic field orientation

- Problem: Earth's magnetic field often overwhelmed by local magnetism when indoors
  - Large chunks of metal in walls, for example
  - Or other metal parts nearby on the circuit board

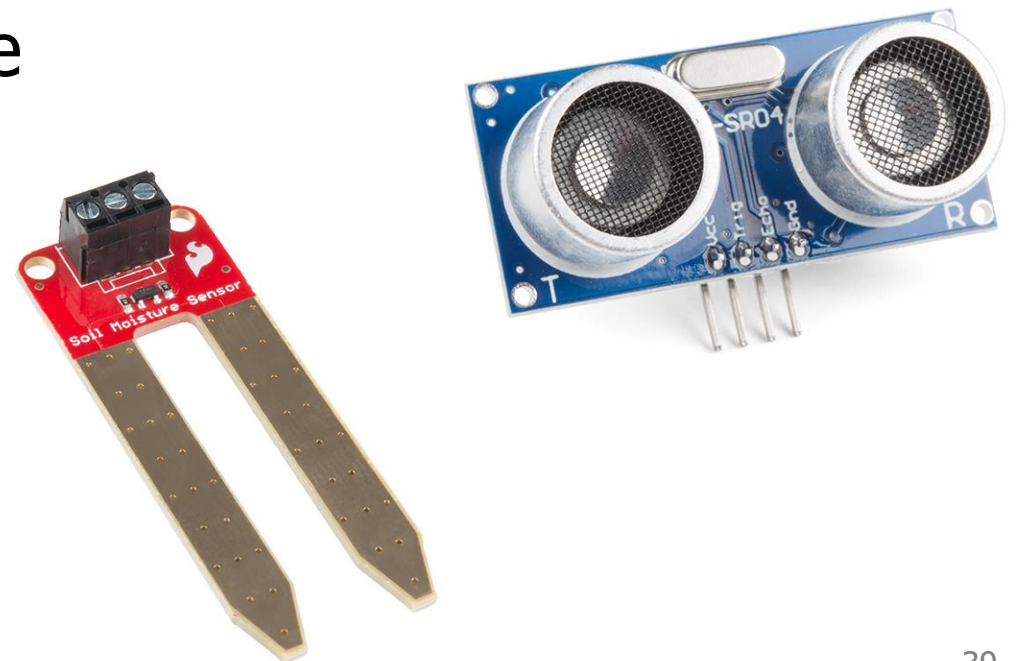- Satellites can use magnetometers for localization
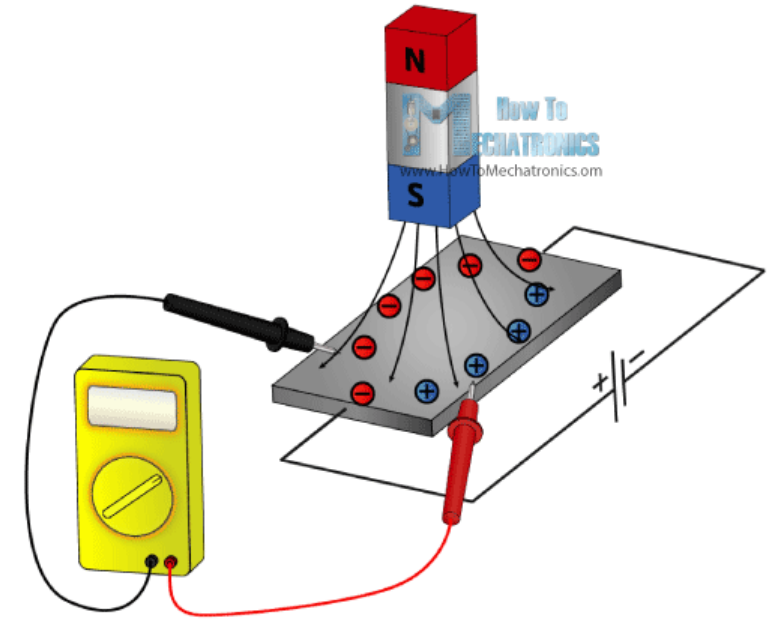
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Other sensors

- Environment: Pressure, Humidity, Air Velocity, Air Quality

- Distance: Ultrasonic, Lidar, or Radar

- Biometric: Pulse Oximeter, Heart Rate

- Agricultural: Soil moisture

Break + Open Question

How are new sensors discovered/created?

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- **Research case study**

PowerBlade current sensing

- Example of creating a custom sensor

- PowerBlade goals
  - Sense current and voltage in real-time
  - Be small enough to be deployable

- Problem
  - To measure current, you *usually* have to break the circuit
 - But PowerBlade attaches in parallel
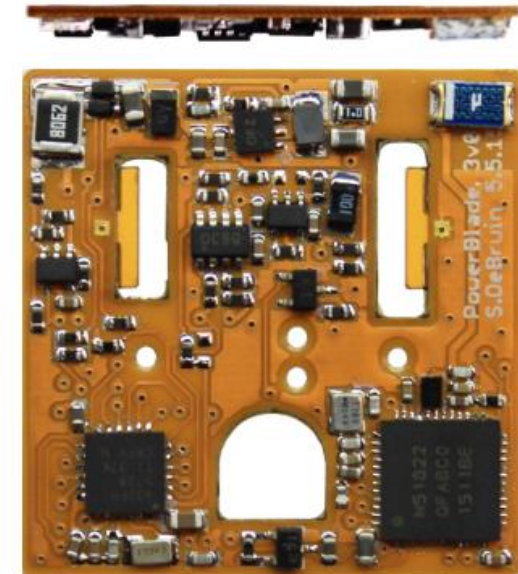
Measuring current

- Coil of wire in a changing electric/magnetic field produces a voltage

- One way to make inductors is as a coil of wire wrapped horizontally around a magnetic core

- Re-purpose horizontally wire-wound inductor as current sensor!
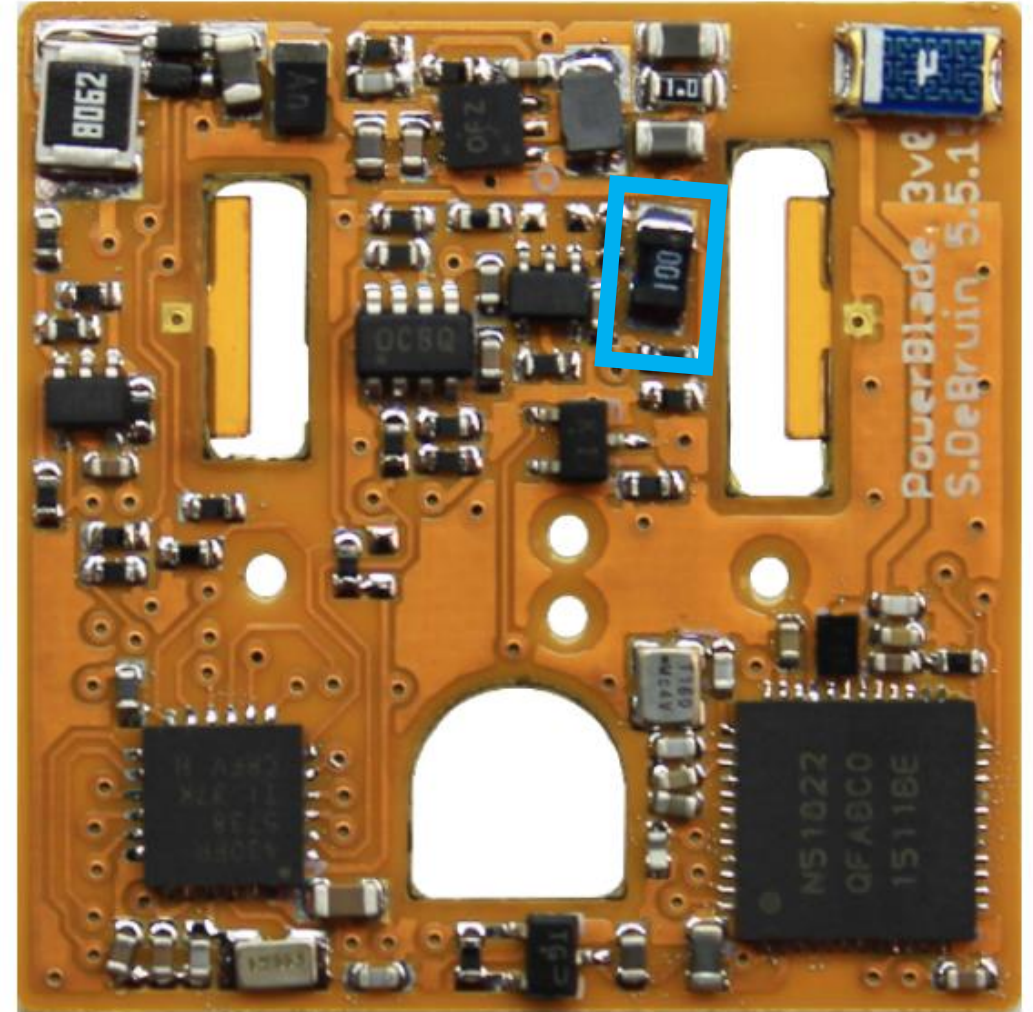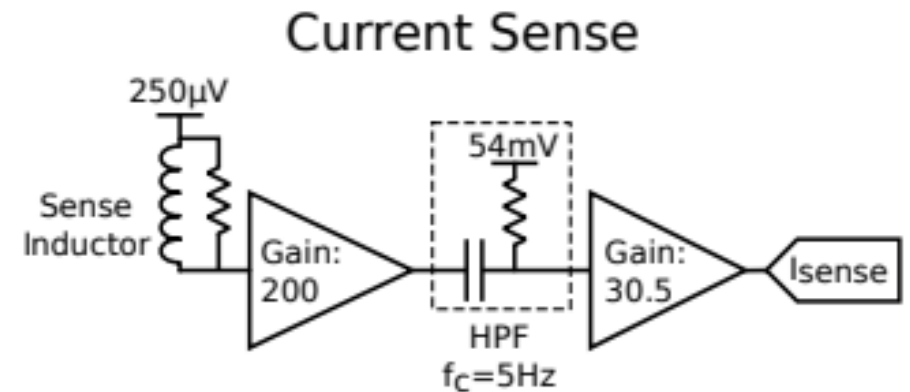
Sensor placement

- Is in the middle or close to a prong the best choice?

- Turns out it's closer to a prong
  - Decreases with distance squared

- Angled like the magnetic field is
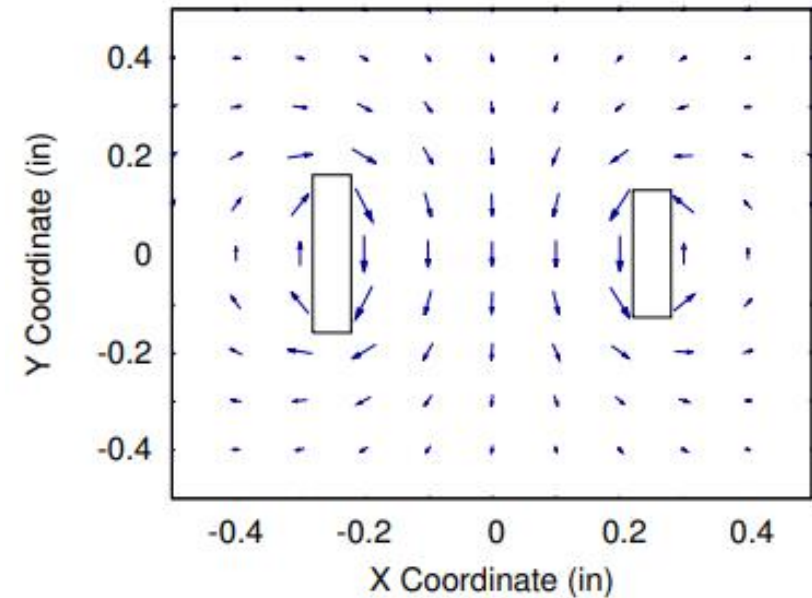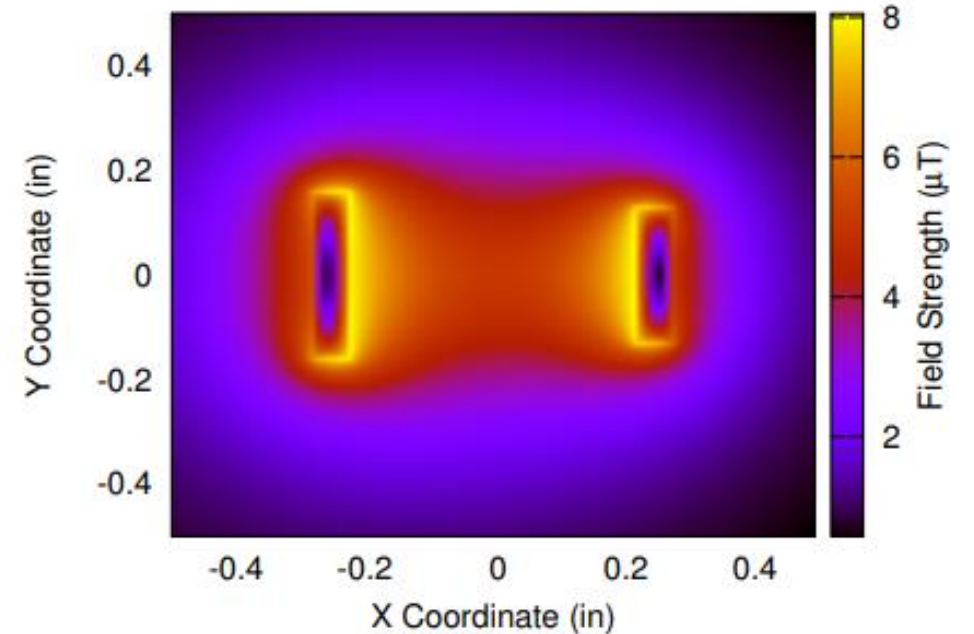
Measuring sensor values

- Sensor output is very small

- Amplify to make output large enough to accurately measure with ADC

- Need to pick sampling rate
  - AC: 60 cycles per second in US
  - Need N * 60 measurements per second
  - N=42 (as fast as we can measure)
    - 2520 measurements per second

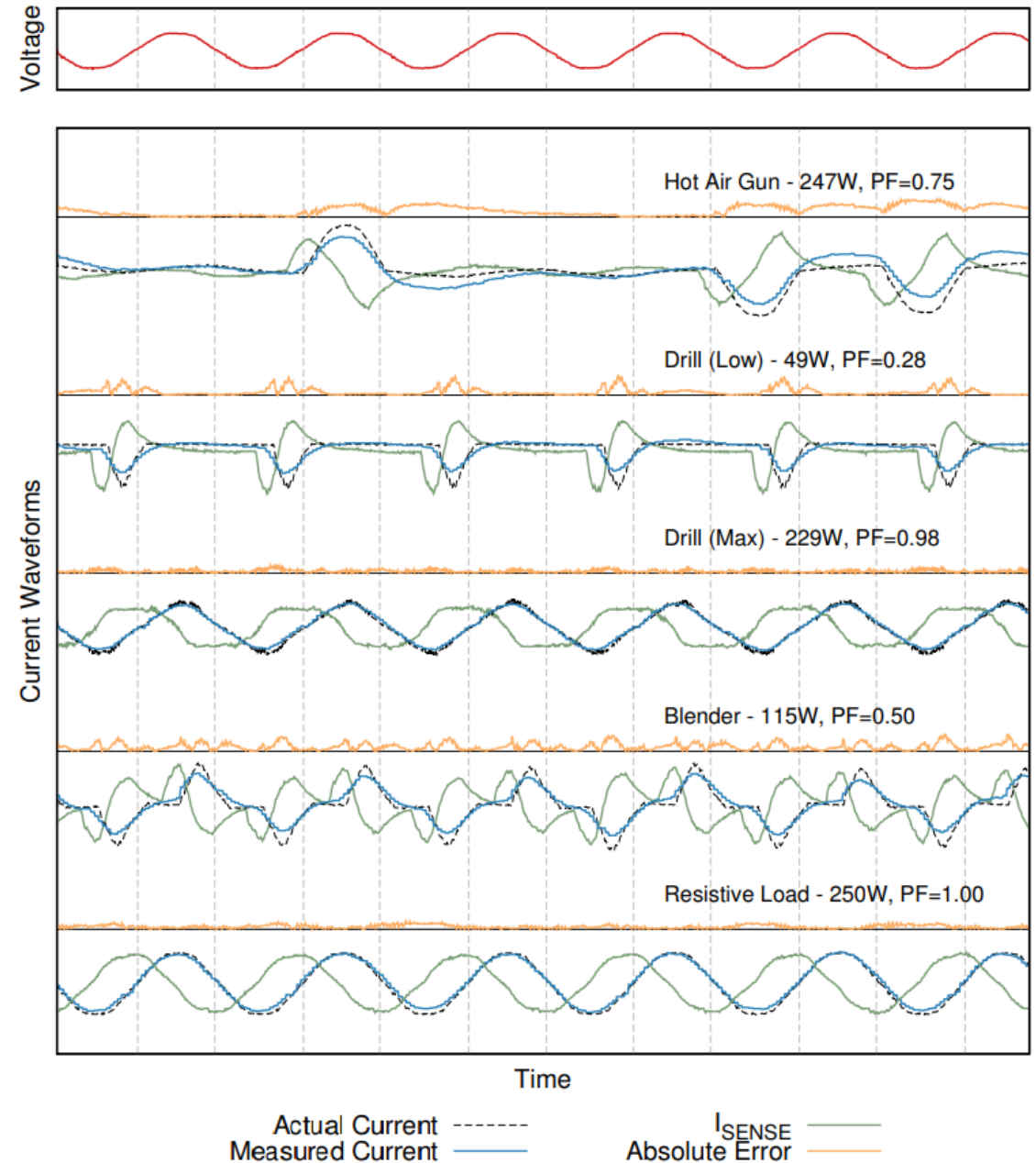Current Sense

At first, our output signal was this green line

Blender - 115W, PF=0.50

Resistive Load - 250W, PF=1.00
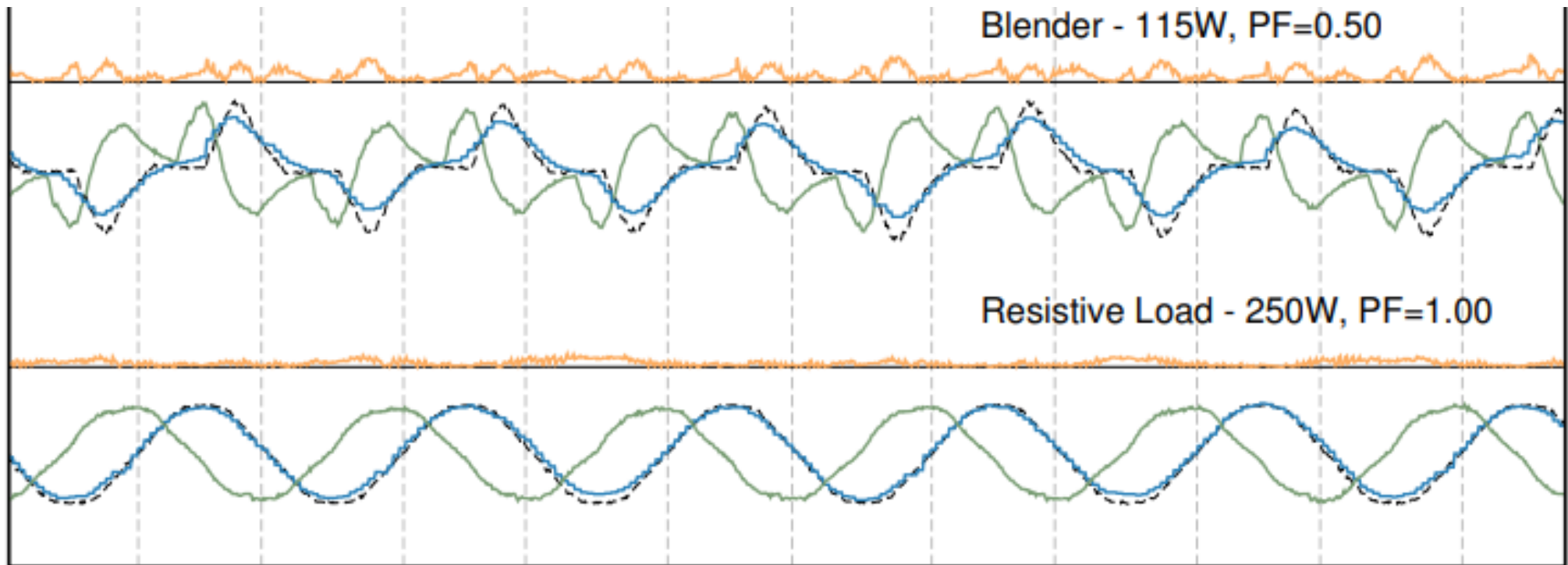
Time

Actual Current — — — — —   I SENSE
Measured Current ———————   Absolute Error

Measurement into current

- Search coil measures the derivative of current!!

- Need to integrate to get signal and apply sensitivity and bias

$$Current \approx \int \left(\frac{V_{CC}}{2} + \alpha \frac{dI}{dt} \right) dt \approx \alpha I + \beta$$

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